REVIEW OF RECENT ADVANCES IN MAGNETIC NANOPARTICLES AND VARIOUS APPLICATIONS

Yadagiri Goud V
Research Scholar
Department of Chemistry
NIILM University, Kaithal.
yadagiri02@gmail.com

Dr. Jyotsna
Research Guide
Department of Chemistry
NIILM University, Kaithal.

Abstract

Numerous uses for nanoparticles (NPs) have transformed a number of societal fields. Due to its applications in specialized fields including medicine, cancer theranostics, biosensing, catalysis, agriculture, and the environment, magnetic nanoparticles (MNPs) in particular have attracted a great deal of attention in the last ten years. The design of multi-functional MNPs must include controlled surface engineering if the intended use is to be realized. The MNPs have shown to be very effective as biosensors, imaging agents, drug delivery systems, and thermoelectric materials. In this review, we have first briefly covered the primary techniques of MNP synthesis before moving on to their characterisation and composition. Then, using illustrative examples, we examined the possible uses of MNPs in various fields. We concluded by providing a summary of the present difficulties and potential futures for MNPs. This thorough analysis not only explains the synthesis, functionalization, and use of MNPs from a mechanistic perspective, but it also discusses their limitations and future possibilities.

***Keywords**: magnetic nanoparticles, synthesis, characterization, composition, applications*

INTRODUCTION

Recent developments in the area of nanotechnology have helped to progress and revolutionize a variety of industries. The number of advantages and uses for nanotechnology is expanding quickly. Nanoparticles (NPs) are tiny particles that typically vary in size from 1 to 100 nm, which sets them apart from their parent bulkier materials and makes them suitable for a variety of applications. Magnetic nanoparticles (MNPs), a nanoscale substance with distinctive magnetic characteristics, are one of them and have been extensively employed in a variety of fields, including biomedical, energy, engineering, and environmental applications. The MNPs have recently been a focus of intense study due to their distinct and special characteristics, which open up the possibility of applications in biology, catalysis, agriculture, and the environment. According to Kefeni et al. (2017), the MNPs are made of several metal elements (either alone or in composites) and their oxides with magnetic properties.

As a result, the kind of surfactant and solvents utilized in various reaction circumstances have a significant impact on the size and form of MNPs (Xie et al., 2018). This review was created with the current interest in MNPs in mind and includes a summary of recent breakthroughs in the synthesis of MNPs as well as historical and contemporary investigations with their associated benefits and drawbacks. This review's purpose is to provide information on the many classifications of MNPs based on different elemental compositions and metals, as well as information on how they are used in the fields of energy, biomedicine, biosensing, environmental protection, agriculture, and cancer catalysis. The next part also discusses the MNPs' potential future difficulties.

MAIN SYNTHESIS METHODS OF MNPS

The development of various methods for the synthesis of MNPs has been the subject of intense study during the last 10 years. To produce MNPs with the necessary size, shape, stability, and biocompatibility, many synthetic techniques are utilized. In order to create MNPs, the most popular techniques are ball milling, coprecipitation, thermal decomposition, hydrothermal, microemulsion, sol-gel, and biological approaches.

Physical Methods

"Top-down" and "bottom-up" strategies make up the physical ways. Through high intensity ball milling, the bulk materials are reduced to nanoparticle size in the top-down method. Mechanical crushing makes it challenging to get the proper form and size of NPs. In contrast to the top-down strategy, the bottom-up method may produce well-dispersed and fine nanoscaled small particles. Laser evaporation is an example of a bottom-up strategy (Biehl et al., 2018). MNPs are also created using different physical techniques such as the wire explosion method and the inert-gas condensation method. Three physical processes—ball milling, laser evaporation, and wire explosion—will be covered in this study.

Laser Evaporation

Nanoparticles are created by condensation from the liquid or gaseous phase during laser evaporation, which is a bottom-up method (Biehl et al., 2018). The simple process of laser evaporation, also known as laser ablation, uses a high intensity laser to produce MNPs. Iron oxide MNPs may also be made using this technique (Shin et al., 2004). In this procedure, coarse-textured raw materials (in the m or mm size ranges) are chosen and evaporated via the laser beam's focus. The material is positioned at the bottom of a cell that is filled with a liquid solution, and the laser beam is focused on it. A laser beam is used to irradiate the substance in a solution. When a substance's vapors are cooled to a gas phase, a rapid condensation and nucleation process occurs, which causes nanoparticles to develop. This process is less costly than wet chemistry procedures and does not need expensive chemicals or result in hazardous waste.

Wire Explosion Method

The wire explosion method is a brand-new physiochemical method that produces MNPs in a secure and hygienic manner. This procedure is a one-step, highly productive one that doesn't call for any extra processes like NP separation from solution or byproduct re-treatment. Iron oxide MNPs were previously made using this technique to remove arsenic from water (Song et al., 2013). Making less polluted nanopowders with this method is safe for the environment and uses less energy. This approach does not result in monodispersed NPs (Kawamura et al., 2015).

Chemical Methods

The many bottom-up processes used in chemical synthesis are diverse. Below is a detailed explanation of a few popular techniques that are often used to create MNPs.

Coprecipitation Method

The most popular technique for creating MNPs with regulated size and magnetic characteristics is coprecipitation (Sandeep Kumar, 2013). It is often used in biomedical applications and involves the use of less toxic materials and techniques (Indira and Lakshmi, 2010). When we require a lot of nanocrystals, the coprecipitation method of making MNPs is highly practical and simple. This process is often used to create NPs with regulated sizes and desirable magnetic characteristics. To create MNPs, various metal ions are dissolved in a solvent. Ferric chloride ($FeCl3$), manganese(II) chloride ($MnCl2$), and salts of sodium hydroxide ($NaOH$) served as the metal ions in the formation of the manganese ferrite nanoparticles ($MnFe2O4$). $Fe3+$ and $Mg2+$ ions may combine to create $MgFe2SO4$ nanocrystals when $NaOH$ is added (Chen et al., 1999). Similar to this, $Fe2+$ and $Fe3+$ ions are coprecipitated to produce $Fe3O4$ NPs in another work.

Thermal Decomposition Method

In this technique, monodispersed NPs are made at high temperature using organometallic precursors. This technique produces MNPs with great crystallinity, regulated size, and well-defined form. To create MNPs of the required size and form, the breakdown of organometallic precursors is carried out in the presence of organic surfactants (Effenberger et al., 2017). Fatty acids, hexadecylamine, and oleic acid are among the stabilizing substances employed in the manufacture of MNPs. The stabilizers utilized in the breakdown process have the ability to slow down the nucleation of NPs, which regulate the development of MNPS and aid in the production of a spherical shape and desired size of less than 30 nm. This method has been reported to manufacture magnetically active iron composites and Fe3O4 nanocrystals (Jana et al., 2004; Ren et al., 2019). Metal NPs are produced via the thermal breakdown of the zero-valent metal precursor Fe (CO)5, although oxidation may also result in the production of high-quality iron oxide MNPs. On the other hand, metal oxide NPs may be directly formed when precursors decompose in the presence of cationic metal centers. We have previously created monodispersed iron oxide MNPs with sizes ranging from 6 to 20 nm by decomposing Fe(CO)5. Depending on the kind of precursor employed, a certain temperature is required. According to the desired form and size, adjustments are made to the degree of temperature, reaction time, kind of surfactants and solvents, and aging duration (Lu et al., 2007; Patsula et al., 2016).

Microemulsion Synthesis Method

Surfactants and sometimes co-surfactants are used to create turbid systems of lipophilic and hydrophilic phases in microemulsions. This system of water, oil, and amphiphile is transparent and isotropic. In this procedure, water is magnetically agitated at room temperature while oil and a surfactant are combined. Three different types of microemulsions exist: 1) oil in water (O/W), which is the aqueous phase with some oil droplets, 2) water in oil (W/O), which is oil as the dominant phase with some water droplets, and 3) microemulsions in which the amounts of oil and water are about equal. For instance, a surfactant was coated on a microemulsion of the w/o type, which included droplets of water in an organic solvent and reduced the size of MNPs. The kind of surfactant utilized determines the size and form of MNPs produced using this approach (Lu et al., 2013). Using two microdroplets, one with a metal percussor and the other with a precipitating agent, the w/o type of microemulsion was employed to generate some iron oxide MNPs (Okoli et al., 2011). Following this procedure, MNPS were prepared with a silica coating and then modified with amino, which was helpful for separating tumor cells (Zhang et al., 2016). The MNPs created by microemulsion are sparse and evenly distributed.

One of the effective solution reaction-based methods for producing MNPs at high pressure and temperature is hydrothermal synthesis, also known as solvothermal synthesis. According to the hydrothermal procedure, MNPs are created by a hydrolysis and oxidation reaction (Reddy et al., 2012). The degree of mineral solubility in the water affects how crystals form. This technique produced uniformly sized particles of different magnetic nanomaterials (Wang et al., 2005). For instance, 15 nm-sized Fe3O4 nanoparticles with a spherical shape were produced and used in tumor MRI (Li et al., 2013). Similar to this, 25 nm-sized Chitosan-coated Fe3O4 NPs were created and used to immobilize enzymes (Li et al., 2008).

Sol-Gel Method

The whole chemistry of this procedure includes the hydrolysis and polycondensation of metal alkoxides to create gels at room temperature. To create a sol or colloidal solution, metallic salts are dissolved in water or other solvents and uniformly distributed (Ansari et al., 2019). By stirring and raising the temperature, the van der Waals forces between the particles take place and the interaction between particles grows. Once the solvent has been removed from the mixture and it has dried, gel will eventually develop (Hasany et al., 2012; Mohamed and Mohamed, 2019). The creation of iron oxide and silica-coated MNPs may be accomplished using this technique. The MNPs' size and form may be controlled, and they can be generated in vast numbers (Lu et al., 2007). In the past, MNPs were made by heating a solution of FeCl3 and NaOH to a temperature between 50 and 100 °C (Gu et al., 2006). The sol-gel approach is less expensive than other techniques since it may be performed at ambient temperature without the requirement for specialized equipment. The composition, shape, and size of MNPs may be easily controlled using this technique. This approach yields very pure solid materials with excellent crystallinity and tunability. To get pure MNPs, the technique must sometimes be repeated because of contamination brought on by byproduct reactions. Its effectiveness in producing scattered NPs is limited by the formation of three-dimensional oxide networks (Hasany et al., 2012). This method's prolonged reaction time and use of hazardous organic solvents are further drawbacks.

Biological Synthesis Method

According to Verma et al. (2021) biological synthesis is a well-known technique for creating MNPs by using living things like plants and microorganisms (fungi, viruses, bacteria, and actinomycetes). The MNPs created using this technology have a high degree of biocompatibility and have practical applications in the biomedical industry. The effectiveness, environmental friendliness, and clean procedure of this technology are advantages. While its weak NP dispersion is a drawback (Komeili, 2012). Researchers are now very interested in the production of NPs utilizing plant tissue, extracts, exudates, and other plant components (Gul et al., 2019). For instance, ferromagnetic magnetite particles with an average size of 60 nm have been reported to be produced physiologically (Lenders et al., 2014). Although biological synthesis is a potential technology that has just come to light, it is still unknown how NPs are created utilizing microbes and plants (Komeili, 2012; Duan et al., 2018). For instance, some research offered potential processes for the mycosynthesis of metal nanoparticles.

Comparison of Different Synthesis Methods

The synthesis of MNPs has been carried out using a variety of methods. Physical, chemical, and biological procedures are the three categories into which these synthetic processes are divided. In earlier sections, we briefly examined several ways to synthesize MNPs. Comparing physical and chemical approaches, it becomes clear that physical methods have difficulty producing NPs with sizes in the nanoscale range (Cuenya, 2010).

CHARACTERIZATION OF MNPS

To evaluate their physicochemical characteristics, the MNPs are examined using a variety of equipment. The display of various physicochemical features of NPs depends significantly on their size. Their characteristics may be altered by even a little change in their nanoscale dimension. Atomic Force Microscopy (AFM), Energy Dispersive X-ray Diffraction (EDXD), Scanning Electron Microscopy (SEM), Fourier Transform Infrared (FT-IR) Spectroscopy, UV Spectrophotometer, Transmission Electron Microscopy (TEM), and Mossbauer Spectroscopy (MS) are a few of the instruments used for their characterization (Galloway et al., 2015).

Size and Surface Morphology

The form and size of MNPs may alter their physicochemical characteristics. Surface area, size, and particle dispersion are measured using the Brunauer Emmet Teller (BET) and Dynamic Light Scattering (DLS) procedures. AFM, TEM/HRTEM, SEM/FESEM, and other methods may be used to analyze the surface morphology of MNPs. The photos we get using these tools offer us a general notion of their size and form, from which we may compute their diameter. Surface roughness, step height, and location of scattered particles are all measured using the AFM method. Information on the composition, shape, and size of NPs may be found via TEM. SEM provides information on sample composition and surface topography. Ultrathin electrical conducting elements sputtering is used if the surface of the nanomaterials is nonconductive. Size computation may be done using high-resolution TEM (HRTEM), field-emission SEM (FESEM), and XRD methods. The assessment of crystallinity, NP aggregation state, lattice spacing, and electron phase shift may all be accomplished with the aid of TEM

(Gabbasov et al., 2015; Chekli et al., 2016). The Scherrer equation makes it simple to determine the size of NPs from the sharp XRD peaks. Non-crystalline NPs produce broad peaks, making it challenging to estimate their size. To determine NPs' crystallinity, utilize XRD. Techniques like DLS, photon correlation spectroscopy, and Mossbauer spectroscopy can assess particle dispersion and average size.

Elemental Mapping/Composition

Elemental composition and surface morphology may be determined using a variety of equipment, including EDS/EDXD, XRF (X-ray fluorescence), TEM, SEM, and XPS (X-ray photoelectron spectroscopy). The elemental composition of NPs is also studied using the instruments Atomic Absorption Spectrophotometry (AAS) and Inductively Coupled Plasma Mass Spectroscopy (ICP-MS). However, when the NPs are in solid form and must be dissolved in acids or bases before usage, AAS cannot detect the elemental composition. The composition and chemical state of the elements present in an NPs may be learned by the XPS. The elemental analysis and chemical composition of manufactured MNPs are both aided by the EDXD approach (Faraji et al., 2010). Through XRF, it is possible to ascertain a sample's elemental makeup. In comparison to other techniques, the sample preparation for XRF analysis is simple, quick, and safe. It has a 100 ppb (parts per billion) detection limit (Ida et al., 2005; Al-Eshaikh and Kadachi, 2016). Through the use of X-rays, it is a non-destructive approach of solid sample analysis (Weltje and Tjallingii, 2008).

Bonding Type and Structure

The structure and bonding properties of MNPs are studied using a variety of methods. FT-IR, XAS (X-ray absorption spectroscopy), TGA (thermogravimetric analysis), XPS, and RS (Raman spectroscopy) are the methods used. According to Karabelli et al. (2008), the XPS is appropriate for the surface configuration of NPs because it shows the mechanism of reactions that occur on the surface of MNPs and offers information on the structure and speciation of elements. The oxidation state, particle binding energy, and the bonding between organic and inorganic materials may all be determined using FT-IR and XPS. The functional groups of organic compounds may be understood with the use of FT-IR spectroscopy. The RS method is used to determine the compound's structure and spinal lattice. By giving us information on coating development, particularly regarding surfactants and polymers, the TGA approach allows us to evaluate binding efficiency on the surface of the particle. According to Reddy et al. (2012), the XAS approach is helpful for gathering data on oxidation states and necessary components of electrical configuration.

Magnetism

The creation of MNPs via various synthetic techniques affects their magnetic properties. The MNPs, whose sizes span from nano to micro scales, exhibit the superparamagnetic feature. These NPs exhibit magnetic sensitivity and may interact with external magnetic fields when they are exposed to them (Pathak et al., 2021). However, there is no magnetism seen when there is no external magnetic field. This characteristic of MNPs may enable them to be crucial components of regulated treatment and focused drug delivery. A variety of approaches with varying levels of sensitivity and information quality are used to quantify the magnetic of NPs. The net magnetization is measured using methods such as superconducting quantum interference device (SQUID) magnetometry and vibrating sample magnetometry (VSM). The SQUID is helpful for analyzing materials in a variety of states, including thin films, crystals, powders, liquids, and gases. Both the VSM and the SQUID are very sensitive instruments, with the VSM having a sensitivity of 10-6 emu and the SQUID having a sensitivity of up to 10-10 emu (Zahid et al., 2019). If the external magnetic field is continuously provided, the SQUID and VSM may also measure the magnetic saturation and residual magnetization (Krzyminiewski et al., 2018).

COMPOSITION OF MAGNETIC NANOSTRUCTURES

Monocomponent Magnetic Nanostructures

Fe, Ni, Co-Based Magnetic Nanostructures

MNPs of a particular kind called iron NPs have particular magnetic characteristics. the most thoroughly investigated NPs in the realm of nanomedicine due to their magnetic properties and exceptional biocompatibility. They are reasonably priced, ecologically safe, and have high physical and chemical stability. Iron carbonyl [Fe (CO)5] was previously broken down to create monostructure Fe NPs in the presence of oleic acid (OA) (Suslick et al., 1996). Because iron NPs are sensitive to oxygen, they were made using a simple aqueous phase synthesis technique that included poly (N-vinylpyrrolidone), which is helpful in preventing oxidation of the metal surface (Hou and Gao, 2004). The reduction of Ni (acac)3 in the presence of hexadecyl amine (HDA) produced monodisperse nickel (Ni) NPs with an average particle size of 3.7 nm (Hou and Gao, 2003). Cobalt (Co) NPs with a size range of 2–6 nm were made using a bulky trialkyl phosphine reducing agent, whereas NPs with a size range of 7–11 nm were made using a less bulky trialkyl phosphine (Sun and Murray, 1999). This demonstrates the coordination of the surfactant trialkyl phosphine with neutral metal surface sites.

Metal Alloys Magnetic Nanostructure

Metal alloy NPs with super magnetic features are very promising. Due to their great chemical stability and magnetic crystallinity, iron-palladium (FePd) and iron-plateau (FePt) are examples of metal alloy nanostructures (Hou et al., 2004). FePt NPs are excellent for usage in biomedical applications and may be made via vacuum deposition or solution-phase synthesis. utilizing tributyl phosphine and adamantine carboxylic acid as stabilizers, FePd NPs were made utilizing the organic phase thermal decomposition technique at room temperature. With an adjustable size range of 11–16 nm, the FePd NPs exhibit super magnetic characteristics. Monodisperse FePd NPs with a face-centered cubic form were previously made using a wet chemical method by decreasing Pt (acac)2 and breaking down Fe (CO)5 (Sun et al., 2000). However, it has a tendency to aggregate when converted to fct (facial centered tetragonal).

Metal Oxide Magnetic Nanostructures

Due to their magnetic properties and chemical durability, metal oxide nanoparticles (NPs) have lately attracted a lot of interest. One of them, Fe3O4, has shown a good prospective use in magnetic separation and biomedicine. They are made using a straightforward procedure that primarily relies on Fe complexes under alkaline conditions (Hou et al., 2003). Controlling the solvent and surfactant will enable the required size to be achieved (Sun and Zeng, 2002; Xu et al., 2009). When the surfactant oleyl amine, which serves as a capping agent, came in contact with Fe3+ to create Fe3+ OOC, particle development was constrained. When oleyl amine surfactant is used to tune the energy of the particle surface to encourage development in a certain direction, several forms of iron oxides, such as octahedral Fe3O4 NPs and Fe3O4 nano prisms, may be produced (Zhang et al., 2009; Zeng et al., 2010). According to Hou et al. (2007b), the quantity of surfactant utilized may regulate the direction in which particles expand. Additionally, thermal annealing of FeO NPs may cause them to change into iron oxides (Fe3O4). Cobalt oxides were produced using comparable methods. Cobalt nitrate [Co (NO3)3] generated nanoplatelets (NPLs) of cobalt(II) hydroxide [Co(OH)2] during a hydrothermal process in the presence of PVP, which may further lead to cobalt oxide (CoO) NPLs (Hou et al., 2005).

Metal Carbides Magnetic Nanostructures

Despite their amazing stability and magnetic qualities, iron carbides (Fe_5C_2, Fe_3C, and Fe_2C) are not magnetic. Because of the difficulties in synthesizing them and regulating the size and shape, they are seldom researched. $Fe(CO)_5$ was broken down in the presence of octadecyl amine to form NPs of Fe_5C_2 (Yang et al., 2012). To create Fe_5C_2, iron NPs with excellent crystalline structure were carbonized. When carbide NPs were created, bromide was added to adjust the surface energy, but the mechanism behind this addition remained unknown. This method generated Fe_5C_2 NPs with a 20 nm size that had an amorphous shell. Iron carbide NPs with various crystallinity configurations were created using a chemically synthesized process that was devised (Yang et al., 2017). These iron carbides had modest ferromagnetic characteristics, which indicated that various types of iron carbides may arise depending on the synthetic processes used to create them. The penetration of carbon content by selective absorption may be impacted, particularly when halide ions are present.

Multicomponent Magnetic Nanostructures

Heterostructure Magnetic Nanostructures

The MNPs with heterostructures are made up of a variety of parts, including a magnetic component and other parts, and as a whole, they display unique features. These many parts together to form a multicomponent magnetic structure provide novel features. Through a seed-mediated process, monocomponents were employed as seeds to create MNPs. Studies are being done on core@shell heterostructures, which are made up of several parts encased in shells that have synergistic effects. For instance, Fe_3O_4@Au@Ag NPs with adjustable characteristics were created (Xu et al., 2007). FePt-based heterostructures, such as FePt-Au, have received much research due to their outstanding magnetism. Au is renowned for its many uses in the areas of biology and catalysis.

Exchange Couple Magnetic Nanostructures

To satisfy the demands of a higher energy barrier product, the impact of an exchange-coupled between a hard and soft origin magnetic phase is crucial. When pre- and post-i.v. injection of uIONP at various time intervals resulted in particles with soft orthotopic 4T1 tumors (Wang L. et al., 2017). 2017 American Chemical Society (D) copyright For in situ real-time reporting of Fenton-based dose-dependent •OH production using tumor-specific nanotheranostics NQ-Cy@Fe&GOD: 1) Due to its passive and active targeting capabilities, NQ-Cy@Fe&GOD is delivered into tumor sites along with an enhanced MRI signal; 2) The released dose of Fenton agents is assessed by turning on the NIR fluorescence signal at 830 nm (NIR-1) in synchrony with its intracellular dissociation.

APPLICATION OF MNPS

The MNPs have attracted a lot of interest in the last 10 years due to their promising outcomes in several sectors. The use of MNPs is made more promising by their super-magnetic characteristics, distinctive size, shape, high surface area and volume ratio, and biocompatibility. These characteristics have drew many scholars from other fields to it. We have outlined the uses of MNPs in this review in a number of well-known industries, including biomedicine, biosensing, environment, agriculture, and catalysis. The possible uses of MNP in various fields are briefly described below.

Biomedicine

Due to their many physical and chemical characteristics, simplicity in manufacture, stability, and biocompatibility, MNPs have lately been extensively employed in several biological applications. MNPs may communicate with outside magnetic fields. Magnetic resonance imaging (MRI) is improved by MNPs since they have the ability to change the magnetic fields nearby. Different types of force and torque are produced and generated by the externally applied magnetic field at dipoles, leading to energy loss via translation, rotation, and dissipation. Such phenomena have a wide range of uses, including cell separation/biomarker, magnetic drug delivery, magneto-mechanical activation of cell surface receptors, biomedical imaging, bacterial theranostics, drug release triggering, and hyperthermia.

Medical imaging is often used to examine biological processes, identify anomalies, and track the development of diseases. The resolution of medical pictures is being improved via the development of innovative imaging methods. For anatomical diagnosis, a number of imaging methods are currently in use. These include magnetic resonance imaging (MRI), computed tomography (CT), positron emission tomography (PET), single-photon emission computed tomography (SPECT), ultrasound (US) imaging, optical fluorescence imaging, and photoacoustic (PA) imaging. With superior characteristics including high spatial resolution, low radiation exposure, and high contrast imaging of soft tissues, MRI is a desirable imaging method and an efficient cancer diagnostic tool when compared to CT and PET.

Bacterial Theranostics

Serious health concerns have been raised by antimicrobial resistance in both industrialized and poor nations. It is predicted that bacterial infections would result in 300 million fatalities by the end of 2050 due to the introduction of numerous multidrug-resistant strains and the lack of new medications (Shi et al., 2019). This situation has heightened the need to investigate novel, creative antimicrobial therapy approaches. Antimicrobial peptides, therapeutic antibodies, phage treatment, and antimicrobial NPs are a few cutting-edge strategies that are presently being researched (Simoes et al., 2017). Recently, techniques based on MNPs have been created to treat illnesses brought on by bacteria that are multi-drug resistant as well as bacterium-related biofilm. According to Reddy et al. (2012) and Huang et al. (2014), the MNPs primarily kill germs by disrupting their plasma membranes, releasing toxic metals, and producing ROS that interfere with key components of bacteria.

In addition to the conventional methods that do not comply with regular analysis in food technology, the identification of foodborne pathogens often calls for quick and easy methodologies. In order to identify infections, biosensors using impedance spectroscopy and interdigitated electrodes (IDEs) functionalized with antimicrobial peptides are now being used (Etayash et al., 2014). Due to their poor selectivity and lack of action against bacteria, fungi, and viruses, AMPs are often used in these biosensors at the expense of performance (Zasloff, 2002). To this purpose, a biosensor based on electrical impedance spectroscopy was created to detect bacteria in food samples by integrating AMP (melittin) functionalized MNPs with screen-printed digitized electrodes (Figure 3D) (Wilson et al., 2019).

Biosensing

In a variety of industries, including food technology, laboratory testing, clinical diagnostics, and environmental monitoring, MNPs-based sensors have shown impressive applicability. In particular, the MNPs-based biosensing sector has attracted strong attention in the field of nanomedicines due to biocompatibility, durability, and safety. MNPs-based biosensors have envisioned a broad applicability in the biomedical field due to their compact size, high sensitivity, and intriguing noninvasive detection characteristic (Chen et al., 2016). MNPs-based biosensors have significantly outperformed other traditional biosensors because to unique characteristics including magnetic signaling and magnetic separation. Additionally, MNPs may be employed as magnetic probes to find analytes in biological samples due to the high signal-to-background ratio (Xie et al., 2011). Iron, cobalt, nickel, and their oxides are magnetic-origin elements that make up MNPs (Mornet et al., 2006). There is no potential magnetization in the absence of an external magnetic field because superparamagnetic particles can only be magnetized by an external magnetic field (Majetich and Jin, 1999).

For the purpose of detecting proteins, enzymes, nucleic acids, and cells, MNPs may also be successfully functionalized with a range of biological substances (Haun et al., 2010; Tran et al., 2010; Suaifan et al., 2013; Zhang et al., 2013). MNPs are excellent candidates for detection in both in vitro and in vivo without interfering with biological interactions due to their intriguing physicochemical characteristics and stability. MNPs biosensors have undergone substantial design work to ensure their simplicity of use and excellent sensitivity for precise detection.

Environment

Due to the rising release of hazardous and deadly chemicals and compounds as a consequence of human activities, the degradation and pollution of water, soil, and atmosphere are emerging as a major environmental issue. The atmosphere contains a variety of persistent organic pollutants, such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), pharmaceuticals, pesticides, and industrial wastes (Rodriguez-Narvaez et al., 2017; Richardson and Ternes, 2018). Groundwater, ocean, sewage effluents, and drinking water all include various types of organic contaminants. When these kinds of persistent organic pollutants enter the food chain, they may seriously harm human health (Jin et al., 2014; Govan, 2020).

Compared to traditional techniques, wastewater treatment with nanotechnology has a huge potential to enhance environmental quality. These methods for cleaning water have the potential to utilize less electricity and energy, chemicals, and leftover garbage. In this sense, using MNPs might significantly reduce the dangers connected to water cleaning procedures. According to Alvarez et al. (2018), nanotechnology has the potential to significantly improve water and environmental quality.

Agriculture

Metallic nanoparticles have been successfully used in a number of studies to protect plants, promote seed germination, and enhance soil quality (El-Temsah et al., 2016; Rui et al., 2016). According to Mishra et al. (2017), iron oxide MNPs may be employed as soil nutrition to boost output with the least amount of adverse effects. According to Rout and Sahoo (2015), iron is a crucial metal that is involved in a variety of physiological processes including respiration, biosynthesis, the production of chlorophyll, and redox reactions. Many crops, including peanuts, lack iron. Its supply, nevertheless, continues to be problematic for plants. Therefore, by analytical techniques, functionalized iron oxide NPs may circumvent this issue as well as go past obstacles and absorb by plants. In order to track iron uptake and transport in plants, Ju et al. created water-soluble iron oxide NPs (IONP-EDTA) through a ligand exchange process with N-(trimethoxysilylpropyl) EDTA. They did this by synthesising iron oxide NPs using the thermal decomposition method and capping them with oleic acid (IONP-OA).

Catalysis

For the conversion of reactants into products, several catalytic systems and techniques have been developed to date (Liu and Zhang, 2016). The difficulty in separating homogenous catalysts from the reactions is one of their drawbacks. Utilizing catalysts assisted by MNPs, the heterogeneous catalysis constraint has recently been mitigated and eliminated. When such catalysts are separated, the MNPs combine the advantages of great dispersion and reactivity with the capacity to give a large surface area to support active sites for reactants to be transformed into products readily (Lee et al., 2008). Magnetic materials with excellent repeatability have been observed in heterogeneous catalytic processes.

CONCLUSION

MNPs are used in a variety of industries, including biomedicine, the environment, agriculture, catalysis, and biosensing. We outlined current developments in the synthesis, characterisation, and possible uses of MNPs in this study. Different MNP types with potential features are being created utilizing various synthetic techniques. These techniques include sol-gel, ball milling, thermal decomposition, hydrothermal synthesis, microemulsion synthesis, and thermal decomposition. Ball milling is a physical approach that is used to synthesize MNPs in large quantities, although this process introduces contamination from the milling jars and balls. On the other hand, monodisperse MNPs are made using the thermal breakdown or pyrolysis process. The pyrolysis process offers benefits since it is easy to implement and provides excellent control over MNP size. At low processing temperatures, the sol-gel synthesis approach is employed to create MNPs with uniform size distribution and enhanced stoichiometric control.

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