

# A Detailed Review of Synthesis, Characterization, and Applications of Metallic Nanoparticles

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## Abstract

Nanotechnology is a rapidly evolving interdisciplinary domain that focuses on the design, synthesis, and application of materials at the nanoscale. Central to this field are nanoparticles, typically ranging from 1 to 100 nanometres in size, which can be classified into inorganic, organic, ceramic, and carbon-based categories. Inorganic nanoparticles are further divided into metal and metal oxide nanoparticles, whereas carbon-based nanoparticles encompass structures such as fullerenes, carbon nanotubes, graphene, carbon nanofibers, and carbon black. Nanoparticles are synthesized using two primary strategies: top-down and bottom-up approaches. This review explores various synthesis methodologies, including chemical, physical, and green synthesis routes. A comprehensive overview of characterization techniques is presented, including UV-Visible spectroscopy for optical properties, FT-IR spectroscopy for functional group identification, and Scanning Electron Microscopy (SEM) for surface morphology. To provide a holistic understanding, the review also includes X-ray Diffraction (XRD) for crystalline structure analysis, Transmission Electron Microscopy (TEM) for detailed size and shape evaluation, Brunauer–Emmett–Teller (BET) analysis for surface area determination, and Dynamic Light Scattering (DLS) for assessing hydrodynamic size, zeta potential, and colloidal stability. In the present manuscript, we have discussed the pros and cons of each technique to understand their role in the characterization of nanoparticles. Review article also explored the application of green synthesized nanoparticle in targeted drug delivery, photocatalytic degradation of organic pollutants, water bioremediation, and cosmetic formulations. In summary, present review explored the importance of green synthesis method over other chemical and physical method. The green synthesized nanoparticles can serve as pivotal components across sectors such as healthcare, pharmaceuticals, cosmetics, and electronics.

**Keywords:-** Nanoparticles Synthesis; Thermal decomposition; Laser ablation; SEM; XRD; Microorganism

## 1. Introduction

Nanotechnology refers to a revolutionary field that involves the manipulation and control of matter at the nanoscale, which is typically at the atomic and molecular level. It enables researchers to create, design, and utilize materials, devices, and systems with exceptional properties and functionalities because of their nanoscale dimensions. Nanotechnology has the potential to revolutionize various industries, including electronics, medicine, energy, materials science, and many more. Nanoparticles are extremely small particles with dimensions between 1 and 100 nanometres. They can be engineered to possess unique properties and behaviours that are not present in bulk materials. There are several techniques for synthesizing nanoparticles, each with its

own advantages and limitations. Chemical Methods: Chemical synthesis involves the reduction of precursor materials to form nanoparticles. This method includes techniques like sol-gel synthesis, precipitation, and chemical vapor deposition. These methods are versatile and can produce a wide range of nanoparticle types (Dubey et al., 2015; Habte et al., 2019; Tang et al., 2008; Zorkipli et al., 2016). Physical Methods: Physical methods involve processes such as mechanical milling, laser ablation, and plasma methods (Gondal et al., 2009; Kumar & Thareja, 2010; Patel et al., 2013; Zhang & Wen, 2020). These methods are often used for producing metallic nanoparticles. Biological Methods: Biological methods use living organisms or biomolecules to synthesize nanoparticles. For example, bacteria or plant extracts can be used to reduce metal ions into

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nanoparticles (Gómez-Zavaglia et al., 2022; Pushparaj et al., 2023; Tailor et al., 2020). Nanoparticles find applications in various fields, including medicine, where nanoparticles can be designed to deliver drugs to specific targets in the body, improving therapeutic outcomes and reducing side effects. Electronics: Nanoparticles are used in electronic components to enhance conductivity, create ultra-small transistors, and develop high-resolution displays. Catalysis: Nanoparticles can serve as highly efficient catalysts in chemical reactions due to their high surface area and unique properties. Materials Science: Nanoparticles are integrated into materials to enhance properties like strength, durability, and conductivity. Energy: Nanoparticles play a role in improving energy storage (batteries and supercapacitors) and energy conversion (solar cells and fuel cells) technologies. The synthesis of nanoparticles and their subsequent integration into various applications underscore the transformative potential of nanotechnology, offering solutions to some of the most pressing challenges across different sectors. As research continues, nanotechnology is likely to bring about groundbreaking advancements that reshape industries and our daily lives. (Abdelghany et al., 2023; Ali et al., 2024; Bhosale et al., 2025; Kiran et al., 2021; Klink et al., 2022b; Naik & David, 2023; Norouzi Jobie et al., 2021; Pereira et al., 2023; Tiwari et al., 2016)

## 2. Methods for Synthesis of Nanoparticles:

The synthesis of metallic nanoparticles (MNPs) is a fundamental aspect of nanotechnology, as it directly influences their size, shape, surface properties, and subsequent applications. Broadly, the synthesis methods are categorized into chemical, physical, and green (biological) approaches. Chemical synthesis is one of the most commonly employed methods due to its efficiency and control over particle characteristics. It typically involves the reduction of metal salts using chemical reducing agents such as sodium borohydride, citrate, or hydrazine. Techniques such as the sol-gel method, co-precipitation, and microemulsion offer further refinement in controlling nanoparticle morphology and dispersion. However, these methods often rely on toxic chemicals and may leave residues that pose challenges for biomedical or environmental applications. In contrast, physical methods involve energy-intensive processes that do not rely on chemical reagents. Techniques such as mechanical milling, laser ablation, and evaporation-condensation physically reduce bulk metals into nanoscale particles. These approaches offer the advantage of producing high-purity nanoparticles free from chemical contaminants, but they generally require sophisticated equipment, high energy input, and often lack precise control over particle shape and uniformity. Green synthesis, an emerging and environmentally sustainable approach, utilizes biological resources such as plant extracts, bacteria, fungi, and algae for nanoparticle production. Plant-mediated synthesis is particularly promising, as phytochemicals like flavonoids,

alkaloids, and terpenoids act as natural reducing and stabilizing agents. Similarly, microorganisms can biosynthesize nanoparticles either intracellularly or extracellularly under mild conditions. This method is considered eco-friendly, cost-effective, and suitable for biomedical and environmental applications due to the absence of toxic chemicals. However, challenges related to scale-up, reproducibility, and particle uniformity remain. Overall, the choice of synthesis method depends on the specific application, desired nanoparticle properties, and environmental considerations. While chemical and physical methods offer precision and scalability, green synthesis aligns with the principles of green chemistry and offers a safer, more sustainable alternative for nanoparticle production.

Synthesis Methods of Metallic Nanoparticles

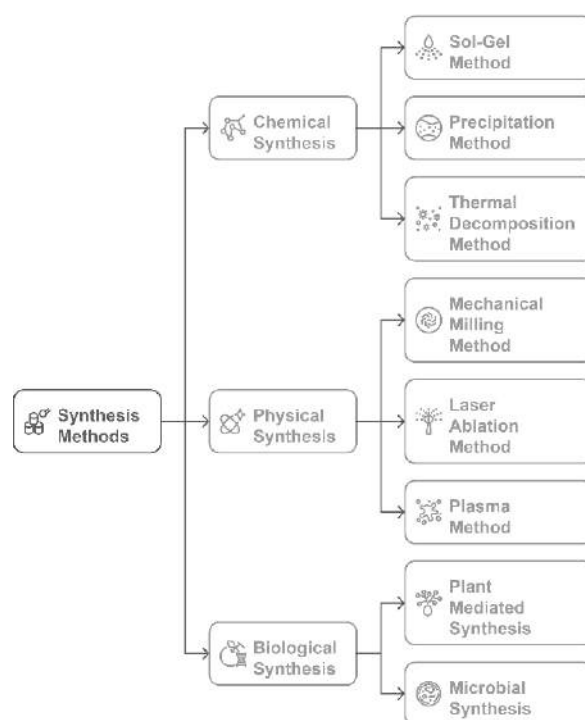


Figure 1 : Synthesis Methods for Metallic Nanoparticles by various methods

### 2.1 Chemical Methods

Chemical methods are widely used for the synthesis of metallic nanoparticles due to their simplicity, scalability, and control over particle size and morphology. These methods typically involve the reduction of metal salts using chemical reducing agents such as sodium borohydride, citrate, or hydrazine. Common techniques include the sol-gel method, co-precipitation, and microemulsion, which allow for fine-tuning of nanoparticle properties. While chemical synthesis provides uniform and stable nanoparticles, it often involves toxic solvents and reagents, which may limit their use in biomedical or environmental applications without proper purification.

### 2.1.1 Thermal Decomposition Method

This method is a top-down approach for the synthesis of nanoparticles. Heat is the source of chemical degradation in this endothermic reaction. The chemical bond in a compound is broken by this heat. The decomposition temperature may be defined as the specific temperature at which an element is chemically decomposed. The nanoparticles are consequences of the decomposition of meta at a specific temperature. Ahab, Atika, et al. Synthesized gadolinium oxide nanoparticles functionalized by paramagnetic poly ethylene glycol by using the thermal decomposition method. Process Steps: Choose Precursor Compounds: Pick precursor compounds that have the components your nanoparticles will include. Typically, metal-organic complexes or metal salts make up these precursor chemicals. Metal acetylacetonates, metal chlorides, and metal nitrates are a few examples of frequently utilized metals. Choose an appropriate solvent to dissolve the pre-selected precursor chemicals in. The precursors and the desired properties of the nanoparticles influence the solvent choice. Organic solvents like toluene, hexane, or oleyl amine are examples of common solvents. Stabilizing Ligands: You can add stabilizing ligands or surfactants to the solution to regulate the size and form of the nanoparticles. These substances can facilitate the creation of well-defined nanoparticles and prevent agglomeration. Heating: Heat the solution to a specific temperature under controlled conditions. The heating process can be carried out in various ways, such as in an oven, microwave, or on a hotplate. The temperature and heating rate are crucial parameters that influence the size and crystallinity of the nanoparticles. Inert Atmosphere: Often, thermal decomposition is performed under an inert atmosphere (e.g., nitrogen or argon) to prevent oxidation of the nanoparticles during the process. Nucleation and Growth: As the solution is heated, the precursor compounds decompose, forming the nuclei of nanoparticles. These nuclei then grow into larger nanoparticles as more precursor molecules decompose and deposit on the existing nuclei. Cooling and quenching: After the desired nanoparticle size is achieved, the reaction is typically quenched by cooling the solution rapidly. This step helps stabilize the nanoparticles and prevent further growth. Purification: The synthesized nanoparticles may be purified by techniques such as centrifugation, precipitation, or solvent washing to remove unreacted precursors and byproducts. Decomposition-precipitation Gold nanoparticles supported on ZnO (Au/ZnO) were prepared by the decomposition-precipitation method with some modifications. 15 Gold(III) chloride trihydrate (HAuCl<sub>4</sub>·3H<sub>2</sub>O) was used as the gold precursor. In a typical preparation, 100 mL of HAuCl<sub>4</sub> (4.2 × 10<sup>-3</sup> M) solution was heated to 80 °C. The pH was adjusted to the desired value by dropwise addition of 0.5 M NaOH. Approximately 1.00g of the zinc oxide support was dispersed into the solution. Insertion of the support resulted in a pH change, so the pH was kept

constant by the dropwise addition of 0.5 M HCl. The suspension was thermostat at 80 °C and stirred vigorously for 2 hours. Precipitates were washed several times with distilled water to remove residual sodium and chloride ions as well as the unreacted Au species. The washing was considered complete when no AgCl precipitate was detected when the filtrate was added to an AgNO<sub>3</sub> solution. Lastly, the precipitates were gathered by centrifugation and dried at 100 °C overnight. The calcination procedure was carried out at 450 °C under air for 4 h with a gradient temperature of 50 °C min<sup>-1</sup>. The calcination process was necessary as it allowed for the decomposition of gold precursors to their metallic state. 26 preparations of gold nanoparticles supported on ZnO at different pH values of 7, 9.78, and 11, which were below, at, and above the IEP of ZnO, respectively, were repeated using the same procedure. A pH of 9.78 was achieved by the insertion of ZnO into a gold (III) chloride solution without pH adjustment. However, adjustments to pH 7 and 11 were conducted in two ways: (1) two-time adjustment, i.e., before and after the addition of ZnO; and (2) one-time adjustment, i.e., only after the addition of ZnO to the HAuCl<sub>4</sub> solution, with the pH not maintained before the addition of ZnO. (Jan et al., 2021; Kiran et al., 2021; Tran et al., 2023)

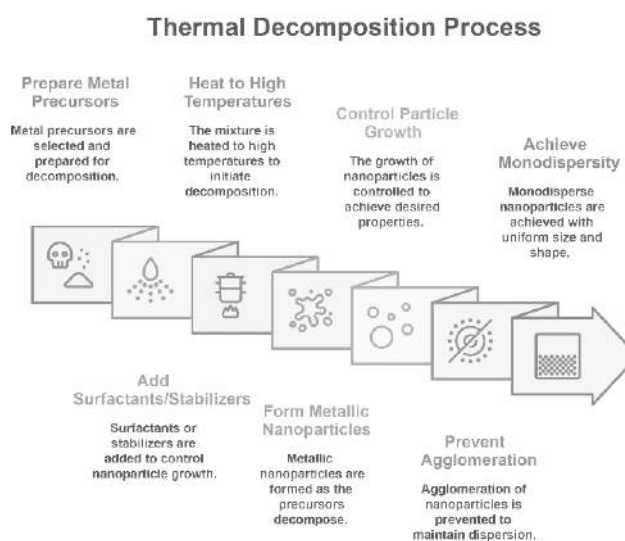


Figure 2 : process of production of nanoparticles by Thermal Decomposition Method (Chemical Method)

### 2.1.2 Sol-Gel Method

The primary chemical reactions in this process are hydrolysis and condensation. Metal alkoxide or metal chloride precursors are typically used. They undergo hydrolysis in the presence of water or a hydrolysing agent. It produces metal hydroxides  $M(OR)_n + nH_2O \rightarrow M(OH)_n + nROH$ . The metal hydroxides then undergo condensation reactions, where they form metal-oxygen-metal (M-O-M) bonds by losing water molecules. This process leads to the growth of nanoparticles:  $M(OH)_n \rightarrow M-O-M + nH_2O$  Formation of Colloidal Solution (Sol): Initially, as the hydrolysis and condensation reactions

progress, the system forms a colloidal suspension known as a "sol." This sol consists of tiny nanoparticles or nanoclusters dispersed in a liquid medium. The size and properties of the nanoparticles in the sol can be controlled by manipulating the reaction parameters. Gelation: Over time, as the condensation reactions continue, the sol undergoes a transition into a three-dimensional network structure known as a "gel." The gel consists of interconnected nanoparticles or nanoclusters, and the extent of gelation can be controlled by adjusting the aging time. Procedure: Precursor Selection: Choosing suitable chemical precursors (typically metal alkoxides or metal chlorides) for the desired nanoparticles. These precursors should be soluble in a suitable solvent. Solvent Selection: Selecting a solvent (usually an alcohol like ethanol or isopropanol) that can dissolve the chosen precursors and promote the formation of a homogeneous solution. Hydrolysis: The first step in the sol-gel process involves the hydrolysis of the precursor compounds. This is typically achieved by adding water (or a hydrolysing agent) dropwise to the precursor solution under controlled

conditions. The hydrolysis reaction can be represented as follows for a metal alkoxide precursor (M(OR)<sub>n</sub>):  

$$M(OR)_n + nH_2O \rightarrow M(OH)_n + nROH$$
 Condensation: After hydrolysis, the metal hydroxides formed in step 3 can undergo condensation reactions to form the nanoparticles. These reactions involve the removal of water molecules, leading to the formation of metal-oxygen-metal (M-O-M) bonds. The extent of condensation can be controlled by factors like temperature, pH, and the presence of catalysts. Gel Formation: As the condensation reactions progress, a three-dimensional network of interconnected nanoparticles forms within the solution. This network is known as a sol-gel or gel network. Aging: To achieve desired nanoparticle properties, the sol-gel is typically allowed to age for a specific period of time. Aging can lead to changes in the size, shape, and crystallinity of the nanoparticles. (Dubey et al., 2015; Habte et al., 2019; Hasnidawani et al., 2016; Jan et al., 2021; Khan et al., 2022a, 2022b; Prasad et al., 2020; Tran et al., 2023; Zorkipli et al., 2016)

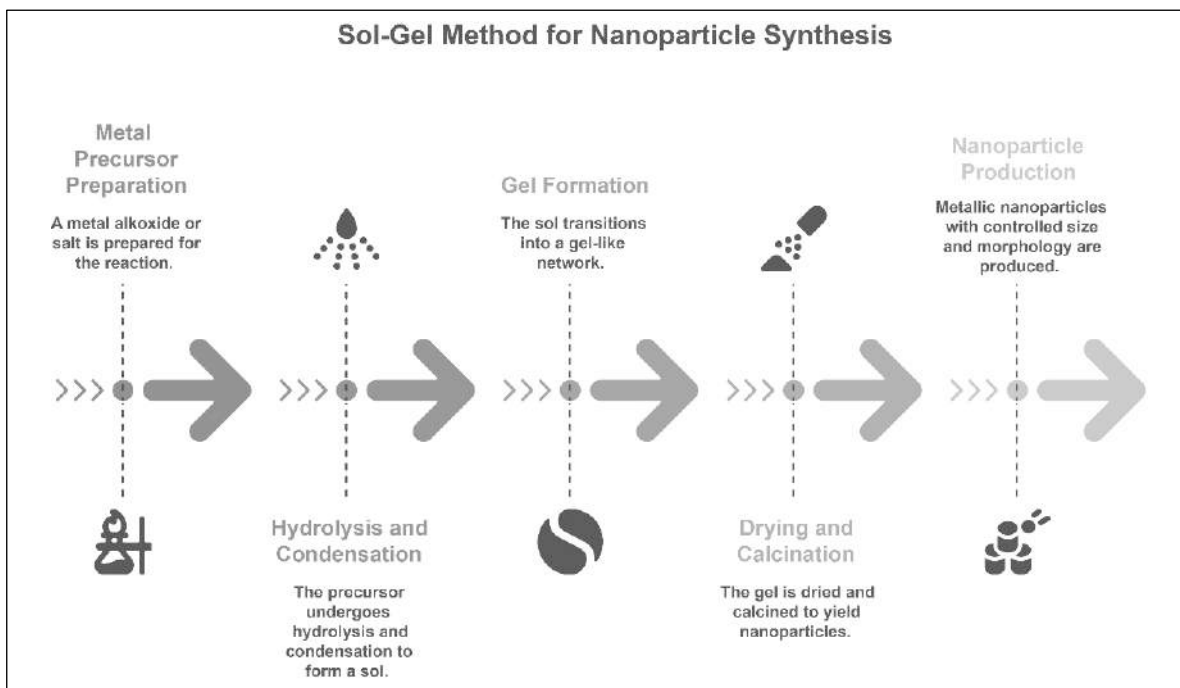


Figure 3 : Process of production of CaO nanoparticles by Sol-Gel method (Chemical Method)

## 2.2 Physical Methods

Physical methods involve top-down approaches that use mechanical or energy-based techniques to produce metallic nanoparticles without the use of chemical reducing agents. Common techniques include high-energy ball milling, laser ablation, evaporation-condensation, and physical vapor deposition. These methods can yield high-purity nanoparticles and avoid chemical contamination, making them suitable for specific industrial and electronic applications. However, they often require expensive equipment, consume high energy, and may offer limited control over particle size distribution

and shape compared to chemical methods.

### 2.2.1 Mechanical Milling

In mechanical milling, bulk materials are milled down to nanoscale particles using mechanical forces. High-energy ball milling, for example, involves milling materials in a ball mill where balls and powder collide, leading to particle size reduction. This method is commonly used for metallic and ceramic nanoparticles. Mechanical methods like ball milling involve the use of grinding media (balls or beads) to break down bulk materials into nanoparticles. This method is particularly useful for producing nanoparticles from brittle materials.

Mechanical milling relies on the principles of mechanical attrition and impact. It involves the use of a high-energy ball mill to reduce the size of particles in a solid powder or mixture. **Process Steps:** **Selection of Materials:** Mechanical milling can be applied to a wide range of materials, including metals, ceramics, polymers, and composite materials. The starting material is typically in the form of coarse powders or solid chunks. **Loading the Mill:** The chosen material, along with grinding balls (typically made of metal or ceramics), is loaded into a milling chamber, which may be a stainless steel container or a vial made of a suitable material. **Milling Operation:**

The milling chamber is sealed, and the mill is operated under controlled conditions. The rotation of the mill and the movement of the grinding balls generate mechanical forces that lead to a reduction in particle size through repeated impacts and attrition. **Duration and Speed Control:** The duration of milling and the rotation speed of the mill are crucial parameters that can be adjusted to control the size, shape, and properties of the resulting nanoparticles. Longer milling times and higher rotation speeds generally result in smaller nanoparticles. (Cheng et al., 2025; Montemayor Palos et al., 2023; Salah et al., 2011; Zhang & Wen, 2020)

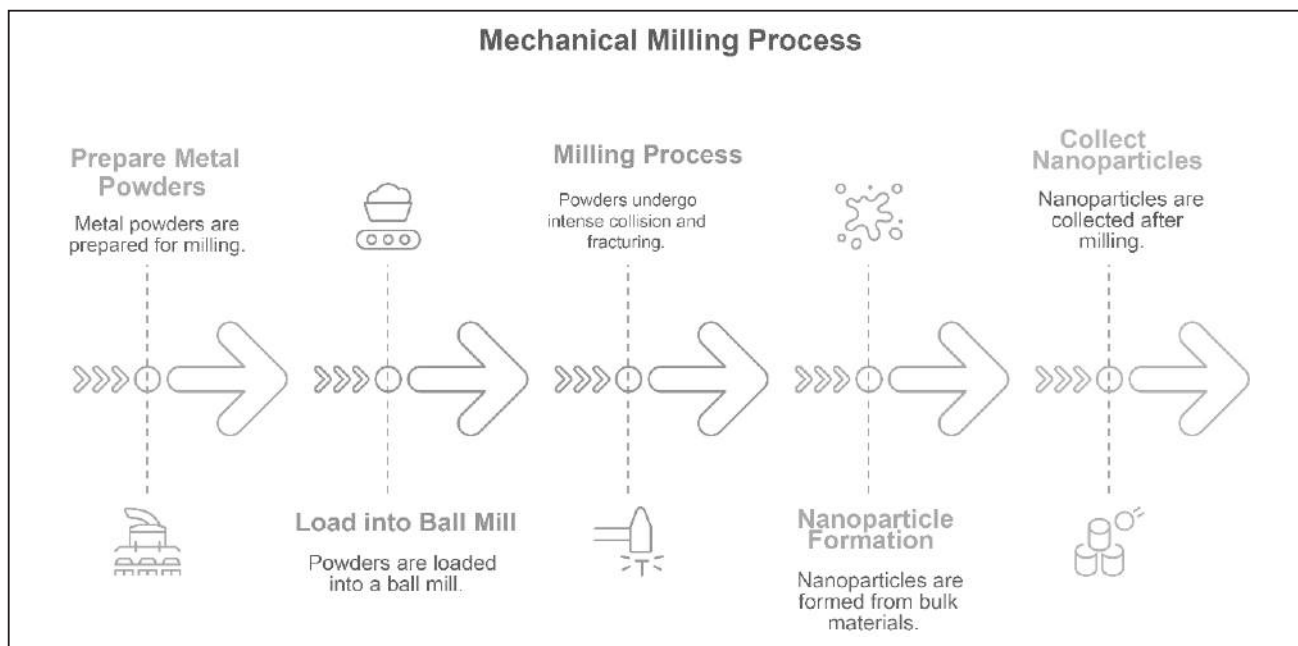


Figure 4 : Process of production of nanoparticles by Mechanical Milling (Physical Method)

### 2.2.2 Laser Ablation

In laser ablation, a high-intensity laser beam is focused on a target material, causing the target material to vaporize and form nanoparticles in the vapor phase. These nanoparticles can then be collected on a substrate. Laser ablation is based on the principle of using a focused, high-intensity laser beam to irradiate a solid target material. When the laser energy is absorbed by the target, it can lead to the vaporization or ablation of target atoms or molecules, creating a plasma plume. As this plasma plume cools and condenses, it forms nanoparticles with the same composition as the target material. **Process steps:** **target selection:** The first step is to select a target material. **Laser Setup:** A high-energy laser system is set up, typically an Nd:YAG (neodymium-doped yttrium aluminum garnet) or an excimer laser, depending on the specific application and target material. **Target Preparation:** The selected target material is prepared as a solid target, often in the form of a disk or pellet. The target is placed in a controlled environment or vacuum chamber to prevent unwanted interactions with atmospheric gases.

**Laser Ablation:** The laser beam is focused onto the surface of the target material. The high-energy photons from the laser interact with the target, causing localized heating and vaporization. This process creates a plasma plume consisting of atoms, ions, and clusters. **Nanoparticle Formation:** As the plasma plume expands and cools, the atoms and ions recombine and condense to form nanoparticles with sizes ranging from a few nanometres to a few hundred nanometres. The properties of the nanoparticles, including size, shape, and composition, can be controlled by adjusting laser parameters such as energy, pulse duration, and repetition rate. (Cheng et al., 2025; Gondal et al., 2009; Kumar & Thareja, 2010; Prasad et al., 2020)

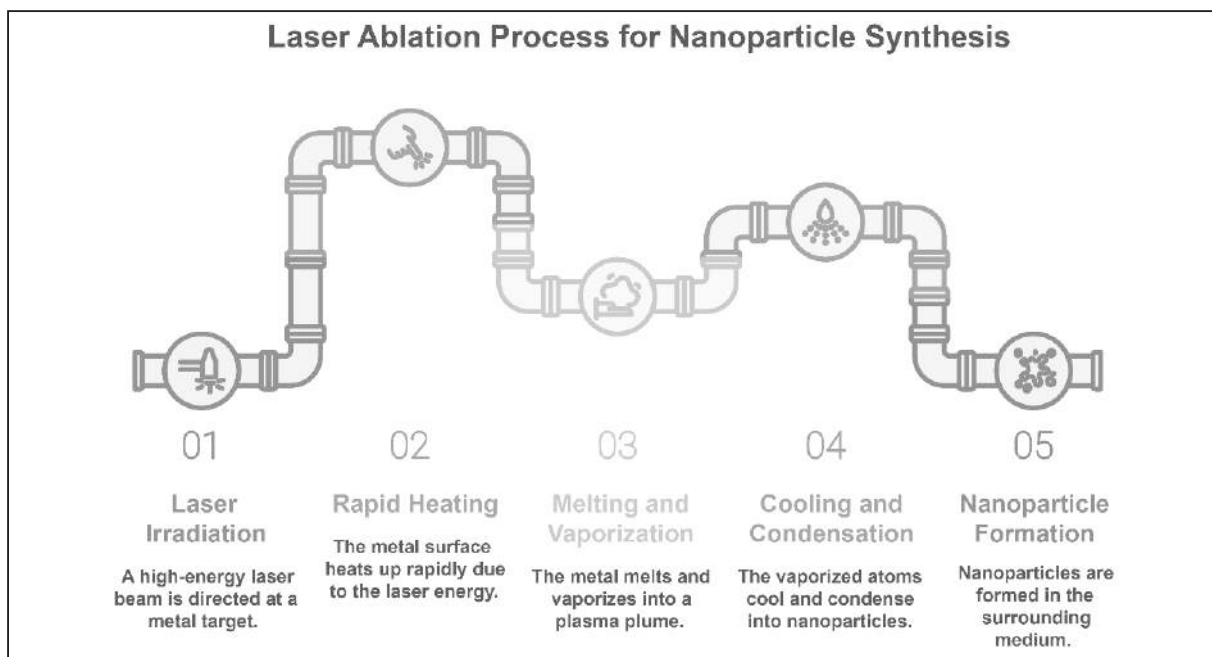


Figure 5 : Process of production of nanoparticles by Laser Ablation (Physical Method)

### 2.2.3 Plasma method

Plasma is a high-energy, ionized gas consisting of electrons, ions, and neutral species. It can be generated using various techniques, including radiofrequency (RF), microwave, and direct current (DC) discharges. In the plasma synthesis method, nanoparticles are produced through a series of chemical reactions and physical processes within the plasma. **Process Steps:** **Plasma Generation:** A plasma source, such as a plasma torch or plasma jet, is used to generate the plasma. The choice of plasma source depends on the specific application and the desired characteristics of the nanoparticles. **Introduction of Precursors:** Gaseous or liquid precursor materials, which contain the elements needed for nanoparticle formation, are introduced into the plasma zone. These precursors may include metal organic compounds, metal salts, or precursor gases like nitrogen and oxygen. **Plasma Heating:** The plasma provides a high-energy environment, causing the precursor materials to dissociate, ionize, and undergo chemical reactions. The high temperatures and energy levels in the plasma promote the vaporization and atomization of the precursors. **Nucleation and Growth:** Within the plasma, nucleation of nanoparticles occurs as atoms and ions collide and aggregate to form small

clusters. These clusters serve as the nuclei for nanoparticle growth. The nanoparticles continue to grow as more precursor species attach to their surfaces. **Cooling and Agglomeration:** As nanoparticles leave the plasma zone and enter a quenching region, they cool rapidly. This cooling step is critical to controlling the size and morphology of the nanoparticles. In the quenching region, nanoparticles may agglomerate or form aggregates. (Ashwini et al., 2021; Hammad et al., 2023; Montemayor Palos et al., 2023; Patel et al., 2013)

### 2.2.4 Biological Synthesis

Biological or green synthesis methods utilize natural biological resources such as plant extracts, bacteria, fungi, and algae to produce metallic nanoparticles in an eco-friendly manner. These organisms or their metabolites act as reducing and stabilizing agents, enabling nanoparticle formation under mild, non-toxic conditions. Plant-mediated synthesis is especially popular due to its simplicity, scalability, and the abundance of phytochemicals like flavonoids and phenolics. Biological methods are cost-effective and sustainable, making them highly suitable for biomedical and environmental applications. However, challenges remain in achieving consistent particle size, shape, and large-scale production.

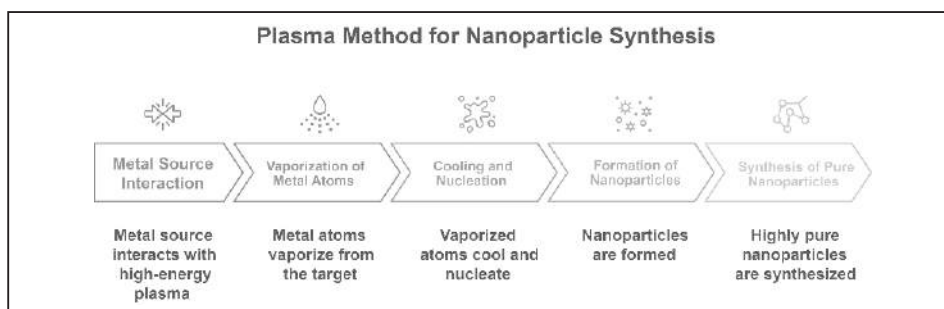


Figure 6: Process of production of nanoparticles by Plasma (Physical Method)

### 2.3 By using microorganisms

Microbial nanoparticle synthesis is based on the following principles: reduction of metal ions from metal salt precursors, such as silver nitrate ( $\text{AgNO}_3$ ), gold chloride ( $\text{HAuCl}_4$ ), or metal oxides, to their corresponding zero-valent metal atoms. This reduction step is usually mediated by microbial enzymes, proteins, or secondary metabolites. Nucleation and Growth: Once reduced metal atoms are generated, they serve as nucleation sites for nanoparticle growth. Further reduction and aggregation of these atoms lead to the formation of nanoparticles with controlled size and morphology. Surface Capping: Microorganisms can also produce biomolecules (e.g., proteins, polysaccharides, and secondary metabolites) that act as capping agents. These molecules adhere to the nanoparticle surface, preventing agglomeration and stabilizing the nanoparticles. Process steps: selection of microorganisms: microorganisms are chosen based on their ability to reduce specific metal ions

and synthesize nanoparticles. Commonly used organisms include bacteria (e.g., *Escherichia coli*, *Bacillus* spp.), fungi (e.g., *Aspergillus*, *Fusarium*), and algae (e.g., *Chlorella*, *Spirulina*). Culturing and Growth: Microorganisms are cultured in a suitable medium containing the metal salt precursor. Under specific growth conditions (e.g., temperature, pH, and aeration), the microorganism uptake and accumulate metal ions. Reduction and nucleation: The accumulated metal ions are reduced by enzymes or biomolecules produced by the microorganisms. This reduction process leads to the formation of metal nanoparticles within or on the microbial cells. Nanoparticle Extraction: After nanoparticle formation, the biomass is separated from the reaction mixture through centrifugation or filtration. The collected biomass can be further processed or used for subsequent synthesis batches. (Asghar et al., 2020; Irshad et al., n.d.)

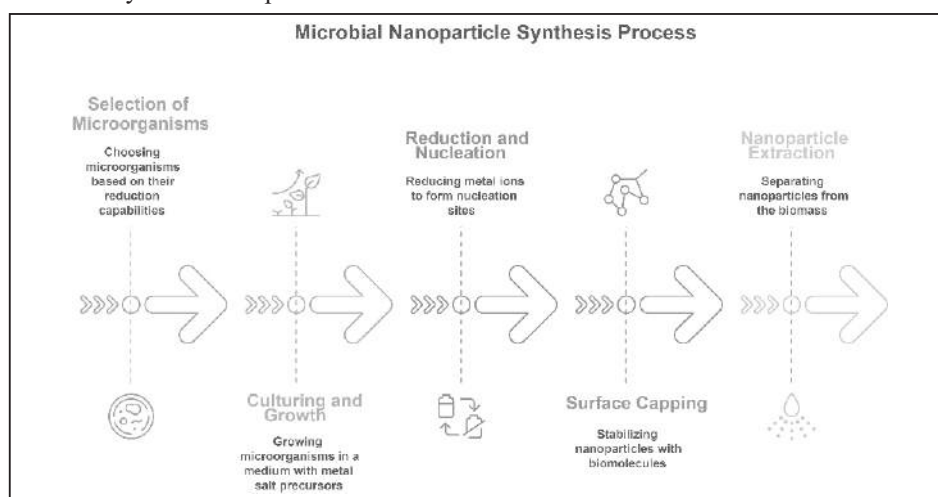


Figure 7 : Synthesis Methods for Metallic Nanoparticles by Microbial Method

#### 2.3.1 Green synthesis (Plant-mediated) method

Principle of Plant-Mediated Nanoparticle Synthesis: The synthesis of nanoparticles by plants is based on the following principles: Biological Reduction: Certain plants, especially those with medicinal and therapeutic properties, have the ability to accumulate and reduce metal ions from their environment. This reduction is often facilitated by the action of plant secondary metabolites, such as flavonoids, phenolic compounds, and enzymes. Nucleation and Growth: Once the metal ions are reduced, they serve as nucleation sites for nanoparticle formation. The reduced metal ions further aggregate and grow into nanoparticles with controlled size and morphology. Biological Capping: Plants also produce a variety of biomolecules, such as proteins, polysaccharides, and polyphenols, that can act as capping agents. These molecules bind to the nanoparticle surfaces, preventing their agglomeration and stabilizing them. Process Steps: Selection of Plant Material: Certain plant species are chosen for their ability to accumulate and reduce specific

metal ions. These plants are often called "biomass" in the context of nanoparticle synthesis. Cultivation and Growth: The selected plant biomass is cultivated under controlled conditions in a medium containing metal salt precursor. The plants uptake and accumulate the metal ions from the medium. Reduction and nucleation: Within the plant tissues, metal ions are reduced by plant metabolites or enzymes. The reduced metal ions nucleate and form nanoparticles. Nanoparticle Extraction: After nanoparticle formation, the plant biomass is harvested and separated from the reaction mixture. The nanoparticles can be extracted from the plant biomass using various methods, such as digestion, solvent extraction, or mechanical disruption. The green synthesis of nanoparticles using microorganisms such as bacteria, fungi, and yeast involves cultivating selected strains in suitable growth media under optimal conditions, followed by exposure to metal salt solutions (e.g.,  $\text{AgNO}_3$ ,  $\text{HAuCl}_4$ ) that are biologically reduced to nanoparticles. Bacteria and yeast are typically incubated for 24–72 hours, while fungi may require longer due to slower growth. Nanoparticle formation occurs

either extracellularly, via secreted enzymes and metabolites, or intracellularly within microbial cells. The synthesis is indicated by a visible color change in the reaction mixture. After incubation, nanoparticles are recovered through centrifugation, washed to remove impurities, and dried. (Aswathi et al., 2023; Bahrulolum et

al., 2021; Basiratnia et al., 2021; Gürsoy et al., 2021a, 2021b; Jha et al., 2021; Khan et al., 2022a, 2022b; Kiran et al., 2021; Kwatra et al., 2025; Lal et al., 2022; Mousa et al., 2024; Perumal et al., 2024; Pushparaj et al., 2023; Radulescu et al., 2023; Rajkumar et al., 2021; Tailor et al., 2020)

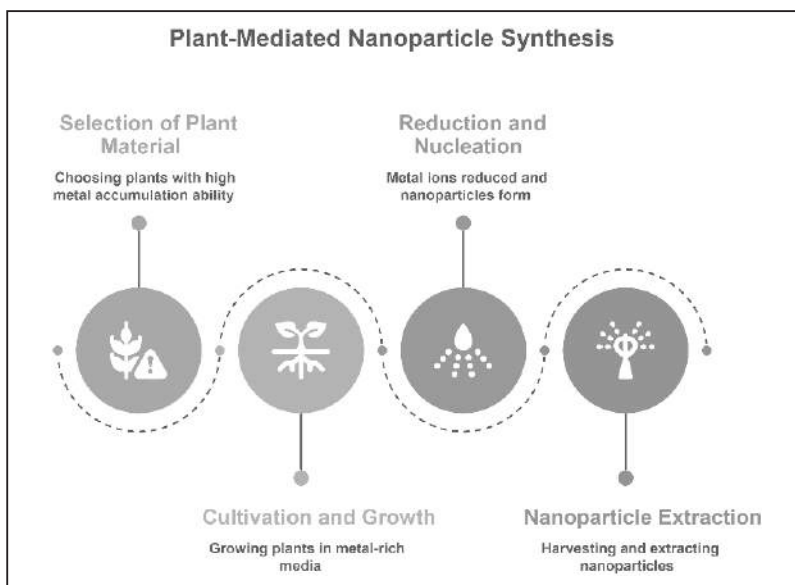


Figure 8 : Plant-Mediated Synthesis for Metallic Nanoparticles

Table 1: Information of nanoparticle, synthesis method, characterization according to the references.

Nanoparticles	Method	Size	Reference
Fe	Mechanical milling	3-10 nm	(Zhang & Wen, 2020)
CaO	Thermal decomposition	12-18 nm	(Tang et al., 2008)
ZnO	Precipitation	24.2-30.2 nm	(Pudukudy & Yaakob, 2014)
Au	Plasma	35 nm	(Patel et al., 2013)
Al	Laser ablation	25-28 nm	(Kumar & Thareja, 2010)
ZnO	Mechanical milling	20-30 nm	(Salah et al., 2011)
ZnO	Sol-gel method	84.98 nm	(Hasnidawani et al., 2016)
ZnO <sub>2</sub>	Laser ablation	5-9 nm	(Gondal et al., 2009)
SiO <sub>2</sub>	Sol-gel method	200-400 nm	(Dubey et al., 2015)
Cu	Microorganism mediated	23 nm	(Din & Rehan, 2017)

**Table 2: Methods for synthesis of nanoparticles:**

Category	Method	Principle	Key Steps	References/Notes
Chemical	Thermal Decomposition	Heat-induced breakdown of precursors	1. Precursor & solvent selection 2. Add stabilizers 3. Heat under inert gas 4. Nucleation & growth 5. Quenching 6. Purification	Top-down approach
	Decomposition-Precipitation	Thermal & pH-based decomposition onto support (e.g., ZnO)	1. Dissolve precursor (e.g., HAuCl <sub>4</sub> ) 2. Adjust pH 3. Add ZnO support 4. Stir at 80 °C 5. Wash & centrifuge 6. Calcine at 450 °C	(Rohana et al., n.d.; Yazid et al., 2010).
	Sol-Gel	Hydrolysis & condensation of precursors	1. Precursor & solvent selection 2. Hydrolysis 3. Condensation 4. Gelation 5. Aging	(Habte et al., 2019)
Physical	Mechanical Milling	Mechanical force reduces size (top-down)	1. Material selection 2. Load into ball mill 3. High-energy milling 4. Adjust duration & speed	(Salah et al., 2011; Xu et al., 2022; Zhang & Wen, 2020)
	Laser Ablation	Laser-induced vaporization of target material	1. Target selection & prep 2. Laser setup 3. Ablation to create plasma 4. Cooling & condensation into nanoparticles	(Arya et al., 2019; Gondal et al., 2009; Lal et al., 2022)
	Plasma Method	High-energy plasma initiates vaporization and nucleation	1. Plasma generation 2. Precursor introduction 3. Plasma heating 4. Nucleation & growth 5. Cooling & agglomeration	(Joshi et al., 2024; Patel et al., 2013)
Biological	Microorganism-mediated	Enzyme-mediated reduction of metal ions	1. Microbe selection 2. Growth with metal salt 3. Reduction by enzymes 4. Nucleation 5. Biomolecule capping 6. Extraction	(Asghar et al., 2020; Irshad et al., n.d.)
	Plant-mediated	Phytochemical-mediated reduction & capping	1. Plant selection 2. Cultivation in metal salt medium 3. Reduction by metabolites 4. Nucleation 5. Extraction	(Chaudhary et al., 2024; Pushparaj et al., 2023; Tailor et al., 2020)

### 3. Characterization

The comprehensive characterization of nanoparticles is vital for understanding their physicochemical properties, ensuring reproducibility, and optimizing their performance in diverse applications such as drug delivery, environmental remediation, catalysis, and diagnostics. Characterization techniques allow researchers to evaluate key parameters including particle size, morphology, surface area, composition, crystallinity, surface chemistry, and stability. Dynamic Light Scattering (DLS) is widely used to determine hydrodynamic size and size distribution in colloidal systems, while Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) provide high-resolution images for analyzing particle shape and structure. The Brunauer–Emmett–Teller (BET) method helps estimate the specific surface area, which is crucial in applications involving catalysis and adsorption. X-ray Diffraction (XRD) reveals information about crystal structure, phase

purity, and degree of crystallinity. Surface chemical composition and bonding states are analyzed using Fourier-Transform Infrared Spectroscopy (FTIR) and X-ray Photoelectron Spectroscopy (XPS), whereas Energy-Dispersive X-ray Spectroscopy (EDS) provides elemental composition data, often in conjunction with electron microscopy. To assess nanoparticle stability and surface charge, zeta potential analysis is performed, which is essential in predicting dispersion behavior and colloidal interactions. Additionally, UV-Visible spectroscopy is commonly employed to investigate optical properties and confirm nanoparticle formation, especially in metallic systems. Thermal Gravimetric Analysis (TGA) is used to determine thermal stability and the presence of organic coatings or residual solvents. When nanoparticles are intended for biomedical or agricultural applications, *in vitro* and *in vivo* toxicity studies are conducted to evaluate their safety and biocompatibility. Rheological assessments are also performed to understand the impact of

nanoparticles on the flow behavior of formulations. Together, these techniques offer a comprehensive understanding of nanoparticle systems, guiding their design and application in targeted fields.

### 3.1 Dynamic Light Scattering (DLS)

A widely used technique for determining the hydrodynamic diameter and size distribution of nanoparticles in colloidal suspension. It functions based on the measurement of fluctuations in light intensity scattered by particles undergoing Brownian motion. Using the Stokes-Einstein equation, these fluctuations are translated into particle size data. DLS is rapid, non-destructive, and particularly valuable for evaluating nanoparticle dispersion and colloidal stability.

### 3.2 Scanning Electron Microscopy (SEM)

Provides high-resolution images of nanoparticle surfaces by scanning a focused beam of electrons across the sample. The interaction between the electrons and the sample surface results in the emission of secondary electrons, which are detected to generate detailed surface morphology, size, and shape information. SEM is particularly effective in visualizing surface topography and structural aggregation.

### 3.3 Transmission Electron Microscopy (TEM)

Allows for internal structure and size analysis by transmitting electrons through an ultra-thin sample. The differences in electron density produce high-resolution images that can resolve features at the atomic scale. TEM is ideal for analyzing particle morphology, crystallinity, and shape—especially in metallic and metal oxide nanoparticles.

### 3.4 Atomic Force Microscopy (AFM)

Uses a nanometer-scale sharp tip attached to a flexible cantilever that scans across the nanoparticle surface. By measuring deflection due to van der Waals or electrostatic forces between the tip and the sample, AFM creates a three-dimensional surface profile. It provides valuable data on nanoparticle height, surface roughness, and morphology at nanometre precision, especially in non-conductive samples where electron microscopy may not be effective.

### 3.5 Brunauer-Emmett-Teller (BET) analysis

Is employed to determine the specific surface area of nanoparticles. It relies on nitrogen gas adsorption onto the surface of particles at cryogenic temperatures. The BET equation is applied to the adsorption isotherm data to quantify the surface area, which is a critical parameter in catalysis, adsorption, and drug delivery systems.

### 3.6 Fourier-Transform Infrared Spectroscopy (FTIR)

Is used to identify functional groups and assess surface chemistry by analyzing the absorption of infrared radiation by molecular vibrations. It provides a fingerprint of the chemical bonds present in the nanoparticle surface

or coatings. FTIR is widely used to confirm bioconjugation, surface modifications, or the presence of plant-based capping agents in green synthesis.

### 3.7 X-ray Photoelectron Spectroscopy (XPS)

Offers information about elemental composition and chemical states at the surface of nanoparticles. It operates by irradiating a sample with X-rays, causing the emission of photoelectrons. By measuring their kinetic energy, XPS determines binding energies and reveals oxidation states, functional groups, and elemental ratios at the surface, making it critical for surface functionalization studies.

### 3.8 X-ray Diffraction (XRD)

Is a key technique for evaluating crystallinity and crystal structure. It is based on the diffraction of X-rays by the atomic planes in a crystalline lattice. The resulting diffraction pattern is characteristic of the material's phase and structure, and can be used to calculate lattice parameters, crystallite size (using the Scherrer equation), and identify phase purity.

### 3.9 Energy-Dispersive X-ray Spectroscopy (EDS or EDX)

Is typically coupled with SEM or TEM and is used for elemental analysis. It works by detecting characteristic X-rays emitted from a sample upon electron beam interaction. Each element emits X-rays at a specific energy, allowing for both qualitative and semi-quantitative analysis of elemental composition. This is particularly important for identifying metallic constituents in nanoparticles.

### 3.10 Zeta Potential Analysis

Measures the electrical potential at the slipping plane of particles in a colloidal dispersion. It is an indicator of surface charge, which influences particle-particle interactions and overall stability. Higher absolute values of zeta potential imply strong repulsive forces and better dispersion stability, which is essential in biomedical and environmental applications.

### 3.11 UV-Visible Spectroscopy

Assesses the optical properties of nanoparticles by measuring light absorbance across UV and visible wavelengths. Metallic nanoparticles exhibit characteristic surface plasmon resonance (SPR) peaks, which can provide indirect information about size, shape, and aggregation state. This technique is simple, fast, and frequently used to monitor nanoparticle synthesis and stability over time.

### 3.12 Photoluminescence (PL) Spectroscopy

It is used to investigate the emission characteristics of nanoparticles upon excitation with light. This technique provides insights into electronic properties, defects, and energy band structures, particularly useful for semiconducting nanoparticles, quantum dots, and

bioimaging applications.

### 3.13 Vibrating Sample Magnetometry (VSM)

It is used to measure magnetic properties such as magnetization, coercivity, and remanence. In this technique, the sample is physically vibrated within a uniform magnetic field, and the induced voltage is detected. VSM is essential for characterizing magnetic nanoparticles, which are employed in magnetic resonance imaging (MRI), targeted drug delivery, and hyperthermia therapy.

### 3.14 Thermogravimetric Analysis (TGA)

Quantifies the thermal stability and organic content of nanoparticles by recording weight changes upon heating. It is commonly used to assess the amount of surface-bound ligands or capping agents and to study decomposition behavior, which is crucial in determining shelf life and thermal resistance.

### 3.15 Rheological Measurements

They are employed to analyze the flow behavior of nanoparticle suspensions. By applying controlled shear

stress or strain, rheometry can determine viscosity, viscoelasticity, and shear-thinning behavior. This is important for formulations involving nanofluids, biomedical gels, or paints where flow properties affect performance.

### 3.16 In Vitro Cytotoxicity Assays

Such as MTT and LDH, evaluate the biocompatibility of nanoparticles by assessing cell viability, membrane integrity, or enzyme activity. These assays are critical for initial toxicity screening before in vivo studies. Meanwhile, in vivo studies provide insights into biodistribution, systemic toxicity, immune response, and potential organ accumulation, forming a cornerstone of preclinical nanoparticle safety assessments. (Aljabali et al., 2022; Asif et al., 2023; Bhosale et al., 2025; Chaudhary et al., 2024; Din & Rehan, 2017; Gómez-Zavaglia et al., 2022; Hutchinson et al., 2022; Ijaz et al., 2020; Jha et al., 2021; Karan et al., 2022; Klink et al., 2022b; Nazma et al., 2024; Pucelik et al., 2022; Rohana et al., n.d.; Suryakant et al., 2023; Uniyal et al., 2022)

## Nanoparticle Characterization Techniques

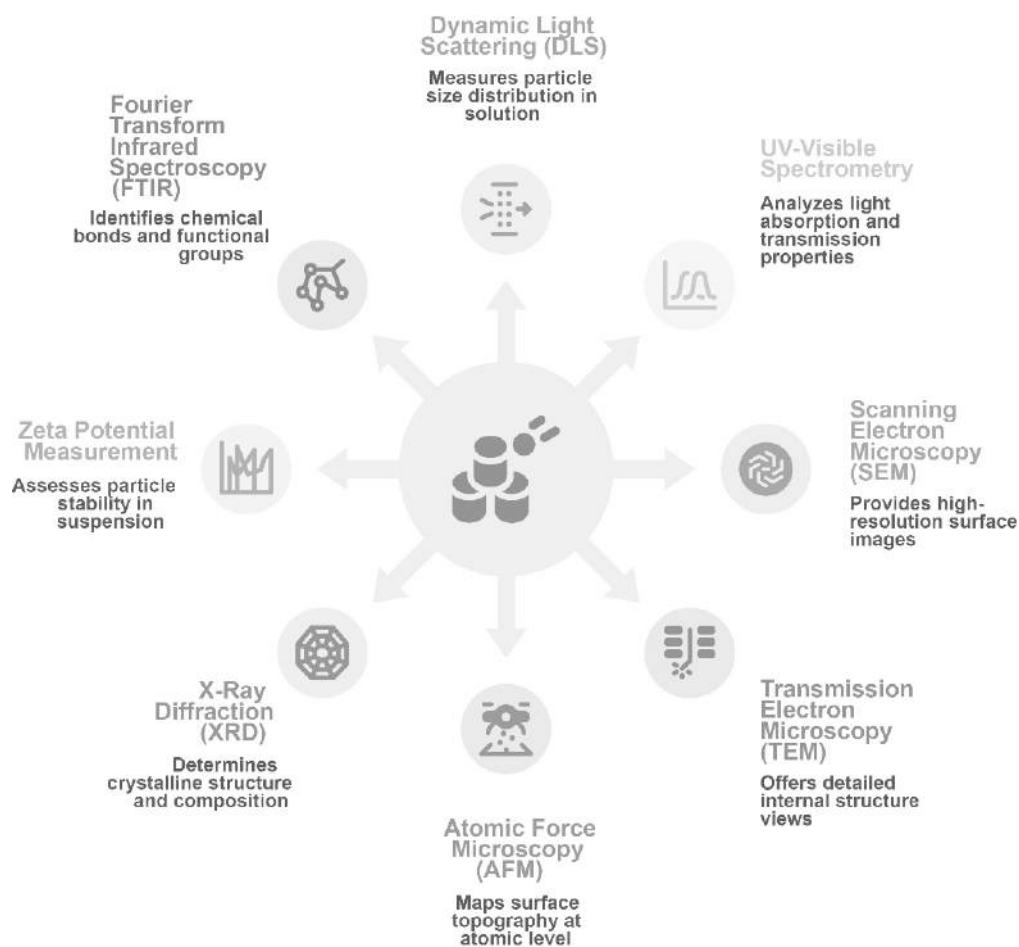


Figure 9 : Characterization Techniques For Metallic Nanoparticles

## 4. Applications of Nanoparticles

Nanoparticles (NPs) possess unique physicochemical properties such as high surface area-to-volume ratio, quantum size effects, and surface reactivity, making them highly versatile for applications across various sectors. Their tunable size, shape, and surface chemistry allow them to be tailored for specific functionalities. Below are the detailed applications of nanoparticles in diverse fields:

### 4.1 Medicine and Healthcare

#### 4.1.1 Drug Delivery

Nanoparticles can encapsulate therapeutic agents, enabling controlled and targeted delivery. This improves bioavailability, minimizes toxicity, and allows for site-specific action. Polymeric nanoparticles, liposomes, dendrimers, and metal-based NPs are commonly used. For example, PLGA nanoparticles have been employed for sustained drug release, while gold nanoparticles are functionalized for tumor-specific delivery.

#### 4.1.2 Cancer Therapy

Nanoparticles like gold, silver, and iron oxide are used for photothermal therapy, where they absorb light and convert it into heat to destroy cancer cells. Additionally, they can carry chemotherapeutic agents directly to tumor sites, reducing damage to healthy tissues.

#### 4.1.3 Medical Imaging

Quantum dots, iron oxide nanoparticles, and gold nanoparticles serve as contrast agents in MRI, CT, and fluorescence imaging, enabling early diagnosis and real-time monitoring of diseases.

#### 4.1.4 Vaccine Delivery

Lipid-based nanoparticles (LNPs) have gained significant attention for delivering nucleic acid-based vaccines, such as mRNA COVID-19 vaccines (Pfizer-BioNTech and Moderna). These systems protect the mRNA from degradation and facilitate efficient delivery into host cells.

### 4.2 Materials Science

#### 4.2.1 Reinforcement of Composites

Nanoparticles like carbon nanotubes, silica, and nanoclays are incorporated into polymers or ceramics to improve mechanical strength, elasticity, and thermal resistance of materials, which is vital for aerospace, automotive, and biomedical applications.

#### 4.2.2 Catalysis

Metal nanoparticles (e.g., platinum, gold, palladium) exhibit exceptional catalytic activity due to their large surface area and high surface energy. They are used in oxidation, hydrogenation, and environmental catalysis processes.

#### 4.2.3 Smart and Self-Cleaning Materials

Nanoparticles such as TiO<sub>2</sub> exhibit photocatalytic properties, making them useful in self-cleaning surfaces, anti-fogging coatings, and antimicrobial applications.

### 4.3 Environmental Applications

#### 4.3.1 Water Purification

Silver nanoparticles are well-known for their antimicrobial properties and are used in water filters to eliminate pathogens. Other NPs like iron oxide and zinc oxide help in adsorption of heavy metals and degradation of organic pollutants.

#### 4.3.2 Air Filtration

Nanoparticles incorporated into filter membranes enhance the capture of airborne contaminants, particulate matter, and even viruses, contributing to indoor air quality improvement.

#### 4.3.3 Environmental Remediation

Zero-valent iron nanoparticles are widely studied for in-situ groundwater remediation. They reduce toxic metal ions and chlorinated compounds through redox reactions.

### 4.4 Cosmetics and Personal Care

#### 4.4.1 Sunscreens

Zinc oxide and titanium dioxide nanoparticles provide broad-spectrum UV protection while maintaining cosmetic transparency, unlike their bulk counterparts that appear white on the skin.

#### 4.4.2 Enhanced Cosmetic Delivery

Nanocarriers improve the delivery and penetration of active ingredients such as vitamins, antioxidants, and moisturizers into the skin, enhancing product efficacy.

### 4.5 Construction and Building Materials

#### 4.5.1 Concrete Strengthening

Incorporation of nanosilica and other nanomaterials into concrete improves its mechanical strength, durability, and resistance to environmental stressors, thus extending the lifespan of infrastructure. Thermal Insulation: Nanoporous materials and aerogels are used for energy-efficient insulation due to their low thermal conductivity.

### 4.6 Electronics and Photonics

#### 4.6.1 Transistors

Silicon nanoparticles enable the development of smaller and more efficient transistors, contributing to the miniaturization of electronic devices.

#### 4.6.2 Quantum dots

These semiconductor nanoparticles have unique electronic properties and are used in displays, LEDs, and solar cells.

### 4.6.3 Memory Storage

Magnetic nanoparticles are used in magnetic random-access memory (MRAM) for high-speed, non-

volatile storage. (Asif et al., 2023; Dubey et al., 2015; Gómez-Zavaglia et al., 2022; Rahuman et al., 2022)

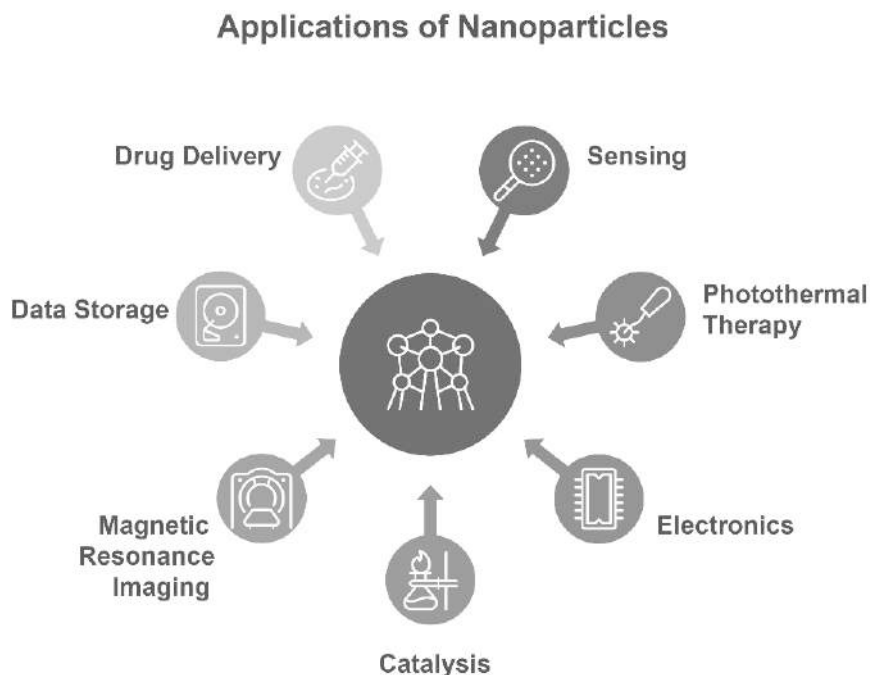


Figure 10 : Application of Metallic Nanoparticles

Table 3 : Applications of Nanoparticles

Nanoparticle Type	Application Area	Specific Use
Lipid Nanoparticles	Medicine & Healthcare	Delivery of mRNA vaccines (e.g., COVID-19 vaccines by Pfizer/Moderna)
Gold Nanoparticles	Medicine & Healthcare	Targeted cancer therapy, photothermal therapy
Iron Oxide Nanoparticles	Medicine & Healthcare	MRI contrast agents, targeted drug delivery
Quantum Dots	Medicine & Imaging	Fluorescence imaging, biosensors, display technologies
Carbon Nanotubes	Materials Science	Strengthening of composites, lightweight structural materials
Metal Nanoparticles	Materials Science/Catalysis	Catalysts for accelerating industrial chemical reactions
Titanium Dioxide (TiO <sub>2</sub> )	Materials / Environment / Cosmetics	Self-cleaning surfaces, sunscreens (UV protection), photocatalysis
Zinc Oxide (ZnO)	Cosmetics	Transparent UV filters in sunscreens
Silver Nanoparticles	Environmental Science	Water purification, antibacterial agents
Iron Nanoparticles	Environmental Remediation	Degradation of pollutants in contaminated water
Various Metal NPs	Air Filtration	Enhanced trapping of fine particles and pollutants
Silicon Nanoparticles	Electronics	Miniaturized transistors, photonics, sensors
Quantum Dots	Electronics & Photonics	LEDs, solar cells, high-resolution displays
Magnetic Nanoparticles	Data Storage	Used in MRAM for fast, stable, non-volatile memory
Nanoparticles (General)	Construction	Improve concrete strength, thermal insulation, and durability

## 5. Conclusion

Chemical and physical methods are likely to be more costly as compared to the biological method. The methods of synthesizing nanoparticles are diverse and continually evolving, offering a wide range of techniques to produce nanoparticles with specific properties. The choice of synthesis method depends on factors such as material type, desired nanoparticle size, shape, and purity, as well as scalability and cost considerations. Green and environmentally friendly synthesis approaches are gaining importance, aiming to reduce the environmental impact and toxicity associated with certain chemical processes. Accurate characterization is essential for understanding the physical, chemical, and structural properties of nanoparticles, enabling researchers to tailor nanoparticles for specific applications. A combination of techniques, including microscopy (TEM, SEM), spectroscopy (UV-Vis, FTIR, XPS), diffraction (XRD), and Dynamic Light Scattering (DLS), provides a comprehensive characterization toolkit. Advanced characterization

methods are continually emerging, allowing for deeper insights into nanoparticles at the nanoscale. Nanoparticles have found extensive and diverse applications across various fields, including medicine, electronics, materials science, environmental science, energy production, and more. In medicine, nanoparticles play a pivotal role in drug delivery, cancer therapy, medical imaging, and vaccine development, promising significant advancements in healthcare. In electronics, nanoparticles contribute to the miniaturization and enhanced performance of devices, such as transistors, memory storage, and quantum dot-based displays. Nanoparticles also offer solutions to environmental challenges through water purification, air filtration, and pollutant remediation. Energy-related applications include improving solar cells, batteries, fuel cells, and energy-efficient construction materials. The versatility and adaptability of nanoparticles continue to drive innovation, with emerging applications continually expanding their impact on science, technology, and society.

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