Published by The College of Science & Information Technology (COSIT), TASUED, Vol. 19, No. 1, pp. 304-319.

COSIT, TASUED
Journal of Science and Information Technology (JOSIT)

Recent Advances in the Synthesis of Metal Nanoparticles: A Comparative Review of Physical, Chemical and Biological Methods

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Abstract

Metal Nanoparticles (MNPs) have been a subject of great interest because of their exclusive physical-chemical characteristics and extensive applications in many areas, including biomedicine, environmental cleanup, catalysis, and electronics. The way they are prepared is vital to their determination in size, morphology, and functionality. In this review, the current advances in the physical, chemical, and biological synthesis of MNPs are synthesized by using the recent high-impact articles. Focus is made on the mechanisms of the techniques, their benefits, limitations, and relative efficiencies. Future research areas and research gaps on scalable and sustainable nanoparticle production are also discussed in the review.

Keywords: Nanotechnology, Metal nanoparticles, Synthesis method, Nanoparticle production

INTRODUCTION

Nanotechnology is a discipline that is concerned with the preparation of nano-size particles between 1 nm and 100 nm using various synthesis procedures as well as the alteration of the structure and the size of the particles (Akinsipo et al., 2023). Applications of nanoparticles in various disciplines such as molecular biology, physics, organic and inorganic chemistry, medicine, and material science are surprisingly enhanced today (Altammar, 2023). Reduced particle size to nano size exhibits odd and better properties like particle size distribution and morphology as not exhibited in larger particles of bulk material (Szczyglewska et al., 2023). "Nanoparticles" (NPs) is a term based on the Greek word "nano," which means "dwarf" or "small," and as a prefix it denotes size 10−9, one billionth of a meter, which is equal to 1 nm (Akinsipo et al., 2022). Nanoparticles possess the solute and distinct particle phase characteristics. It is this special extrinsic characteristic of the specific surface area of nanoparticles that also gives rise to their high value, as well as contributes to various intrinsic properties such as high reactivity at the surface, which in itself depends on size (Khulbe and Matsuura, 2021). Comprehensively, these unique attributes of nanoparticles are the reasons for their multifunctional nature and the emerging interest in utilizing them in other sectors as varied as energy sectors, medicines, and nutrition (Akinsipo et al. 2024). Gold, silver, and palladium in the NPs forms are some of the most promising nanotech trends, particularly as a source of bioengineering materials likely to emerge as state-of-the-art diagnostic tools and equipment to treat critical illnesses. As an example, silver and gold NPs tend to be of great interest to nanotechnology and materials science because of their individual useful properties and broad applicability. Regarding distinguished optical, catalytic, and

Cite as:

Akinsipo, O. B. (2025). Recent Advances in the Synthesis of Metal Nanoparticles: A Comparative Review of Physical, Chemical and Biological Methods. *Journal of Science and Information Technology (JOSIT)*, Vol. 19, No. 1, pp. 304-319.

antimicrobial qualities and targeted drug delivery efficiency in differing types of cancers, these noble metal nanoparticles (MNPs) are distinguished (Yaqoob et al. 2020). Silver has a long history of antimicrobial and anti-inflammatory prospects. The selective use of this property has been exploited to accelerate wound healing and also adopted commercially in wound dressings, various pharmaceutical dosing formulations, and medical implant coatings. Other types of metal nanoparticles, such as platinum nanoparticles, also have coatings to have a health-beneficial effect that are used in biomedicals individually or as metal alloyed with other MNPs. MNPs find steadily increasing application globally in biomedicine and allied fields (Akinsipo et al. 2023).

With this in consideration, the current review is a compilation of diverse techniques that have been applied in the synthesis of metal nanoparticles along with their strengths, weaknesses, and areas of application.

METAL NANOPARTICLES, MAIN PROPERTIES, CLASSES AND TYPES

Nanoparticles Made of a Noble Metal

Noble metal nanoparticles such as gold (Au), silver (Ag) have attracted much research attention because of their high localized surface plasmon resonance (LSPR), inertness, and biocompatibility. As an example, AuNPs synthesized by the conventional Turkevich protocol (reduction of HAuCl 4 by citrate) produce spherical structures of 10–20 nm that can be manipulated in size by a slight alteration in citrate concentration (Zhang, 2018).

Chemically synthesized silver nanoparticles through the Brust-Schiffrin or Turkevich-like reduction in the presence of citrate or sodium borohydride also exhibit a well-characterized insurgence; these can be used in antimicrobial coatings and plasmonic sensors. Although broadly used, chemical approaches to noble MNPs present disadvantages associated with ecological risk and the presence of contaminant reagents on the surface (Burlec et al., 2023)

Transition Metals Nanoparticles

More rarely used but more extensively used in catalysis and energy-related applications are transition metal nanoparticles (e.g., Cu, Ni, Pt). Their typical materials are prepared using chemical reduction, most commonly using a metal alkoxide or salt precursor in a solgel or thermal decomposition reaction. As an example, transition metal oxides such as Fe_3O_4 are produced through co-precipitation of Fe^{2+}/Fe^{3+}salts and often stabilized by adding additives like citrate and oleic acid to alter dispersion and limit aggregation behavior (Heuer-Jungemann et al., 2019).

Magnetic Nanoparticles

Magnetic nanoparticles focused on mostly iron oxides play a central role in biomedical separation procedures and imaging. Surface modification with surfactants and stabilizers is normally done after the preparation of their monodisperse magnetite NPs by co-precipitation method of processing . The alternative methods, including thermal decomposition, provide more control over size and crystallinity, but usually involve the usage of organic solvent and/or high temperature reaction (Ali et al. 2016)

Bimetallic Nanoparticles

Alloys of two or more metals (bimetallic nanoparticles or BNP), including core shell structures or heterostructured structures, can incorporate the properties of two (or more) metals. Such NPs have been prepared to improve catalytic, optical or magnetic response compared to monometallic analogs.

Recent reviews highlight the versatility of BNP fabrication via physical, chemical, or green synthetic routes. Chemical reduction remains dominant for alloyed structures, enabling precise stoichiometric control and tunable LSPR/magnetic characteristics. However, these methods often introduce surface ligands that may impair catalytic or sensing activities . Notably, plant-extract-mediated routes have emerged as sustainable alternatives for BNP synthesis. Phytochemicals such as flavonoids and tannins serve dual roles. This includes reducing metal ions and capping particles, yielding ligand-capped bimetallics with reduced environmental impact (Nyabadza et al., 2023). Nonetheless, this route may yield heterogeneous surface chemistries and limited suitability in applications demanding clean, ligand-free surfaces (Nyabadza et al., 2023). Physical methods like laser ablation offer ligand-free BNP production and high reactivity surfaces, yet these are constrained to small batch sizes and require specialized equipment (Rani et al. 2025). Table 1 shows the summary of major types of metal nanoparticles (MNPs), highlighting their core features, synthesis characteristics, and functional advantages. The classification includes noble, transition, magnetic, and bimetallic nanoparticles, each exhibiting distinct physicochemical properties that determine their suitability for specific applications in biomedical, catalytic, environmental, and sensing fields.

MECHANISM AND METHODOLOGY OF METAL NANOPARTICLES SYNTHESIS

Production of MNPs forms the basis of controlling their physicochemical properties that directly affect their use as catalysts, in medicines, sensors and energy purposes. The overall approach to synthesis (Fig.1) can be categorized into three, which include physical (top-down), chemical (bottom-up) and biological (green). The technologies have their own pros and cons when it comes to scalability, purity, control over particle size, and environmental footprint (Rai et al., 2023).

Physically-Based Approaches

Physical methods normally entail the breakdown of macrosized materials into nanopowders due to the application of external energies, namely, mechanical energy, high temperature, or radiations. The methods produce products of high purity because they lack chemical polluter but frequently needs costly equipment and a hefty portion of energy (Al Harbi et al. 2025).

Evaporation-Condensation

Evaporation-condensation is one of the most popular processes where metals are vaporized and subsequently condensed in products of nanoparticles in an inert gas environment. The technique yields a clean environment to synthesize pure nanoparticles, though it lacks control over the distribution of particle size. Based on this approach, nanoparticles obtained are spherical in shape, and the methods used to scale it up, such as cluster beam evaporation, are rather costly (Srinivasan and Rana, 2024).

Removal by Laser Ablation

In laser ablation, a high-powered pulsed laser is attempted in addition to radiating a metal target suspended in a liquid medium. The furious energy results in localized heating and vaporization of the metal, nucleation and subsequent formation of nanoparticles. Rai et al. (2023) emphasized the use of this method to be environmentally friendly which avoids the addition of stabilizers or surfactants. The high cost of capital and limited throughput however are the major drawbacks to it since it works best in the related laboratory concept (Isyaka et al. 2024).

Mechanical Milling

In this technique, metal powders are put through intense mechanical impact with the aid of a ball mill. Cold welding and fracturing are recurrent to form nanoparticles. Mechanical milling is uncomplicated, and economically favorable and can be used with numerous materials, but foremost, it results in the inhomogeneous particle size and possible contamination with the milling media (Joy et al. 2022).

Chemical Methods

The chemical approaches include the atom- or molecule-by-molecule synthesis to assemble nanoparticles giving high control of size and shape monodispersity. They are scalable, as well as commonly achieved in industry environments.

Chemical Reduction Process

The synthesis of metal nanoparticles is usually achieved through a chemical reduction process. These metal precursors are reduced (in presence of stabilizer, e.g., polyvinylpyrrolidone or citrate) with reducing reagents, e.g., sodium borohydride ($NaBH_4$), hydrazine, or ascorbic acid, including $AgNO_3$, $HAuCl_4$ or $CuSO_4$. Szczyglewska et al. (2023) keep insisting that the nucleation and growth kinetics depend on the reaction parameters, including pH, temperature, and precursor concentration and ultimately determine the properties of the target nanoparticles.

Sol-Gel Technique

The sol-gel process allows the hydrolysis and the polycondensation of metal alkoxides or salts to a sol which undergoes a gel state and finally undergoes calcination to give nanoparticles. This method is particularly effective in generating metal oxide nanoparticles and provides an accurate method of creating porosity levels and composition of the acquired product (Esposito, 2019).

Microemulsion Approach

Microemulsions are an oil in water mixture that is thermodynamically stable and composed of a combination of oil, water, surfactant and co-surfactant in some cases. They produce nanodroplets with nanometer dimensions, which serve as nano-reactors to carry out controlled nucleation and growth of nanoparticles. Salvador et al. 2021 observe that reverse micelles (water-in-oil emulsion) are especially useful in making monodisperse particles synthesis, but the final product may be hard to recapture and surfactants to remove.

Thermal Decomposition

In this procedure, metal-organic precursors are broken into pieces at high temperatures under the influence of the surfactants. It can be very useful in the synthesis of highly crystalline monodisperse nanoparticles and in the synthesis of materials with controlled morphology, especially magnetic metals such as Fe and Co. Demessie et al. (2022) indicate that the method of thermal decomposition is often utilized to create core-shell nanoparticles and even doped materials.

Green Synthesis (Biological) Methods

Green synthesis methodologies are very trendy due to their cost-effectiveness and environmental friendliness in the replacement of conventional physical and chemical processes. They engage biological entities such as plants, microbes, enzymes or biopolymers to stabilize nanoparticles and to allow the reduction of metal ions (Alayande et al. 2021).

Plant-Mediated Synthesis

Phytochemicals, which include flavonoids, alkaloids, and terpenoids found in plant extracts, have two activities: they reduce metal ions as well as capping the resulting nanoparticles. As an example, the antimicrobial and catalytic potential of silver and gold nanoparticles synthesized via green tea or neem extract of green tea has been excellent (Akinsipo et al., 2022). It avoids use of toxic chemicals and can be scaled up with biomass wastes but reproducibility is an issue.

Synthesis by Microbials

Metals ions can be bio-reduced by certain bacteria (e.g. Pseudomonas stutzeri), fungi (Fusarium oxysporum), and algae (Chlorella vulgaris) through enzymatic processes. Using microbial synthesis, size and shape of nanoparitcles can be easily controlled with regulated metabolic properties. Nevertheless, it has the limitation in a longer reaction time of reaction, complexities in purification procedures, and sterile conditions (Vimal et al. 2025).

Synthesis by Enzyme

Mild conditions are hampered by using the enzymes like nitrate reductase or hydrogenase to reduce the metal ions. In its early stage of development, this method provides a pinpointed regulation of nucleation and shape of the particles, which would be appealing in biomedical research involving monodispersity and non-toxicity requirements (Bilal et al. 2022).

THE PHENOMENA THAT INFLUENCE THE SYNTHESIS OF METAL NANOPARTICLES

A variety of synthesis parameters have a strong influence on the physicochemical properties of metal nanoparticles, including size, shape, surface charge, dispensability, and stability. Maximizing these factors enables one to fully regulate the nucleation and growth stages of nanoparticle synthesis.

pH of the Medium of Reaction

pH is one of the most important factors that determines the process of reduction, ionization of functional groups, and stability of nanoparticles in solution. The forming of redox agents within green synthesis through plant extracts has a slower rate reduced by the reduced amount of proton available at low pH values; this slows down the reduction reaction, and hence a larger particle is obtained. However, at raised pH, the presence of hydroxide ions enhances the speed of nucleation, thereby resulting in the creation of smaller and monodisperse nanoparticles (Akhter et al., 2024). Take, for instance, the example of biosynthesizing silver nanoparticle, where alkaline conditions would facilitate the colloidal stability and produce smaller nanoparticle but with a defined shape compared to acidic conditions which can experience aggregation to a greater extent because of reduced repulsion between the particles.

Temperature

Reaction kinetics are directly affected by temperature, and thus temperature affects not only the rate of nucleation of nanoparticles, but also the rate of their growth. A rise in temperature normally increases the rate of reduction of the metals charges and increases atom mobility that results in faster nuclei formation. Consequently, the sample of nanoparticles tends to be smaller in size and more homogeneous in nature with increased temperatures. Meanwhile, high temperatures can destabilize biological reducing agents or denature proteins in green methods of synthesis. In chemical synthesis pathways, including thermal decomposition, temperatures allow the adjustment of the size and crystallinity of the manufactured particles, and particles of magnetism or alloyed nanoparticles in particular (Khelfa et al. 2021).

Precursor concentration

The metal salt precursor concentration influences the availability of the metal ions in the reaction providing a direct effect on supersaturation degree and thus on the nucleation rate. At high concentrations of precursors, the particle expansion or assembly may also rise, assuming precursors have not apt destabilizing components. Conversely, low precursor levels can create nuclei that are unnecessarily limited, making them into larger particles owing to lengthy periods of expansion. Co-doped (Zn-Mn)-ferrites exhibit a strong dependence of magnetic properties and uniformity of particle sizes due to changes in the concentration of the dopants (Mello et al., 2019).

Reducing and Capping Agents

Reducing agent selection, along with the reduction speed of the metal ions and the stabilization of resulting nanostructures, depends on the choice of reducing and capping agent. The fast nucleation occurs when the reducing agent is a strong one, such as sodium borohydride, which is highly likely to generate small but unstable particles. On the contrary, less vigorous reducers like ascorbic acid or phytochemicals are slower and more controlled. Surfactants, e.g., polyvinylpyrrolidone (PVP), citrate, or plant-based compounds, are attached to the surface, and the nanoparticle does not form aggregates and does not flatten out. Biomolecules present in plant extracts are both reducers and stabilizers in a biologically produced synthesis environment, providing a sustainable but customizable environment (Xu et al., 2020).

Reaction Time

The reaction time defines the amount of time a nanoparticle should be left to nucleate and grow. Reduced reaction times might possibly produce incomplete reduction and varying sizes of particles, whereas a longer period can cause Ostwald ripening, in which smaller particles will dissolve after redepositing on those that are bigger, generating polydispersity (Thanh et al., 2014). During green synthesis, increasingly prolonged reaction times are also associated in increasing particle stability, and maximal reduction with softly acting biological reagents. Nevertheless, extremely long times can result in aggregation or generation of by-products especially in extracts that are protein- or sugar-rich in plants (Shahzadi et al. 2025).

Table 1. Key nanoparticle type, their structural feature and major advantages.

S/N	Nanoparticle Type	Core Features and Advantages	References
1.	Noble metals: Gold and Silver	Biocompatible metal nanoparticles that can be easily functionalized. They are ideal for numerous biomedical applications including sensors and drug delivery applications	Burlec et al. 2023
2.	Transition metal nanoparticles	Polyfunctional nanostructures that are common in catalysis, energy storage, and environmental remediation. They have tunable electronic, optical, and magnetic properties, which allows them to be used in fuel cells, batteries and pollutant degradation. Synthesized commonly by sol-gel, thermal decomposition and other wet-chemical processes.”	Zulfiqar et al. 2025
3.	Magnetic nanoparticles	They are mostly made of iron oxides (e.g. magnetite, maghemite) where they demonstrate the characteristic super-paramagnetism at the nanometric scale enabling their easy manipulation when in an external magnetic field. They are biocompatible and exhibit a large surface area and thus can find useful application in targeted drug delivery, magnetic resonance imaging (MRI), hyperthermia cancer ablation, and the removal of pollutants.	Mello et al. 2019
4.	Bimetallic Nanoparticles	Bimetallic nanoparticles have the advantage of alloy/core-shell with synergistic properties and sustainability through the use of green techniques	Rani et al. 2025

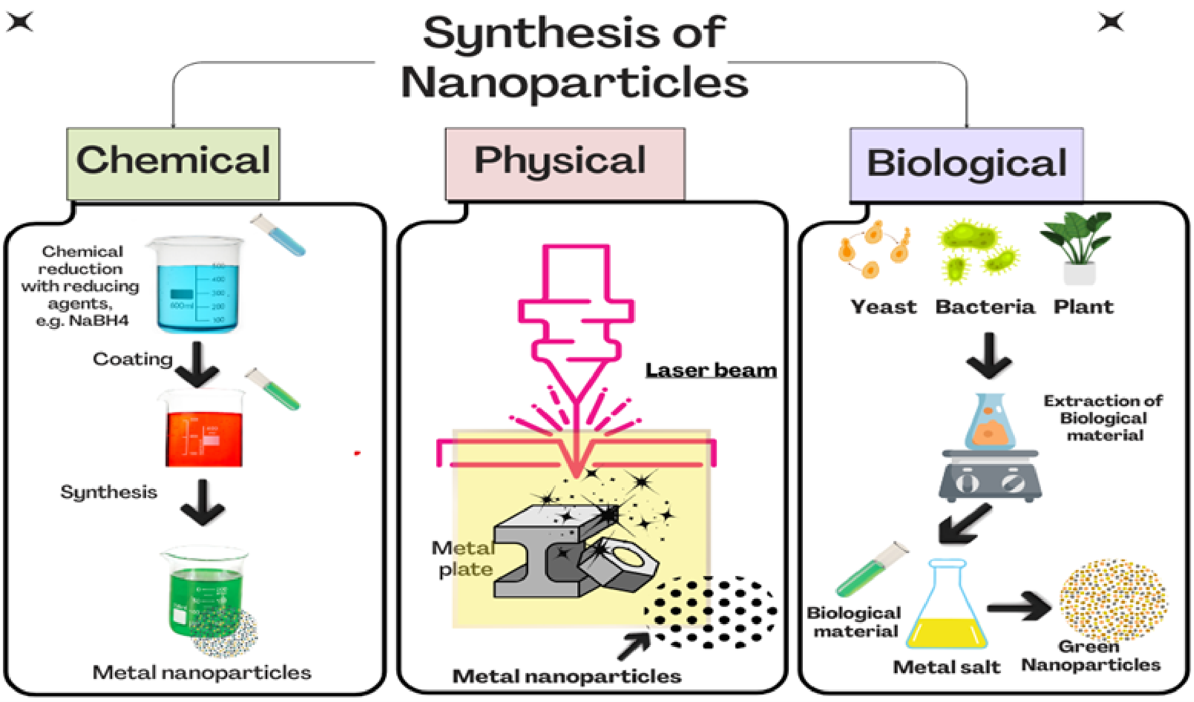

Figure 1. Synthesis methods for metal nanoparticles.

Table 2. Comparative Overview of Physical, Chemical and Biological Methods in Synthesis of Metal Nanoparticles: Major Mechanisms, Strengths, and Constraints.

Method Type	Key Features	Advantages	Limitations
Physical	Top-down, energy-based	Pure products, no chemical residues	High cost, low shape control
Chemical	Bottom-up, reagent-driven	Controlled size, scalable	Toxic by-products, environmental concerns
Biological	Green, bio-reduction	Eco-friendly, biocompatible	Slow kinetics, batch-to-batch variability

METAL NANOPARTICLES CHARACTERIZATION TECHNIQUES

To know the physical, chemical, and functional properties of metal nanoparticles (MNPs), it is important to characterize them. The stability and reactivity of the nanoparticles subsequently depend on many factors, such as size, morphology, the surface charge, elemental composition, crystallinity, and surface chemistry, in which the nanoparticles can be used in catalysis, drug delivery, sensing and environmental remediation.

The Analysis of Morphology and Size

Transmission Electron Microscope (TEM)

TEM offers atomic-scale resolution, particularly imaging of nanoparticles, the shape, the size, and internal structure can be directly revealed. TEM is especially useful in the case of differentiating between spherical, rod-like, and irregular shapes and assessing the core-shell or multi-component-type nano-particles in bimetallic nanoparticles (Wen et al., 2021).

Scanning Electron microscopy (SEM)

SEM has a high resolution to image the surface morphology and may be employed alongside energy-dispersive X-ray spectroscopy (EDX) that can be employed to perform elemental analysis. SEM is frequently used in exploring high particles or clumped systems (Scimeca et al., 2018).

Differential Light Scanning (DLS)

DLS assesses the hydrodynamic diameter of particles in suspension and gives information about the polydispersity index (PDI) which gives the size distribution information. DLS is faster and less destructive but has an overestimation problem when providing the size of a particle because of the impact of the bound molecules or aggregates on the surface of a particle (Filippov et al., 2023).

Structural and Crystallographic Characterization

X-ray Diffraction (XRD)

XRD determines the crystalline phase and structure of nanoparticles as well as supplies details of average crystallite size based on the Debye-Scherrer equation. As an example, the iron oxide nanoproducts with spinel structure show the corresponding peaks in XRD patterns that prove the phase purity (Bashir and Liu, 2015).

Vibrating Sample Magnetometry (VSM)

Magnetic properties such as remanence, coercivity, and saturation magnetization can be analyzed using VSM. VSM, especially with iron-based nanoparticles, has been found to be useful when it comes to applications involving magnetic resonance imaging contrast agents or magnetic hyperthermia (Mittal et al., 2022).

Zeta Potential Analysis

The zeta potential shows the charge on particles at the surface of a nanoparticle suspension, which shows the stability of the colloid. A high absolute value that is at least 30 mV is usually considered to be indicative of good dispersion that can even become aggregated and unstable, with low values (Kin et al., 2014).

Thermal and Surface Area Analysis

Thermogravimetric analysis (TGA)

Thermogravimetric analysis is an efficient thermal analysis tool employed to examine the thermal stability of nanoparticles and to estimate the amount of organic or volatile substances in the specimen. This covers the surfactants, capping agent, residual solvent, or even biomolecules of plants in green-synthesized systems. TGA offers a record of weight loss of a material as a variable of temperature, with varied atmospheric conditions, which offers an understanding of decomposition profiles, moisture content and organic surface functionalization. In nanoparticles biosynthesized, TGA is significantly helpful in verifying the presence, and determination of the contribution of the phytochemicals or polymers used as stabilizers, which could enter the range of biocompatibility as well as dispersibility and reactivity of the purpose (Martincic et al. 2024).

Brunauer, Emmet, and Teller (BET) Surface Area Analysis The significant total surface area of nanoparticles can be calculated using the BET method on the basis of isotherms of adsorption and desorption of nitrogen gas. It gives us very important data on surface area, pore volumes, and pore size distribution, which is directly linked with the catalytic efficiency of the material, adsorption capacity, and reactivity. Nanoparticles with large surface areas and defined mesoporous structures have better performance in catalytic and environmental applications since reactants can access the active site more easily. BET analysis is in the visibility, especially in the optimization of nanoparticles meant to be applied in gas sensing, heterogeneous catalysis, and drug loading, wherein surface properties play pivotal roles in defining the functionality of the nanoparticles.

Optical Properties

UV-Visible Spectroscopy

To monitor nanoparticle synthesis in real-time, it has become standard practice to use Ultraviolet-visible (UV-Vis) spectroscopy as an analytical technique, especially to detect the formation and stability of metallic nanoparticles. One of its most relevant uses is the quantification of surface plasmon resonance (SPR) bands-oscillations of the conduction electrons on an ensemble at the nanoparticle surface driven by the incident light. Such SPR peaks are very sensitive to the size and shape of the nanoparticle, its dielectric space, and the extent of aggregation. Noble metals including gold (Au) and silver (Ag) have characteristic SPR bands usually in 500-600nm and 400-450nm ranges respectively (Kumalasari, 2024). Shifts or broadening of these peaks can be used to track morphological changes, polydispersity, or surface effects so UV-vis spectroscopy is a quick and non-destructive technique to monitor synthesis and quality control in nanomaterials research.

Photoluminescence (PL) Spectroscopy

Photoluminescence (PL) spectroscopy is also a sensitive tool to study the electronic structure and defect states of nanoparticles, in particular those made of semiconducting surfaces or doped surfaces. When stimulated by a source of appropriate light, electrons transfer to higher energy levels and down-convert back to lower levels, emitting characteristic photons of the band gap and defect morphology of the material. This emission gives excellent information about surface defects, the quantum confinement effect, and energy processes. The detection of specific analytes, tracking of molecular interactions, and labeling of biological systems with high specificity and minimal invasivity also make PL a widespread technology in biosensing and biomedical imaging. The brightness, peak location, and the emission band alone represent material purity, surface chemistry, and photostability, all of which are central to the fabrication of optoelectronic and diagnostic nanodevices (Khan et al. 2019).

Surface Chemistry and Composition

In the aspects of chemical, elemental, and functional characterization of metal nanoparticles (MNPs), surface characterization methods perform quite significant roles related to the surface reactions and reactivity and stability issues. The surface functional groups, oxidation states and composition distribution lie in a direct impact on the behavior of nanoparticles in catalysis, biomedical applications and environment interfaces, all of which can be found with these instruments (Khan et al. 2019).

Fourier-Transform Infrared Spectroscopy (FTIR)

The technique of Fourier-Transform Infrared Spectroscopy (FTIR) is an analytical method that should not be ignored because it is necessary to know the functional groups on the nanoparticle surface. It is especially useful to evaluate the character of capping agents, stabilizing ligands, or phytochemical remnants of nanoparticles produced by the green utilizing technique. The information possibilities of FTIR include the detection of vibrational transitions between molecular bonds, permitting the characterization of chemical groups such as -OH, -COOH, and -NH_2, usually brought about via biosynthesis through the usage of plant extracts or surfactants. The technique gives crucial evidence of successful surface functionalization that dictates the colloidal stability, solubility, and biological interactions. Furthermore, the changes in the positions of the peaks or their intensities will provide data concerning the robustness of the bonding of the surface and their interactions with the target biomolecules or contaminants (Pasieczna-Patkowska et al., 2025).

XPS- X-ray Photoelectron Spectroscopy

The X-ray Photoelectron Spectroscopy (XPS) is a technique which presents high resolution surface chemical examination that determines the quantity of the photoelectrons of the material surface and its amount of kinetic energy that is produced when the material is irradiated by X-rays. This can be used to determine the elemental composition, chemical state and electronic environment of atoms to a depth of ~110nm, so is a very useful tool in interrogating the surface of nanoparticles. XPS is particularly important in bimetallic systems whereby it may be possible to either elementally segregate or oxidize to form an outer shell that plays a major role in catalytic behavior, toxicity, or the rate of efficient electron transfer (Krishna and Philip, 2022). As an illustration, it is easy to resolve surface oxidation states of such metals as Au 0/Au + or Fe2+/Fe3+, contributing to the understanding of a redox activity and reactivity profile (Yamashita and Hayes, 2008).

USES OF METAL NANOPARTICLE

Metal nanoparticle (MNP) properties, like their optical properties, magnetic properties, catalytic activities, as well as their biological applications, are highly desirable, and thus they are broadly applicable in different fields of science, industries, and even in the biological field. That is because of their elevated surface area-to-volume ratio, the quantum size effects, and the possibility to modulate their surface functionalities, which have made them excellent candidates in a broad range of applications, including environmental remediation and cancer treatment (Burlec et al. 2023).

Environmental clean-up

The redox properties and the catalytic possibilities make the MNPs, especially the bimetallic and the transition metal-based nanoparticles, of increasing importance to be used in the treatment of pollutants. Bimetallic nanoparticles such as Fe-Pd, Cu-Fe and Ag-Ni are more active in converting chlorinated organic matter, dyes, and pharmaceuticals. The synergistic effects in metal are beneficial since they enhance electron transfer efficiency to increase the rate of redox reactions (Rani et al., 2025). Zero-valent iron (nZVI) and AgNPs have been used in the treatment of ground and wastewater with predictable results in the elimination of heavy metals (e.g., Pb^{2+}, Cr^{6+}) and microbial pollutants. They can be specifically targeted to pollutants, and due to their high reactivity and ease of functionalization, they can undergo functionalization (Younas et al. 2024).

Catalysis

The metal nanoparticles make a very good type of catalyst because of their active-site density and reactive surfaces. They are also small enough to be able to effectively interact with the substrate with a minimum amount of material utilized. Gold, silver, and palladium nanoparticles are used in green catalytic transformations to produce oxidation, hydrogenation, and coupling reactions. Such reactions can be done in mild conditions and produce little waste. Hybrid metal-metal nanoparticles of noble and semiconductor metals can facilitate the degradation of dyes and antibiotics in the form of photocatalysis in the presence of visible light to provide a sustainable method of wastewater detoxification (Rani et al., 2025).

Biomedical Uses

The unprecedented interest in metal nanoparticles (MNPs) in the biomedical research field is based on clinical applications driven by their exceptional physicochemical features such as large surface-area-to-volume ratio, tunable nanoparticle surface functionality, and high biocompatibility (Chandrakala et al. 2022). These characteristics support superior interactions with biomolecules and cellular systems, to support multifaceted use of MNPs in diagnostics, therapeutic treatments, imaging, and in antimicrobial actions. They have the potential to readily enter biological barriers, respond to an external stimulus (e.g., pH, magnetic fields), and selectively target tissues or pathogens which has resulted in a major paradigm shift in personalized medicine and nanotheranostics (Fahim et al. 2025).

Drug Delivery

The controlled and targeted drug delivery systems via nanocarriers of MNPs are one of the most promising applications of MNPs. Among them, gold (AuNPs) and iron oxide nanoparticles (IONPs) are especially notable. Ligands (antibodies, aptamers) and biocompatible polymers (e.g., PEG, chitosan) can easily be assembled on their surfaces, as well as pH-sensitive linkers, allowing the site-specific release of therapeutic payloads. Surface functionalization extends the circulation time, incorporation into cells, and bioavailability of the nanoparticles and minimizes off-target cytotoxicity (Huang et al., 2023). As another illustration, iron oxide nanoparticles have successfully been employed to deliver anticancer drugs like doxorubicin to tumor sites via manipulative external magnetic fields- a technique known as magnetic-targeted drug delivery (Hernandes et al. 2023). Likewise, AuNPs have been exploited in the delivery of nucleic acids and small-molecule drugs with great specificity and low immune response (Huang et al. 2023).

Diagnostics and Imaging

In biomedical application, MNPs are important in increasing the diagnostic sensitivity, and improving image contrast in medical imaging. Magnetic resonance imaging (MRI) has been extensively used to utilize superparamagnetic iron oxide nanoparticles (SPIONs) as contrast agents because the nanoparticles have high magnetization, low toxicity levels, and the capacity to concentrate in the body (Fahim et al. 2025). These characteristics can be used to identify the earliest signs of tumors, vascular anomalies and inflammatory locations. Moreover, the optical property of gold nanoparticles is fantastic and exceptional, especially localized surface plasmon resonance (LSPR), which is highly useful in optical imaging and colorimetric assays. They are constituent parts of lateral flow immunoassays, including rapid tests to diagnose infectious diseases, e.g., rapid diagnostic test kits to diagnose COVID-19, dengue, and malaria (Kumalasari, 2024). The significance of functionalized AuNPs in biosensors is that they are selective in binding to biomarkers, have measurable changes in color, fluorescence or electric potential, thus acting as potential platforms in real-time point-of-care diagnostics.

Photodynamic and Photothermal Therapy

Gold nanoparticles may be used to convert absorbed light (usually near-infrared) into heat; this effect is used in photothermal therapy (PTT). By directing them to cancer cells and irradiating them with laser, these nanoparticles cause hyperthermia within the targeted sphere, causing the preferential ablation of the tumor with limited harm to the surrounding healthy cells. Likewise, photodynamic therapy (PDT) involves the use of nanoparticles as photosensitizer carriers that by absorption of light produce reactive oxygen species (ROS) to kill cells (Badir et al. 2025). The new non-invasive therapy methods serve as an alternative to conventional chemotherapy, radiotherapy and are quite effective in addressing multidrug-resistant cancer types.

Antimicrobial Agents

A number of metal nanoparticles, with silver (AgNPs), copper (CuNPs), and zinc oxide (ZnONPs) being the most promising, have shown a broad-spectrum antimicrobial activity against pathogenic bacteria, viruses, and fungi. They cause their action by disrupting microbial membranes, inducing oxidative stress by production of ROS, interfering with metabolic enzymes, and denaturing structural proteins (AlQurashi et al., 2025). They are nanoparticles that are becoming of interest as a replacement for conventional antibiotics, mainly in the context of antibiotic resistance. It finds use in wound dressings, medical device coatings, water purification systems, and antimicrobial textiles. Moreover, the use of these nanoparticles in dental materials, surgical sutures, and bone implants has been found promising in preventing nosocomial infections and their patient outcomes (Correa et al. 2015).

Energetic Storing and Conversion

Metal nanoparticles are growing in the applications of energy like fuel cells, supercapacitors, and batteries. Hydrogen fuel cells utilize platinum nanoparticles and palladium nanoparticles as catalysts to enhance reaction dynamics and energy efficiency of fuel cells. Metal nanoparticles are used in improving the light absorption and charge transport in generator devices, especially in dye-sensitized and perovskites solar cells (Subhan et al. 2025).

Food and Agricultural Sector

In farming, MNPs are expected to become intelligent delivery technicians, carrying nutrients and pesticides to crops and fields, besides endowing food preservatives in wrapping. It involves the use of zinc and iron nanoparticles that enhance the delivery of micronutrients in crops, such as nutrient uptake and plant growth (Ali et al., 2018). Nanoparticles of silver and ZnO nanoparticles impregnated in biodegradable films are antimicrobial and enhance shelf life and limit food spoilage (Lebaka et al., 2025).

Sensor development

The high surface energy and high ability to participate in the transfer of electrons make metal nanoparticles increase the sensitivity and selectivity of the biosensors. Electrochemical Sensors: Gold and silver nanoparticles are utilized in glucose, heavy metal, and pesticide sensors, where they provide a fast and sensitive analytic tool with a low limit of detection. Sensors based on Surface Plasmon Resonance (SPR) like AuNPs have a strong plasmonic response and thus find application in SPR-sensor-based biomolecule detection, where biomolecules can be detected without a label in real-time (Rani et al., 2025).

CHALLENGES AND FUTURE PERSPECTIVES

Nevertheless, in spite of the monumental achievements in the synthesis, characterization, and use of metal nanoparticles (MNPs), there still exist a number of challenges that either restrict its commercialization and safe implementation in real systems or challenge the potential biological effects of using such particles (Burlec et al., 2023). Greater appreciation of such constraints, as well as strategic future perspectives, will assist in designing more viable and creative nano-based technologies.

Poor reproducibility of most nanoparticle synthesis protocols, especially those entailing green or biological synthesis, is a consequence of batch-to-batch variation in composition of plant extract, microbial performance, or enzyme activity (Ying et al., 2022). The discrepancy will interfere with scalability and comparability among studies and inhibit industrialization. Although the chemical methods are reproducible at laboratory scale, up-scaling means the lack of control in particle size and stability. Physical techniques, providing high purity nanoparticles, are energy intensive and cost-effective to carry out at large scales. The presence of residual chemicals (e.g. reducing agents, surfactants) in chemically produced nanoparticles may be toxic both to the health of humans and natural environments. On the same note, certain metal ions (e.g., silver, copper) may be cytotoxic in high amounts. Safe-by-design synthesis is hence critical (Abady et al., 2025). Nanoparticles have no common regulatory guidelines to be used in biomedical, environmental and consumer applications. Existing toxicological evidence is weak, sometimes contradictory or never including the case of a long or small dose of exposure. Such regulatory gap discourages the reception of nanoparticle-based products and their proliferation in the market (Xuan et al., 2023). Artificial intelligence (AI) and machine learning (ML) models are being investigated in order to forecast nanoparticle synthesis results, optimize parameters, and design experiments. Reproducibility and scalability of nanoparticle production can further be revolutionized by automated microfluidic platforms and high-throughput screening. The principles of eco-design should be highlighted in future research, which should be aimed at paying attention to biodegradable supports, biocompatibility capping agents, and low energy to perform the synthesis. This is in line with the increasing global concern for sustainable nanotechnology and sustainable economy patterns. The next generation of nanoparticles will probably incorporate more than one feature—they will have a combination of catalytic, imaging and therapeutic capabilities in a single construct. Multifunctional materials, such as the construction of hybrid systems (metal-organic frameworks, or MOFs, or core-shell NPs) with complex application requirements, are emerging.

Further developments will continue on customizing MNPs to real-time biosensing, theranostics, and in vivo drug tracking, which would require a better knowledge of their physiological distribution, metabolism, and clearance (Hanmante et al. 2025). Chemists, biologists, toxicologists, and engineers will be important in this interdisciplinary effort.

CONCLUSION

Metal nanoparticles (MNPs) not only form the essential part of modern science because of their numerous and adjustable properties that allow applying them to a broad variety of areas, such as catalysis, biomedicine, environmental clean-ups, energy, and sensors technologies. This review has also elaborated on different synthesis strategies i.e., physical, chemical and green along with key parameter impacting the formation of nanoparticle which are pH, temperature, precursor concentration, reducing/capping agent and reaction time.

The assessment of structural, optical, and surface properties of MNPs relies on vital characterization techniques, which include TEM, XRD, UV-Vis spectroscopy, and zeta potential analysis. The MNPs have various functions, and this fact is proved by a successful cross-disciplinary implementation of this technology in a wide range of applications, including wastewater purification and cancer diagnosis. Nevertheless, there are still some fundamental issues that have to be solved, notwithstanding incredible growth: reproducibility, toxicity, scaling, and absence of standardized regulations.

To overcome this, there is an urgent necessity to have a collaboration in both disciplines: present green chemistry and toxicology, AI, and regulatory science to create safer, sustainable, and multifunctional nanoparticle systems. The next research phase would be characterized by the innovations in the area of in situ characterization, assisted machine learning during the synthesis, and multifunctional nanomaterials. Strategically invested and internationally cooperated, metal nanoparticles would be capable of being revolutionized in the next decades in not only high-tech industries but also in the framework of sustainable development objectives.

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