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"NANOEMULSIONS AND NANOTECHNOLOGY – INDUSTRIAL, AGRICULTURAL AND HEALTHCARE APPLICATIONS"

Review Based Book Chapter

MULTIFACETED ACCESS TO NANOPARTICLES: FABRICATION, CHARACTERIZATION, AND PLANT-BASED APPLICATIONS

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REVIEW BASED BOOK CHAPTER

MULTIFACETED ACCESS TO NANOPARTICLES: FABRICATION, CHARACTERIZATION, AND PLANT-BASED APPLICATIONS

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Abstract

The rapidly growing nanotechnology lending sector offers advanced solutions across multiple sectors, with significant implications for environmental and agricultural sustainability. This chapter presents a meticulous and comprehensive examination of the conceptualization, manufacturing, and practical application of nanoparticles, emphasizing their multifaceted functionality and exceptional potential. It commences with systematic categorization of nanoparticles, including metallic, metal oxide, bimetallic, doped and conjugated variants, emphasizing their distinguishing physicochemical properties that dictate their panoramic applications. The fabrication strategies are comprehensively discussed with critical evaluation of chemical method, green method, and coprecipitation method, each analyzed for its operational efficiency, scalability, and ecological impact. Besides this, the comparative evaluation of important characterization techniques like UV–Visible spectroscopy, X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, and X-ray photoelectron spectroscopy (XPS) is illustrated, illuminating their underlying principles, analytical concerns and interpretive potential in anticipating nanoparticle structure, morphology and elemental composition. The chapter further delves into plant-based applications exhibiting nanomaterials as potent biostimulants, intelligent vectors for agrochemical delivery, antimicrobial agents and nanofungicides. Noteworthy emphasis is placed on the contribution of nanoparticles in fortifying crop resilience, optimizing nutrient delivery approaches and advancing disease control strategies. The chapter concludes with a forward-looking perspective, endorsing sustainable nano-enabled agriculture, the evolution of advanced techniques and strategic incorporation of smart nanomaterials in precision farming paradigms. This work aims to serve as a foundational reference for researchers, agronomists and materials scientists operating at the nexus of nanoscience and plant biotechnology.

Keywords

Nanoparticles, Synthesis, Characterization, Plant-based Applications

1. Introduction

Over the past few years, nanotechnology has progressively gained fame. Nanoparticles are the central element of nanotechnology. They are extremely small, the size of 100 nm or less, and have a composition of metal oxides, metal, carbon and organic substances. Biological, physical and chemical properties of nanoparticles exhibit a unique nature from their large size counterparts. Many factors contribute to this effect, such as having a higher area-to-volume ratio, an increase in chemical stability and creativity, and higher mechanical strength. Due to the remarkable properties of nanoparticles, they have a wide range of applications. The shape, composition, size and dimension of nanoparticles are different. When the spatial dimension of nanoparticles is in three spatial arrangements, then clusters and nanodots are considered zero-dimensional [1].

Additionally, diversity of methods is being developed and is under expansion to improve the quality of nanoparticles and minimize their production cost. Through modifying many methodologies, such nanoparticles are created that have improved physical, optical, chemical and mechanical properties [2]. Nanoparticles show cases of various sizes reaching from 1 to 100 nm, diverse shapes such as conical, cylindrical, spherical, flat, spiral, and tubular etc., along with different compositions. Surfaces of nanoparticles can be flat and uniform or sometimes textured and irregular. Structurally, nanoparticles can be amorphous and crystalline, having one or multiple crystals that may be present as single particles or in an aggregated form [3].

Characterization of nanoparticles is based on properties such as surface charge, shape and size. Various microscopic techniques are used to study surface structure and particle shape of nanoparticles, such as scanning tunneling microscopy (STM), environmental SEM (ESEM), SEM, TEM and tip-enhanced Raman spectroscopy (TERS). While the optical properties of nanoparticles are checked by spectral analysis. Core physicochemical properties of nanoparticles are studied by using Fourier transform infrared spectroscopy (FTIR), X-ray crystallography (XRD), and fluorescence correlation spectroscopy (FCS) [4].

Current innovations in the arena of nanotechnology have created novel possibilities, holding great opportunities to reshape biomedical research and its application. Some features of nanoparticles, such as selective binding to target sites, high reactivity area to volume ratio, extremely small size of metal oxide, diverse surface area, and different forms of carbon nanoparticles (cluster, sheet and hybrid) are highly valuable in the fields of nanomedicine and pharmaceutical sectors as markers, templates, binding agents and carriers. Nanoparticles have numerous applications such as drug delivery, orthopedics, antimicrobial activity, dentistry, optic sensing and cosmetics, fluorescence marking and significant contribution to improve cognitive function in the field of pharmacology and nutraceutics [5].

2. Types of Nanoparticles

There can be different types of nanoparticles based on their size, properties (physical/chemical) and morphology.

2.1 Metallic Nanoparticles

Metallic nanoparticles (MNPs), typically ranging from 1 to 100 nm in size, retain distinctive physicochemical characteristics, including quantum effects, a high surface area-to-volume ratio, adjustable surface properties, and catalytic efficiency. These properties distinguish them from their majority counterparts and have led to increased use in many industrial and scientific fields. Recent literature highlights their central role in biomedicine together with diagnostic imaging, targeted drug delivery, cancer treatment and antimicrobial therapy due to their capability to interact at molecular and cellular levels as well as penetrability in biological barriers. In addition, metallic nanoparticles, such as gold, silver, zinc, and iron oxide, have demonstrated strong antiviral, antifungal, and antibacterial effects, making their use a viable alternative to conventional antimicrobial agents, particularly in the face of increasing antibiotic resistance. In environmental perspectives, MNPs help in the detection of pollutants and their removal via adsorption, photocatalysis and redox reactions. Additionally, in agricultural fields, they increase crop productivity through nanoscale pesticides, fertilizers, and sensors, helping to address worldwide challenges of food security [6]. The different types of metallic nanoparticles and their applications have been illustrated (Figure 1) [7].

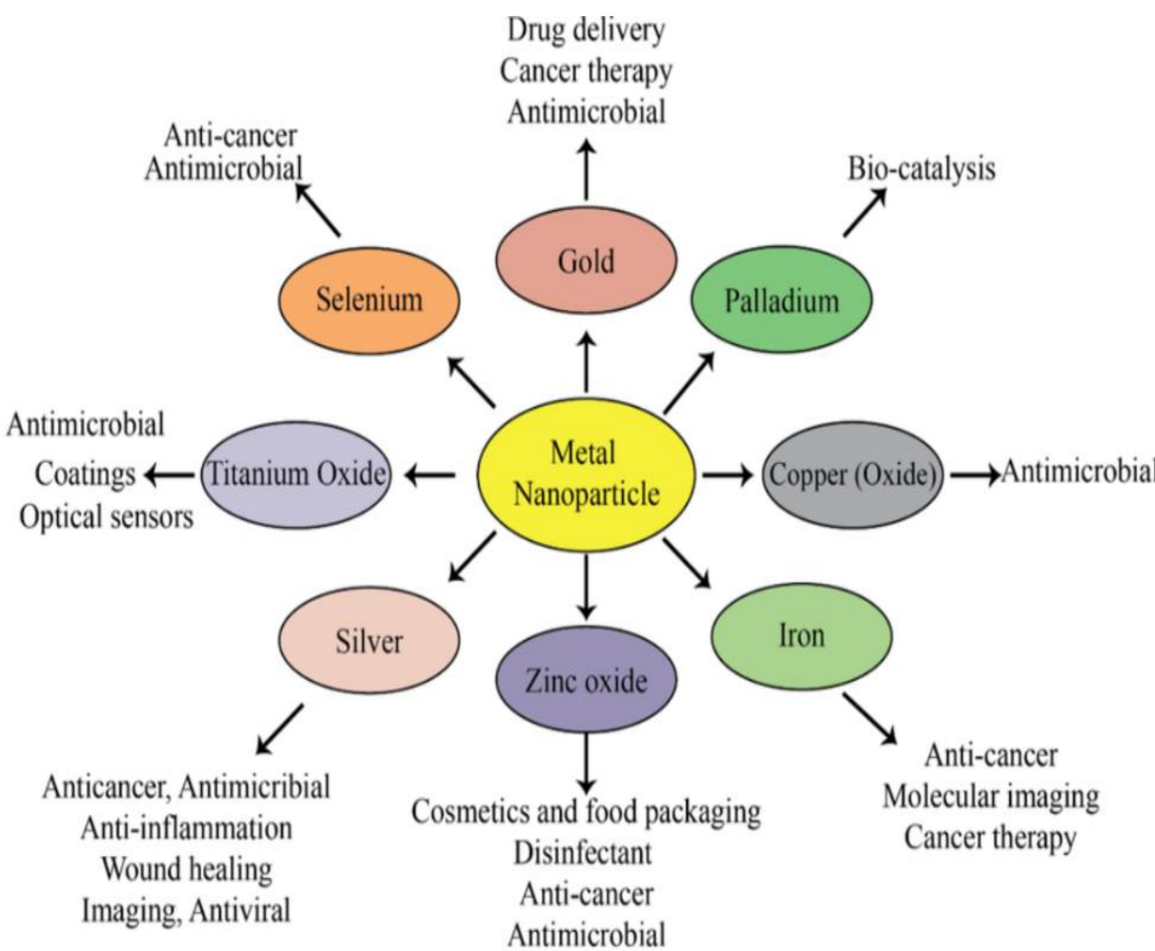

Figure 1. Representing the different types of metallic nanoparticles and their respective applications

2.2 Metal Oxide Nanoparticles

Metal oxide nanoparticles (MONPs) are composed entirely of metal precursors. These nanoparticles have a pivotal role in numerous domains of material sciences, chemistry and physics. An extensive variety of oxide compounds can be formed from thermal elements. These compounds can form a great variety of structural geometries, have electronic structures and exhibit metallic, semiconducting and insulating characteristics. Their eminent localized and surface plasmon resonance features provide these nanoparticles with distinctive opto-electrical characteristics. A wide band of absorption is shown in the zone of visible electromagnetic spectrum by noble metals (i.e., Au, Cu and Ag) and alkali nanoparticles. The size, shape and facet of nanoparticles synthesis have a substantial importance in advanced materials of the present day [8].

The schematic representation of different synthesis approaches for metal oxide nanoparticles has been shown (Figure 2) [9].

2.3 Bi-metallic Nanoparticles

A combination of two dissimilar metals exhibiting a variety of novel and updated properties forms a bi-metallic nanoparticle. Alloys, contact, aggregates and core-shell can be different forms of bi-metallic nano-materials. These nanoparticles have garnered great attention from the industrial and scientific societies because of their innovative characteristic. Bimetallic nanoparticles (BNPs) are composed of two dissimilar metal elements at the nanoscale, often designed to combine the exceptional properties of every component. These nanoparticles show improved physicochemical properties compared to their monometallic counterparts, such as tunable or adjustable optical activity, superior catalytic properties, enhanced stability, and synergistic special effects arising from their compositional variety and interactions at the atomic level. Due to these characteristics, BNPs have arisen as multifunctional areas in different applications, including biosensing, catalysis, antimicrobial treatments, targeted drug delivery and environmental remediation. Latest research highlights their promise in biomedical fields and sustainable energy tools/technologies, where customizable chemistry of the surface allows for controlled reactivity and precise targeting. Their efficiency and versatility make them an important focus in the improvement of next-generation nanotechnologies [10].

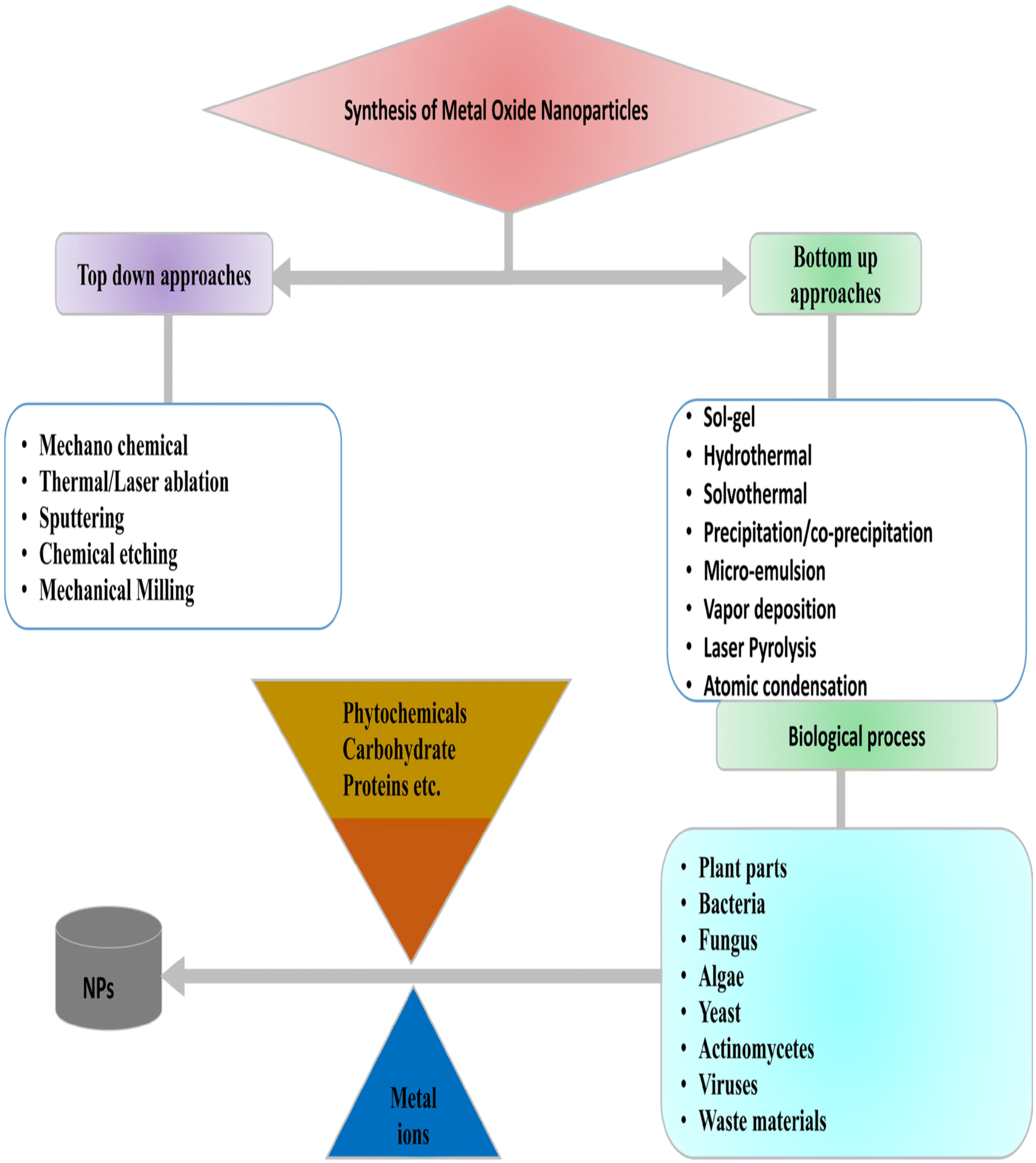

Figure 2. Schematic illustration of different synthesis approaches for metal oxide nanoparticles representing top-down (e.g., mechano chemical, thermal/ablation) and bottom-up methods (e.g., sol-gel, hydrothermal), including biological processes harnessing natural origins like plants, bacteria and fungus for eco-friendly nanoparticle fabrication

Classification of bi-metallic synthesis approaches has been mentioned (Figure 3) [11].

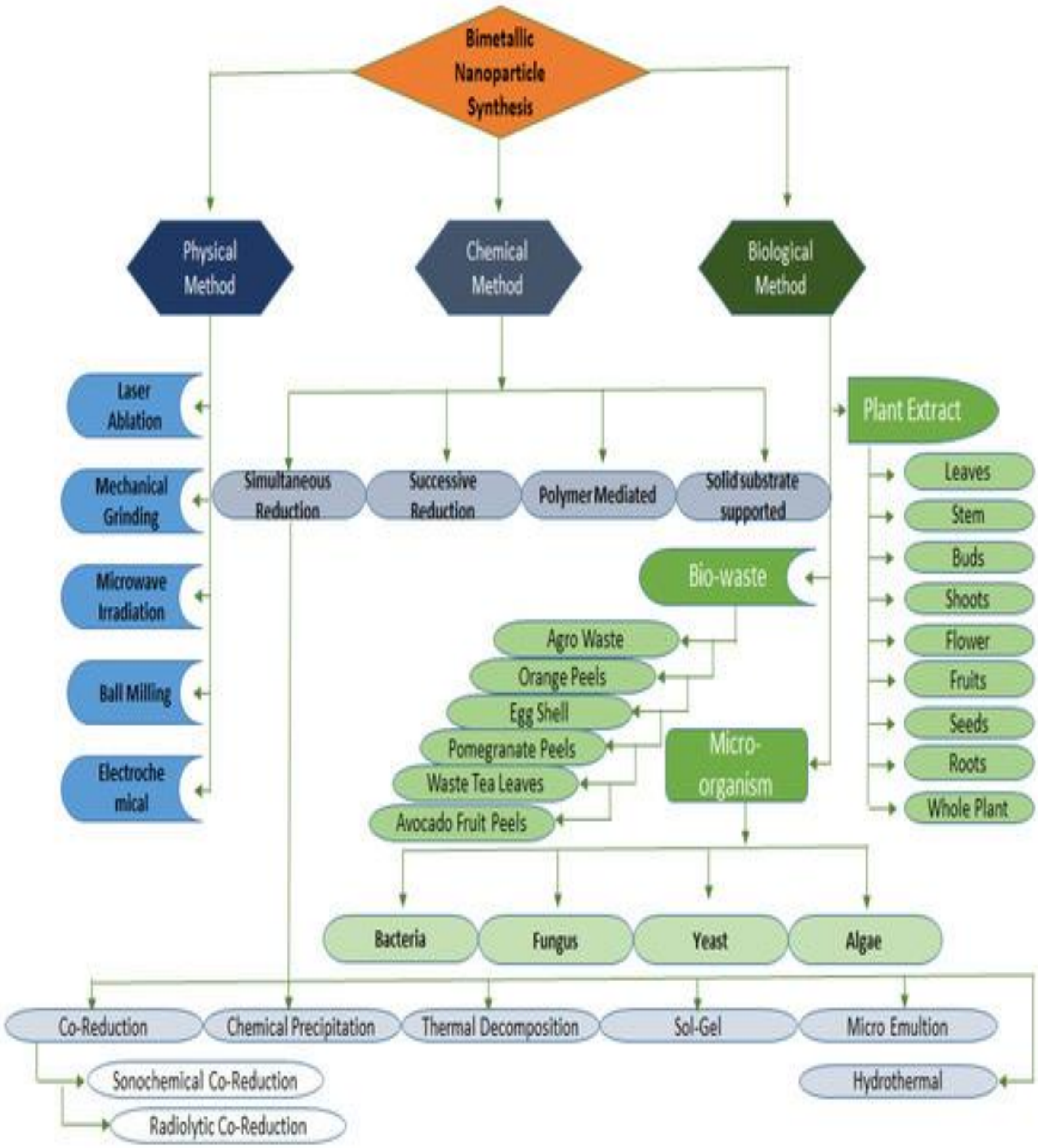

Figure 3. Classification of Bimetallic Nanoparticle Synthesis Approaches

The figure illustrates physical, chemical, and biological methods for synthesizing bimetallic nanoparticles, including techniques such as laser ablation, reduction processes, plant extract utilization, bio-waste recycling, and microorganism-mediated synthesis

2.4 Conjugated Nanoparticles

Conjugated nanoparticles are described by the covalent or non-covalent addition of functional and well-designed molecules such as antibodies, ligands, nucleic acids, or drugs to their surface. Conjugated nanoparticles have multifunctional and highly tunable properties in nanobiotechnology. Their tailored/customizable surface modifications increase target specificity, biocompatibility and therapeutic efficacy. It allows accurate delivery of bio molecules to chosen cellular/subcellular sites.

Conjugated polymer-based nanoparticles (CPNs) are extremely multifaceted nanostructured materials. They are used in a variety of fields, including photonics, optoelectronics, nanomedicine, biosensing and bioimaging due to their inherent non-toxicity and biocompatibility. CPNs have been formed by using numerous diverse conjugated polymers. Though in biological operations there is a great desire for nanoparticles having hydrophilic functional groups of the surface that can restrict CPNs' inherent hydrophobicity, in literature, there are examples mostly of conjugated polymers that are extremely hydrophobic and do not carry any functional groups that can be modified further. But, it's a belief that synthesis of newer versions of CNPs can solve this problem [12]. The overview of synthesis approaches for conjugated nanoparticles and their general applications has been represented (Figure 4) [13].

2.5 Doped Nanoparticles

Nanoparticles are modified to augment their biological, optical, and electrical properties by using the method of doping. Doping is performed using different metals, molecules and materials. Based on doping, nanoparticles may be classified as polymeric nanoparticles, metal nanoparticles, carbon-based nanoparticles, lipid-based nanoparticles, and semiconductor nanoparticles. Previous studies have demonstrated that the antimicrobial effect can be increased by doping. An important role is played by dopant impurities such as Mn^{2+}, Cu^{2+}, Ni^{2+}, Co^{2+}, transition elements and rare earth metals, in the alteration of host material's electronic structure and possibilities of modulation. It was demonstrated that substantial antimicrobial potentials are shown by zinc oxide (ZnO) and chromium-doped (Cr-doped) ZnO nanoparticles [14].

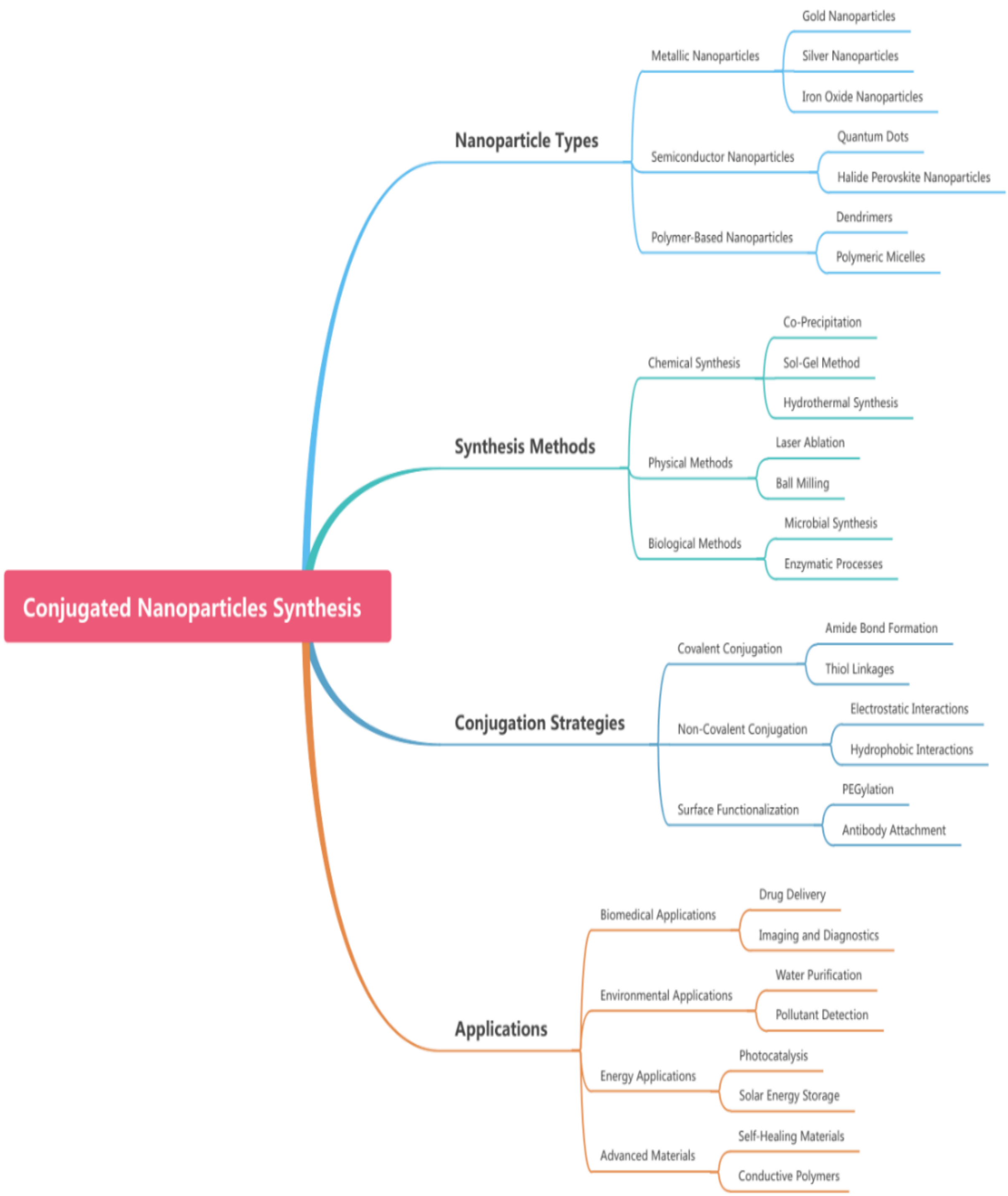

Figure 4. Schematic overview of conjugated nanoparticles synthesis showing the main categories: nanoparticle types (including metallic, semiconductor, quantum dots, and polymer-based variants), synthesis methods (chemical, physical, and biological approaches), conjugation strategies (covalent and non-covalent techniques), and key applications (biomedical, environmental, energy, and advanced materials)

3. Fabrication of Nanoparticles

Numerous further ways for creating nanoparticles with desired size, shape, and composition have been developed by scientists. These parameters have a significant influence on the nanomaterial's characteristics. General methods for the synthesis of nanoparticles have been depicted (Table 1).

Table 1. Representing the biogenic, physical, and chemical methods of synthesis of nanoparticles

Biological Methods	Physical Methods	Chemical Methods
Fungal system–based synthesis	Layer-by-layer growth	Co-precipitation method
Plant extract–based synthesis	Molecular beam epistaxis	Sol-gel method
Microalgae-system–based synthesis	Diffusion flame based Synthesis	Chemical solution-deposition
Bacterial system–based synthesis	Lithographic method	Hydrolysis
	Plasma arcing	Langmuir–Blodgett method
	Solvothermal decomposition	Sonochemical method
	Electrochemical method	Colloidal method
	Ultra-thin film	Wet chemical method
	Spray pyrolysis	Electro deposition
	Sputter deposition	Catalytic route
	Ball milling	Chemical vapor deposition
	Microwave method	Soft chemical method
	Laser ablation	Chemical reduction method
	Lithographic method	

Several of these strategies are discussed below:

3.1 Chemical Method

Chemical synthesis method is one of the best-used techniques for creating nanoparticles because of its ease of use, scalability, and adaptability in regulating particle shape, size, and content. This method often uses chemical reducing agents such as hydrazine, sodium borohydride, or citrate to reduce metallic ions in a solution-phase process. In order to manage morphology and avoid agglomeration, surfactants or stabilizers (such as sodium dodecyl sulphate and polyvinylpyrrolidone) are frequently added.

Co-precipitation, sol-gel, hydrothermal, and microemulsion procedures are important approaches. Metal oxide nanoparticles are usually made via co-precipitation, although sol-gel techniques give precise control over homogeneity and composition. While microemulsions provide limited reaction areas that produce monodisperse nanoparticles, the hydrothermal technique produces high-crystallinity particles under regulated pressure and temperature.

Applications in biomedicine, catalysis, and the environment can benefit from the chemical synthesis method's versatility in doping, functionalization, and physicochemical property tuning. But there is still room for development in areas like reagent toxicity and the requirement for post-synthesis purification [15].

3.2 Green Method

In this approach, plant-based elements such as monosaccharides, vitamins, biodegradable polymers, plant extract, and microorganisms are utilized as capping and reducing agents to synthesize NPs. A few inorganic nanoparticles, which include mainly metal nanoparticles and also a number of salts and metal oxides, have been synthesized by a green method. The above-mentioned plant-related components appear as the best materials and they can be employed for the mass 'biosynthesis' of nanoparticles. Fabrication of metallic nanoparticles is performed by using a plant's leaf, seed, root, stem and latex. The crucial active component of green syntheses includes polyphenols that are found, for example, in wine, tea, red grape paste, and the waste of wine production. The green method comes up with privilege over other methods, being a facile, frugal, and comparably reproducible approach producing highly stable nanomaterials [16].

3.3 Co-precipitation Method

Co-precipitation is a simple and commodious method to synthesize MNPs. In this approach, a combination of metallic ions (for example, Fe^{2+} and Fe^{3}+) is reduced in a basic environment, commonly by using NaOH, N $(CH_3)_4OH$, or NH_3OH at a temperature less than 100°C, as demonstrated by the chemical reaction below:

$$Fe^{2+}{}_{(aq)} + Fe^{3+}{}_{(aq)} + 8OH^{-}{}_{(aq)} \rightarrow Fe_3O_4\downarrow_{(s)} + 4H_2O$$

Practicing this method is associated with privileges like magnified output, augmented purity of product, disembarrassment of organic solvents, relative reproducibility, and frugality. The properties of devised nanoparticles (like shape, size, and composition) are determined by the conditions of reaction, such as ionic strength, temperature, type of acidic and basic solution, etc. To boot, iron oxide NPs developed by this practice are usually unstable; therefore, stabilized by employing surfactants of lower molecular mass, or functionalized polymers [17].

4. Characterization of Nanoparticles

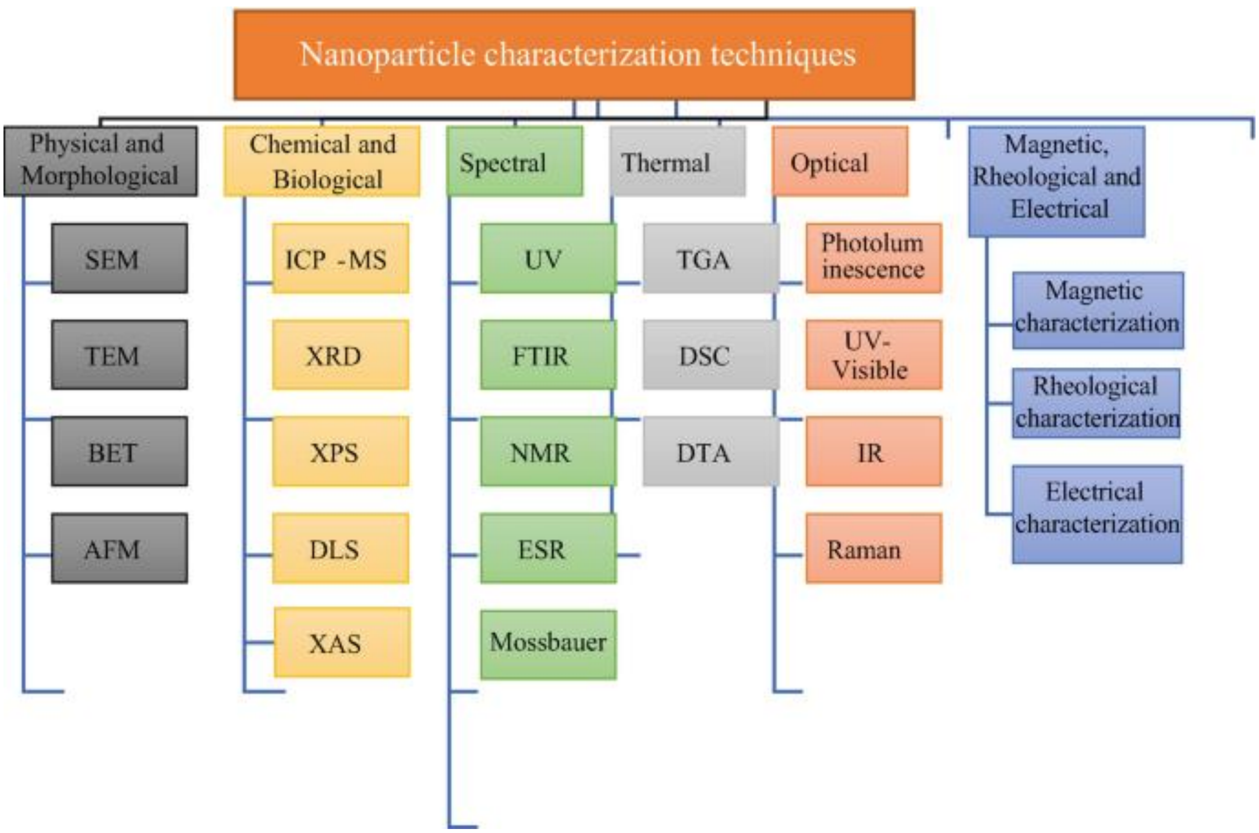

Figure 5. Classification of nanoparticle characterization techniques organized by category: Physical and morphological methods (SEM, TEM, BET, AFM), chemical and biological techniques (ICP-MS, XRD, XPS, DLS, XAS), spectral analysis (UV, FTIR, NMR, ESR, Mössbauer), thermal methods (TGA, DSC, DTA), optical techniques (photoluminescence, UV-Visible, IR, Raman), and magnetic, rheological, and electrical characterization methods

4.1 Ultraviolet Visible Spectrophotometry (UV-Vis)

Ultra Violet-Visible (UV-Vis) spectrophotometry is an extensively used analytical method that measures how particles at the nanoscale absorb light in the UV-visible areas of the electromagnetic spectrum, normally ranging from 200 to 800 nm. Its working principle is based on the absorption of particular wavelengths of light by particles or molecules, causing electronic transitions in their molecules or atoms. Schematic representation of a UV/Vis spectrophotometer for nanoparticle characterization (Figures 6 and 7) [18].

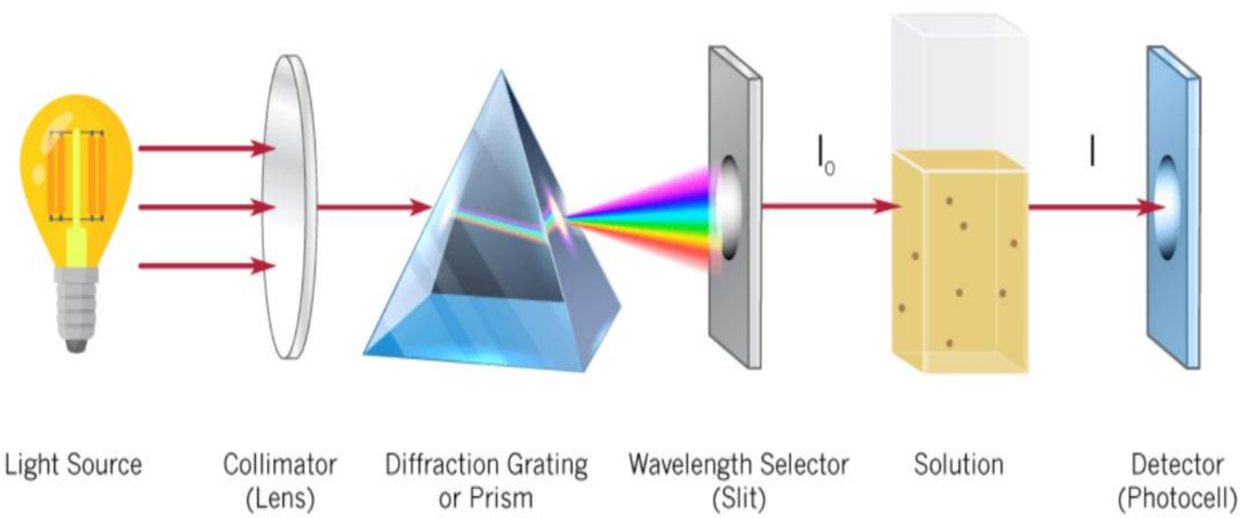

Figure 6. Schematic of a monochromatic UV/Vis spectrophotometer for nanoparticle characterization

The light source emits a broad spectrum that is collimated and dispersed by a diffraction grating or prism. A wavelength selector isolates a single wavelength, which then passes through the nanoparticle-containing solution. The transmitted light is detected by a photocell to measure absorbance, enabling analysis of nanoparticle properties such as concentration and optical behavior

In characterization of nanoparticles, this technique provides significant information related to the shape, size, optical properties, and concentration of nanoparticles. For metallic nanoparticles, particularly silver and gold, UV-Vis can easily detect changes in surface plasmon resonance (SPR) peaks, which depend upon shape, size, aggregation condition, and surrounding environment. For example, gold nanoparticles exhibit a specific SPR peak in the 520 nm range, which can move to longer wavelength ranges if the particles aggregate or grow larger. The interpretation of results (method) of ultraviolet-Visible (UV-Vis) spectrophotometry for characterization of nanoparticles is represented (Table 2).

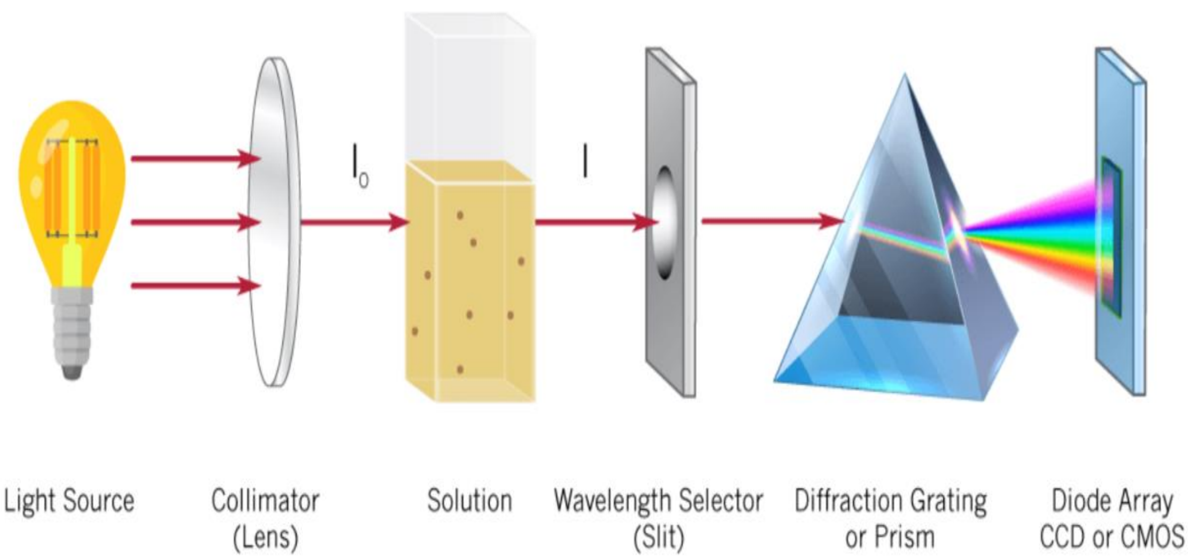

Figure 7. Working principle of a polychromatic UV/Vis spectrophotometer used in nanoparticle characterization

The instrument utilizes a light source that passes through a collimator and the sample solution. The transmitted light is then filtered by a wavelength selector and dispersed by a diffraction grating or prism. A diode array (CCD or CMOS) detects the spectrum, allowing analysis of absorbance or transmittance, which is critical for determining size, concentration, and optical properties of nanoparticles

This sensitivity property makes UV-Vis a quick, valuable, and non-destructive technique to observe the stability and synthesis of nanoparticles in colloidal solutions. Furthermore, UV-Vis performs real-time monitoring of fluctuations in nanoparticles during reaction processes or functionalization. It is predominantly advantageous and helpful due to its low cost, simplicity, and compatibility with organic and aqueous solvents. In spite of its limitations for providing details about structure, when combined with various other methods like DLS or TEM, UV-Vis balances and complements the complete nanoparticle analysis [19, 20].

Table 2. Key UV-Visible Spectrophotometric Parameters for Nanoparticle Characterization and Interpretation. Analyzing spectral features to assess nanoparticle size, concentration, dispersion, and colloidal stability

Analysis Parameter	What to Look For	Interpretation
Peak Position (λmax)	Wavelength of maximum absorption	▪ Red shift indicates larger particles or aggregation ▪ Blue shift indicates smaller particles ▪ Multiple peaks indicate size distribution or different phases
Peak Intensity	Absorbance magnitude at λmax	▪ Higher intensity indicates higher concentration ▪ Compare relative intensities for quantification, account for path length and dilution
Peak Width (FWHM)	Full Width at Half Maximum	▪ Narrow peak indicates uniform size distribution ▪ Broad peak indicates polydisperse particles ▪ Asymmetric peaks indicate multiple populations
Baseline Behavior	Absorption at non-resonant wavelengths	▪ Flat baseline indicates good dispersion ▪ Sloping baseline indicates scattering from aggregates ▪ High baseline indicates turbidity issues
Spectral Shape	Overall curve profile	▪ Sharp, symmetric = monodisperse ▪ Shoulder peaks = bimodal distribution ▪ Tail formation = aggregation onset
Time Stability	Peak changes over time	▪ Stable spectrum = good colloidal stability ▪ Peak shift/broadening = aggregation ▪ Intensity decrease = precipitation

4.2 X-Ray Diffraction Spectroscopy

X-ray Diffraction (XRD) spectroscopy is a generally used technique to determine the crystalline structure of nanomaterials. It works by pointing X-rays at a sample and determining the pattern and configuration of rays that are diffracted by atomic planes inside the crystal. Every single material creates a distinctive diffraction pattern, performing like a fingerprint of atomic structure. The intensity and angle of diffracted rays help to detect the crystallinity, phase composition, and lattice factors of the sample. In case of nanomaterials, XRD provides crucial understanding about the size of the particle (especially crystallite size through Scherrer's equation), strain, shape, and structural purity. Basic setup of X-ray Diffraction (XRD) used for nanoparticle characterization has been represented (Figure 8) [21]. It is particularly crucial for verifying the effective synthesis of nanomaterials and tracking modifications in crystal structure brought on by external treatment or doping. The interpretation of results (method) of X-ray Diffraction (XRD) spectroscopy for characterization of nanoparticles is represented (Table 3). The non-destructive nature of XRD and its capability to analyze samples in bulk, thin film, or powder form are two of its main benefits. Recent research highlights its function in proving phase transitions, finding extremely minute alterations in crystal symmetry at the nanoscale, and distinguishing polymorphism. Nevertheless, there are drawbacks, like the inability to identify overlapping peaks and amorphous materials in multi-component methods [22].

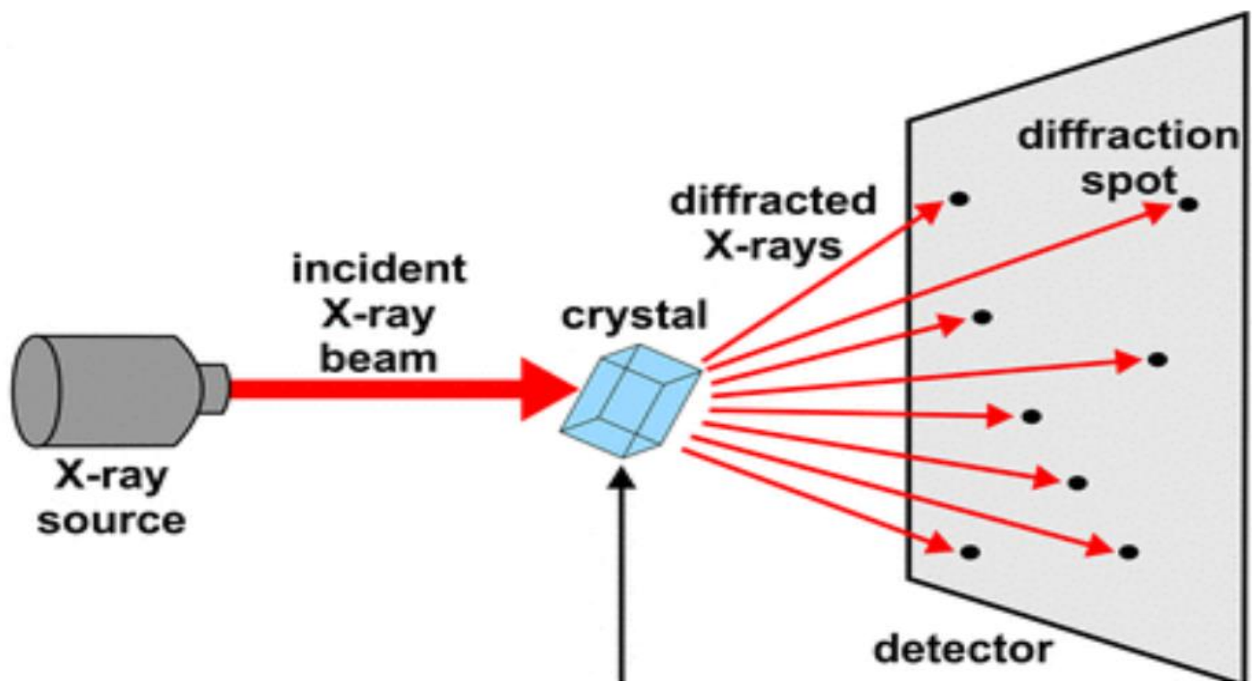

Figure 8. Basic setup of X-ray Diffraction (XRD) used for nanoparticle characterization.

An incident X-ray beam interacts with the crystal lattice of a nanoparticle sample, causing diffraction according to Bragg's Law. The resulting diffracted X-rays form specific patterns (diffraction spots) that are captured by a detector. These patterns provide crucial information about the crystalline structure, phase, and particle size of the nanoparticles

Table 3. Key X-Ray Diffraction (XRD) Parameters for Nanoparticle Characterization and Structural Analysis. Interpreting diffraction patterns to determine crystal structure, crystallite size, phase purity, and material quality

Parameter	What to Look For	Interpretation
Peak Position (2θ)	Sharp, well-defined peaks	▪ Compare with standard databases (JCPDS/ICDD) ▪ Identify crystal phase and structure ▪ Check for peak shifts (strain/doping effects)
Peak Intensity	Relative peak heights	▪ Indicates preferred orientation ▪ Use for phase quantification ▪ Compare I_{100}/I_{110} ratios for texture analysis
Peak Width (FWHM)	Broadening of diffraction spots	▪ Scherrer equation: $D = K\lambda/(\beta\cos\theta)$ ▪ Broader peaks = smaller crystallite size ▪ Distinguish size vs. strain broadening
Background	Baseline noise level	▪ High background may indicate amorphous content ▪ Subtract background for accurate peak analysis ▪ Check for preferred orientation effects
Peak Shape	Gaussian vs. Lorentzian profiles	▪ Symmetric peaks indicate good crystallinity ▪ Asymmetric peaks suggest structural defects ▪ Use profile fitting for accurate parameters
Missing/Extra Peaks	Comparison with reference patterns	▪ Missing peaks: preferred orientation or small size ▪ Extra peaks: impurities or secondary phases

4.3 Raman Spectroscopy

Based on the idea that monochromatic light, normally from a laser, scatters inelastically, Raman spectroscopy is a potent and non-destructive method. The majority of photons disseminate elastically (Rayleigh scattering) when light interacts with a material, but a tiny percentage scatter inelastically, resulting in an energy shift that shows molecular vibrations. A Raman spectrum is created by these energy shifts and works as the material's chemical fingerprint.

Important details regarding phase composition, crystallinity, molecular interactions, and chemical structure are delivered by this method. A schematic diagram of the Raman spectroscopy system for nanoparticle characterization is represented (Figure 9) [23]. In the field of nanomaterials, it is predominantly essential for determining chemical bonding, verifying that nanoparticles are functional, evaluating size-dependent vibrational characteristics, and differentiating between crystalline and amorphous phases. It is normally used to track surface alterations and nanoparticle synthesis because it is very sensitive to changes in surface chemistry. The interpretation of results (method) of Raman spectroscopy for characterization of nanoparticles is represented (Table 4). High spatial resolution in confocal modes, little sample preparation, compatibility with other microscopic methods, and the capacity to analyze aqueous systems are some of the salient features of Raman spectroscopy. Various nanomaterials, including metal, metal oxide, carbon-based, and polymeric nanoparticles, can be engaged with it. It is useful for in situ characterization and real-time monitoring since it can identify vibrational means even at low concentrations [24-26].

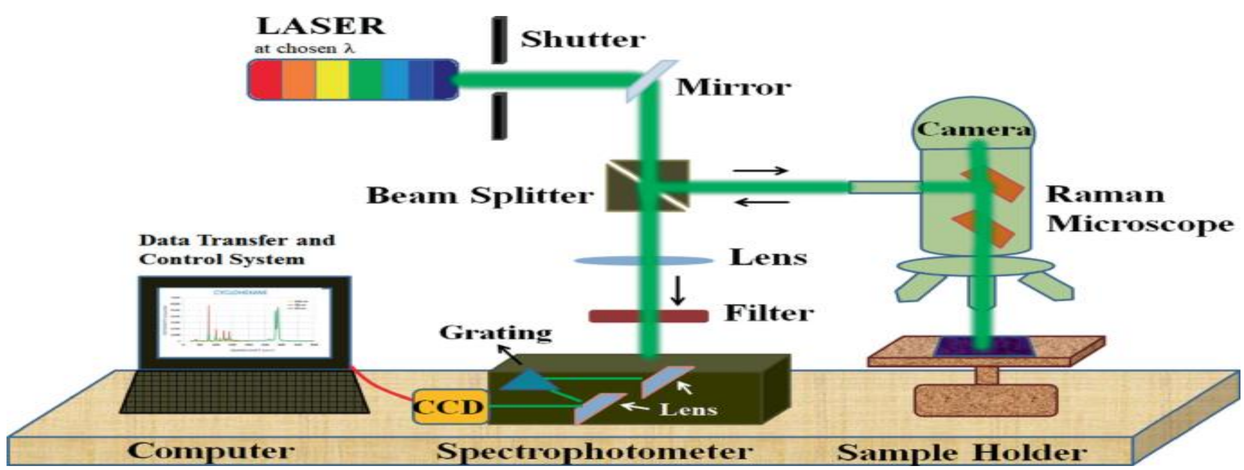

Figure 9. Schematic diagram of Raman spectroscopy system for nanoparticle characterization Single objective lens is used to capture the scattered light, with Rayleigh scattering filters before analysis with grating-based spectrophotometer linked with CCD detection. Detailed analysis of composition and structure of nanoparticles and automated acquisition of spectra is done by integrated control and data transfer system

Table 4. Key Raman Spectroscopy Parameters for Nanoparticle Characterization Evaluating vibrational features to assess crystal quality, stress/strain, particle size, and surface modifications

Parameter	What to Look For	Interpretation
Peak Position	Wavenumber shifts (cm^{-1})	▪ Upshift: compressive stress, smaller size ▪ Downshift: tensile stress, defects
Peak Intensity	Relative peak heights	▪ Higher intensity: better crystallinity ▪ Lower intensity: amorphous content, defects
Peak Width (FWHM)	Full Width at Half Maximum	▪ Broader peaks: smaller crystallites strain ▪ Narrower peaks: larger, well-ordered crystals
Background	Baseline fluorescence	▪ High background: organic contamination ▪ Low background: clean sample
New Peaks	Additional bands	▪ Oxidation ▪ Phase transitions ▪ Surface modifications
Peak Asymmetry	Shape distortion	▪ Fano interference ▪ Carrier concentration ▪ Size distribution effects
Polarization	Intensity variation with laser polarization	▪ Crystal orientation ▪ Symmetry information

4.4 Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) is a commonly developed technique for nanoparticle analysis, because it can identify chemical bonds and functional groups based on their distinct vibrational frequencies. It operates by exposing a sample to infrared radiation; the chemical structure of the sample determines which wavelengths are absorbed. By reflecting the molecules' vibrational modes, the resulting spectrum aids in identifying the chemical makeup of the sample, evaluating the existence of stabilizing agents along with surface functionalization and verifying surface modification. A schematic diagram of a Fourier Transform Infrared (FTIR) spectroscopy setup for nanoparticle characterization is represented (Figure 10) [23].

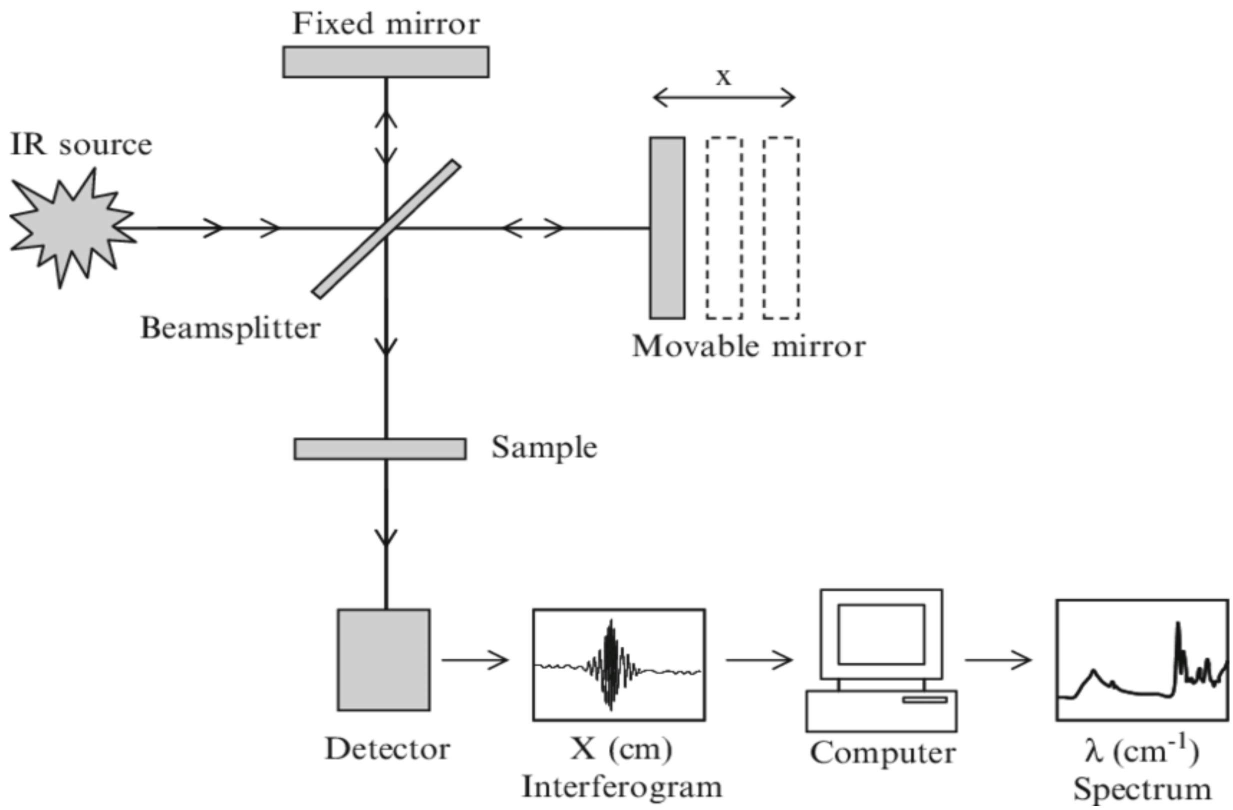

Figure 10. Schematic diagram of Fourier Transform Infrared (FTIR) spectroscopy setup for nanoparticle characterization

The basic principle of this instrument is based on Michelson interferometer, in which a beamsplitter is used to split the infrared radiation into two paths- directing it towards the fixed and moveable mirrors. The merged beams formed with an interferogram that is subsequently captured, and final spectrum is formed by the computer after processing. This approach aids in characterization of functional groups, surface chemistry changes, and determining chemical constituents through their distinct vibrational patterns in infrared spectra

FTIR is very crucial for assessing the interactions between nanoparticles, biological molecules and considering organic or polymeric coatings. It yields results quickly, takes a little sample, and is non-destructive. To offer a comprehensive physicochemical profile of nanoparticles, FTIR is frequently used in conjunction with other methods. Recent research indicates that FTIR is still crucial for verifying surface engineering and nanoparticle production, particularly in environmental and biomedical applications [27]. The interpretation of results (method) of Fourier transform infrared spectroscopy (FTIR**)** for characterization of nanoparticles is represented (Table 5).

Table 5. Key FTIR Spectroscopy Parameters for Nanoparticle Characterization Identifying surface functional groups, interactions, and structural modifications in nanoparticle systems

Analysis Parameter	What to Look For	Interpretation
Peak Position (cm^{-1})	Characteristic functional group frequencies	Compare with reference spectra; shifts indicate surface modifications or interactions
Peak Intensity	Relative absorbance strength	Higher intensity = more functional groups; useful for quantitative analysis
Peak Width/Shape	Broadness and symmetry	▪ Broad peaks = hydrogen bonding or particle size effects ▪ Sharp peaks = crystalline structure
Baseline Drift	Sloping or curved baseline	Common in nanoparticles due to scattering; correct before analysis
New Peak Appearance	Peaks not in bulk material	Indicates surface functionalization, coating, or impurities
Peak Disappearance	Missing expected peaks	May indicate particle aggregation or surface coverage
Peak Shifting	Frequency changes vs. bulk	▪ Blue shift = smaller particles ▪ Red shift = larger particles or strain

4.5 X-ray Photoelectron Spectroscopy (XPS)

X-ray photoelectron spectroscopy (XPS), an effective surface-sensitive method, uses X-ray radiation to cause electrons to be released from a material's surface. In order to identify chemical states, elements present, and the electronic situation of the surface atoms, XPS measures the kinetic energy of these released electrons to calculate the binding energies of atoms. It is perfect for characterizing and exemplifying the surface of nanoparticles because it usually examines the top 1–10 nanometres of the substance. A schematic diagram of the setup for X-ray Photoelectron Spectroscopy (XPS) nanoparticle characterization is represented (Figure 11) [28]. Consideration of stability, usefulness, and reactivity of nanoparticles depends on the essential information that XPS offers regarding oxidation states, surface composition, presence of functional groups, and elemental ratios. It is a vital tool in the field of nanoscience because of its quantitative precision, great surface sensitivity, and capacity to analyze both non-conductive and conductive materials without the need for intricate preparation. The use of XPS to assess surface changes, core-shell configurations, and conjugation competence in catalytic and biomedical nanoparticles has been emphasized in recent research [29].

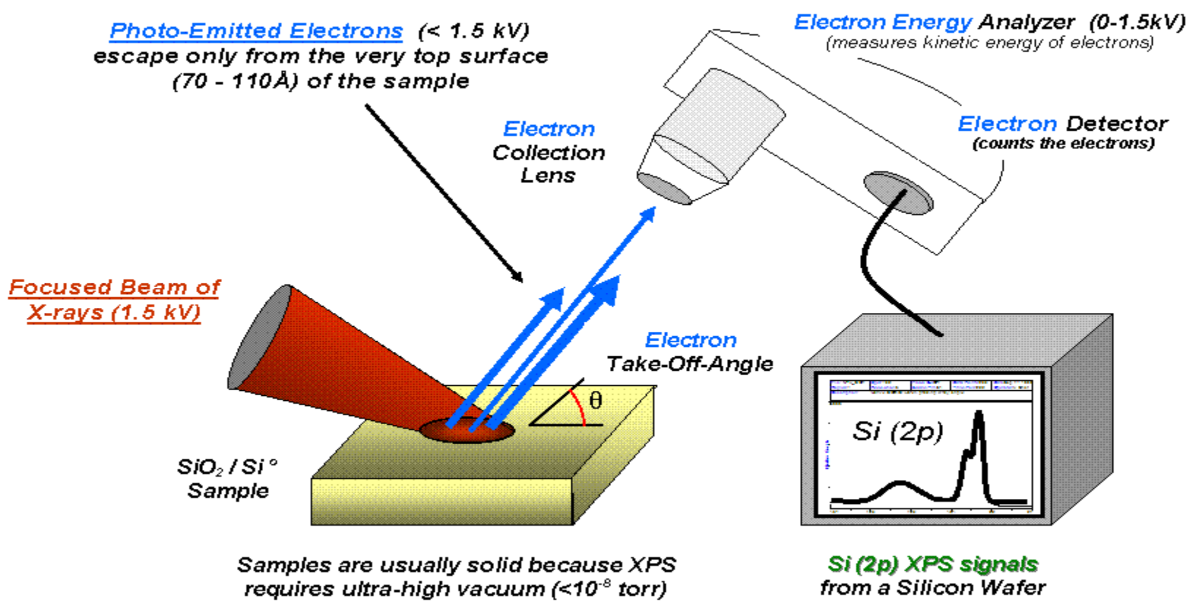

Figure 11. Schematic diagram of setup for X-ray Photoelectron Spectroscopy (XPS) An exact X ray beam with an energy of 1.5 keV is projected on sample, which causes the emission of photoelectrons from the upper layer 70-110 Å because of the photoelectric mechanism. A lens system used for collecting emitted electrons and their kinetic energy is determined by using analyzer ranges 0-1.5 keV. Photoelectrons are captured and recorded by photoelectrons that produce distinctive XPS spectra profile that provides information about surface chemistry, including atomic composition and oxidative states

The interpretation of results (method) of X-ray photoelectron spectroscopy (XPS) for characterization of nanoparticles is represented (Table 6). A comparative overview of nanoparticle characterization techniques with their roles, limitations, and sensitivity ranges has been represented (Table 7).

Table 6. Key XPS Parameters for Nanoparticle Characterization Analyzing surface chemistry, oxidation states, and elemental composition of nanoparticles through binding energy and spectral features

Parameter	What to Analyze	Key Information	Interpretation
Binding Energy (BE)	Peak positions in spectrum	Chemical state, oxidation state, bonding environment	▪ Compare with reference standards ▪ Shifts indicate different chemical environments
Peak Intensity	Area under peaks	Relative atomic concentration	Use sensitivity factors for quantitative analysis normalize to reference peak
Peak Shape/FWHM	Full width at half maximum	Crystallinity, particle size effects	Broader peaks may indicate smaller particles or disorder
Surface Sensitivity	Depth profiling (70-110 Å)	Surface composition vs bulk	Perfect for nanoparticles due to high surface-to-volume ratio
Take-off Angle (θ)	Vary electron collection angle	Depth information	▪ Lower angles = more surface sensitive ▪ Higher angles = more bulk sensitive
Satellite Peaks	Shake-up/shake-off features	Electronic structure, unpaired electrons	Common in transition metals; indicates specific oxidation states
Peak Splitting	Spin-orbit coupling	Doublet separation (e.g., $2p_{1/2}$, $2p_{3/2}$)	Fixed separations help confirm element identification
Chemical Shifts	BE differences from pure element	Functional groups, surface modifications	Essential for identifying surface treatments or contamination

Table 7. Comparative Overview of Nanoparticle Characterization Techniques with Their Roles, Limitations, and Sensitivity Ranges

Technique	Main Role	Limitations	Sensitivity / Detection Range
UV-Visible Spectroscopy (UV-Vis)	Measures concentration and shape of NPs in liquid samples	Only applicable to liquid samples	200–800 nm (UV-visible region)
Fourier Transform Infrared Spectroscopy (FTIR)	Identifies chemical bonds and functional groups	Cannot measure size or structure of NPs	20 Å – 1 µm
X-ray Diffraction (XRD)	Determines size and crystallinity of nanoparticles	Cannot determine composition or plasmonic properties	~1 nm

Technique	Main Role	Limitations	Sensitivity / Detection Range
Scanning Electron Microscopy (SEM)	Visualizes shape and size of nanostructures	Requires solid samples; cannot detect elements with atomic number < 11	< 1 nm
Field Emission SEM (FESEM)	High-resolution morphological and structural analysis	Does not provide NP concentration	< 1 nm
Transmission Electron Microscopy (TEM)	Provides detailed shape and size at atomic resolution	Cannot detect particles < 1.5 nm	< 1.5 nm
Particle Size Analysis (PSA)	Measures size distribution in solid or liquid samples	–	1 nm – 1 µm
Malvern Zetasizer (MZS)	Measures particle size, zeta potential, and protein mobility	Applicable mainly to nano-range particles	–
Energy-Dispersive X-ray Spectroscopy (EDX/EDS)	Analyzes elemental composition of nanoparticles	Cannot analyze particles < 2 nm	< 2 nm
Nanoparticle Tracking Analysis (NTA)	Measures size, concentration, and fluorescence properties	–	30 – 10 nm

5. Plant-based Applications of Nanoparticles

5.1 Nanomaterial as Bio-stimulator

To counteract pathogen attacks, plants have developed innate immune responses, including the synthesis of defense enzymes, the generation of antioxidants, and the fortification of their cell walls. These innate protective responses are non-specific and defend the plants against many types of phytopathogens. For disease suppression in plants, the application of small amounts of nano-formulations has proven to be a bio-stimulant for enhancing the innate immunity of plants, thereby inducing tolerance against biotic stresses [30]. Silver nanoparticles were formulated, which depicted bactericidal action that also helps in increasing immunity. A significant increase in the level of oxidative enzymes, phenolic compounds, and a reduction in pathogenic infection were examined when tomato plants were exposed to 5 µg $ml^{-1}$of silver nanoparticles (Ag NPs), indicating that silver nanoparticles can stimulate plant resistance and enable plants to thrive in the face of pathogen assault. Moreover, a significantly enhanced level of chlorophyll content (23.52%) was also observed in plants treated with silver nanoparticles, which may also play a role in increasing resistance by providing energy to plants [31]. Besides this, strong bactericidal action has been observed against *Ralstonia solanacearum* (*in vitro*) by using magnesium oxide nanoparticles (MgO NPs). Moreover, significant development of inhibited bacterial wilt using MgO NPs suggested the induction of systemic resistance against pathogens in plants. Rapid production of reactive oxygen species, stimulation of jasmonic acid (JA), salicylic acid (SA), and ethylene (ET) signaling pathways, and aggregation of tyloses and β-1,3-glucanase were examined in tomato plants exposed to MgO nanoparticles. On the other hand, joint application of copper nanoparticles(Cu NPs) (50 mg l^{-1}) and selenium (20 mg l^{-1}) in tomato early blight due to *A. solani* led to suppression in severity (6%) by production of non-enzymatic as well as enzymatic antioxidant compounds in fruit and leaves which aided plants to counter stress easily against pathogens [32]. Chitosan nanoparticles (CNPs) have proven to be a more effective immune stimulator than chitosan solution, with 10-fold doses of CNPs less than chitosan solution. The lower doses and higher efficiency of CNPs led to stronger binding of CNPs to plant cells than that of chitosan, as testified by enhanced bioaccumulation and bio-accessibility. In addition to that, the crucial role of nitric oxide (NO) in CNP-mediated innate immune regulation in plants has also been demonstrated [33]. Similarly, magnesium oxide (MgO) nanoparticles depicted strong anti-bacterial action against *solanacearum in vitro* at an amount of 0.1% and significant upregulation of defensive plant marker genes (0.7%) was observed [34]. The results suggested a more toxic threshold in case of plants than that of microbes and depicted less toxicity of nanomaterials (NMs) when utilized as anti-microbial agents. The initiation of oxidative stress in terrestrial plants and microbes is one of the crucial biochemical changes after exposure to nanoparticles, caused by specific properties at the nano scale, and both have been observed to take place in a dose-dependent manner [35]. Because terrestrial plants have evolved more sophisticated defense mechanisms, their reactions to NMs may differ. When oxidative stress does not exceed a hazardous threshold, defense induction occurs in terrestrial plants [36]. For instance, ROS plays a crucial role in activating the protein genes related to pathogenesis. It is suggested that valuable effects of NMs as bio stimulants against disease resistance can be attributed to high surface charge density and surface/volume value, which can bind with the cell surfaces of plants and trigger changes in gene expression and metabolism of cells.

Bio stimulation of NMs takes place by using specific concentrations depending on the properties and types of NMs. As phytotoxicity may occur at higher doses, the usage of minimum effective concentrations should be focused on agricultural applications in the future [37]. Although NMs have greater potential to use as a stimulant to replace pesticides to combat pathogens, extensive study of the mode of action induced by NMs is alluring [38].

5.2 Nanomaterials as Carriers

Nanomaterials are evolving to be delivery vehicles for biological molecules in plants that can be modified to regulate their translocation and spreading to the organelles and cells of plants [39]. Interfacing engineered nanomaterials (ENMs) with plants is bringing about substantial progress in the direction of addressing key challenges for plant genetic element delivery, biochemical sensing, and pesticide as well as nutrient delivery. The wide-ranging capability for engineering plants using ENMs with exclusive chemical and physical characteristics depends on avoiding the barriers that are present in the plant, incorporating cell walls along with membranes, and enhancing the targeting to precise organelles and tissues [40].

Present-day methods and attempts to advance nanoparticle delivery potency (in vivo) to particular plant organelles or cells are grounded on adjusting nanoparticle characteristics, for example, charge and size; nonetheless, they do not accomplish elevated levels of subcellular localization precision. For instance, it has been described that cerium oxide nanoparticles, which were negatively charged, delivered into leaves of the plant, showed around 45% localization rates with chloroplasts. Nanomaterials directed towards specific targets managed by bio-recognition ligands like transit peptides have not been described in plants up to now, as they are incapable of being straightforwardly translated from non-plant systems. In contrast to mammalian cells, plant cells possess a wall around them, which serves as an extra obstacle for the translocation of nanoparticles [41]. The uptake of nanoparticles around plant cell walls is restricted by the size of both the pores of the cell wall and the nanomaterials. Even though the permeability of nanomaterials through the cell walls of plants has not been technically illustrated, it is supposed to be reliant on the species of plant as well as on the characteristics of nanoparticle incorporating hydrophobicity in addition to size such as, amphiphilic nanoparticles (having size ~40 nm) have been described to translocate around the cells of leaf but the hydrophilic nanoparticles of comparable or bigger size does not translocate around the cells of leaf [42].

NMs have also been used for the delivery of nutrients in plants. Due to biocompatible, non-toxic, and biodegradable characteristics, chitosan biopolymer has gained significant importance for broad use in matrices (nano-encapsulating) for agrochemicals. For the treatment of blast disease (finger millet) and *Curvularia* leaf spot (CLS) disorder of maize, both zinc-chitosan nanoparticles (Zn-CNPs) and copper-chitosan nanoparticles (Cu-CNPs) were fabricated by entrapment of metal in a chitosan porous network and it was concluded that at 0.04–0.16% concentration of Cu-CNPs, 24.6–22.6% significant reduction in severity of CLS was observed in pot conditions as compared to water (control) of 44.0%, Bavistin fungicide (29.3%) and chitosan (32.67%) [43]. In addition to that, in Cu-CNP-treated plants, 11.6 % enhancement in the weight of maize was observed as compared to Bavistin. By the combined application of a spray of Cu-CNPs and seed coat in finger millet plants, 75% protection and 89% yield increase were observed. Both metal-CNPs revealed the sustained and slow release of Zn2+ and Cu2+, highlighted the long-lasting interaction of metal ions with plant cells and may also regulate many metabolic processes on the basis of the nutritional effects of Zn and Cu. However, the negative effects on plant growth have been observed by using higher concentrations of Zn-CNPs (0.12%) and Cu-CNPs (0.16%) due to the accumulation of Zn and Cu in plant tissues [44].

Nanomaterials have also been used for the delivery of pesticides in plants. Several studies have demonstrated the steady liberation of pesticides by using NMs. For instance, when fungicide metalaxyl got entangled in mesoporous silica nanoparticles (MSNs), a 7-fold delay was observed in the release of metalaxyl from MSNs into the soil as compared to free metalaxyl with an interval of 30 sec [45]. In the same way, encapsulation of carbendazim and tebuconazole in solid lipid nanoparticles (SLNs) resulted in a smaller number of fungicides for leaching of soil (4.8%) as compared to commercial manufacturing (17%). The effective results were accomplished by using nano-calcium carbonate-loaded validamycin against *Rhizoctonia solani*, with 10% enhanced germicidal efficacy after an interval of 7 days as compared to validamycin alone. The observation of long-lasting efficacy for inhibiting *R. solani* for two weeks was related to sustained liberation of validamycin from a nanobased formulation. Sustained antifungal action has also been observed against *Altenariaalternata* for fungicides trapped in multi-walled carbon nanotube-poly citric acid (MWCNT-*g*-PCA) as compared to fungicide alone. Similarly, at a concentration of 0.5 ppm, carbendazim-loaded chitosan–pectin nano-capsules depicted effective results compared to carbendazim alone against *Aspergillus parasiticus* and *F. oxysporum* with 16% and 20% improvement, respectively [46]. The impact of nanoparticles as protectants and carriers is represented (Figure 12).

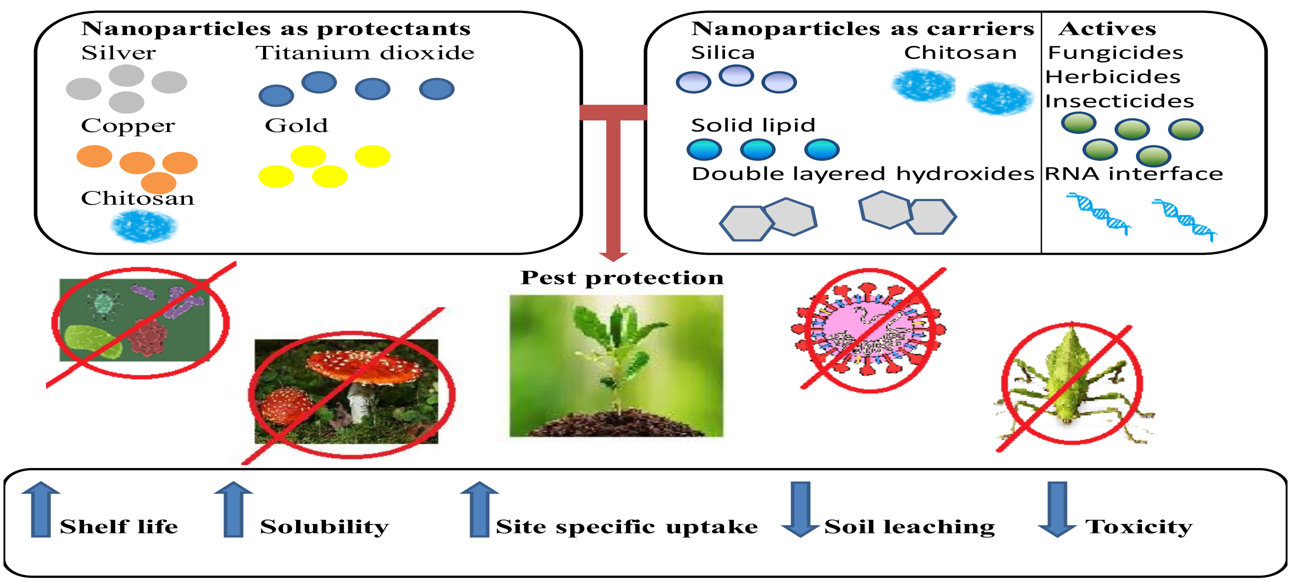

Figure 12. Nanoparticles as protectants (e.g., silver, copper, gold, titanium dioxide, chitosan) and carriers (e.g., silica, solid lipids, chitosan, double-layered hydroxides) enhance pest protection by delivering actives (fungicides, herbicides, insecticides, RNAi). This strategy improves shelf life, solubility, site-specific uptake, reduces soil leaching, and minimizes toxicity while effectively controlling pathogens, fungi, viruses, and pests

5.3 Nanoparticles as Antimicrobial Agents

Nanoparticles can be designed in a particular form of nanochips, nanosensors, carbon nanotubes, and dendrimers, which have been found to have remarkable biological, physical, and chemical features that are not present in their molecular form or bulk molecules. Nanoparticles possess a high surface area that has raised their biological potentials and sensitivity, as well as a significant affinity for their targets, especially proteins. Nanoparticles can be directly put into the seeds of plants, leaves, or on roots to save them from pests and pathogens. The metal's nanoparticles (NPs), such as copper, silver, titanium dioxide and zinc oxide, have been extensively studied for their antimicrobial capabilities, such as antibacterial, antifungal and antiviral activities. Silver nanoparticles have displayed great promise in the fight against fungal and bacterial diseases in plants, but they come with a number of drawbacks, including toxicity, manufacturing, and soil interaction [47].

Silver nanoparticles (Ag NPs) are applied to control the infectious agents in plants possessing antimicrobial action. A small quantity (16 ppm) of DNA-directed silver NPs grown on graphene oxide (GO) Ag-dsDNA-GO, demonstrated outstanding antibacterial capacity against the *Xanthomonas perforans*. In the greenhouse experiment, 100 ppm of foliar utilization of Ag-dsDNA-GO by tomato seedlings fundamentally diminished the bacterial spot disease severity compared to untreated plants, which gave similar results to plants treated with local bactericides (Kocide 3000+mancozeb) at the same time. Given the equivalent potency to commercial medicines and very little dose and harmfulness, these findings demonstrate the utility of nanoscale Ag in the management of Cu-tolerant phytopathogens [48].

It is demonstrated that the 3 ppm concentrations of biosynthesized Ag NPs derived from supernatant culture of *Rhodotorulaglutinis* shown the preventive effects in suppressing pathogenic fungi of plants in potato dextrose agar (PDA) media as compared to their chemically produced Ag Np. Similarly, the Ag NPs produced from *Trichoderma viride* have stronger bactericidal potential than chemically derived Ag NPs, which can be related to *T. viride*'s secondary antibacterial compounds coating the surface. Biosynthesis of NPs is generally considered to be superior to chemical synthesis in terms of biocompatibility, production and cost [49]. The bio-conjugated nano complex that is generated by a complex of AgNPs with surface modification that is attained by conjugation with 2, 4-diacetylphloroglucinol exhibited greater activity against the pathogens as compared to silver NPs because of the synergistic effect of NPs and biological molecules, revealing new antimicrobial possibilities. In the usage of NPs, surface modification is a major limitation nowadays and can address the issue of NP aggregation that can result in a loss of surface area activity and diminishing of antimicrobial potential [50]. Besides the metal-based nanoparticles, new research has shown that carbon-based NMs are poisonous to plant pathogenic fungi such as *Fusarium graminearum, Pseudomonas syringae*, *Undulosa, Xanthomonas campestris pv., and Fusarium oxysporum*. Under in vitro studies, chitosan NPs (CNPs) have remarkable antifungal efficacy. A tomato plant with foliar spray of CNPs challenged with *F. oxysporum* and *f. sp. lycopersici* delayed the appearance of wilt disease symptoms, resulting in 81 percent wilt disease protection and increased production.

The interaction of nanomaterials with microbes causes the suppression of growth and multiplication of cells and distorts the cells. Bacterial and fungal pathogens can enclose or interweave with the graphene oxide (GO) sheets, causing the cells to disintegrate. It is hypothesized that NM-induced cell distortion is primarily due to the disruption of the cell membrane. This is the main principal cytotoxic effect of nanomaterials against the phytopathogens. The adherence of metal-based NP with cell membranes causes the release of ions like Ag+, Zn2+ and Cu2+, resulting in the generation of reactive oxygen species (ROS), destroying biomolecules [51]. List of nanomaterials as antimicrobial agents for disease control is mentioned (Table 8).

5.4 <u>Nano-formulations as Nano-fungicide</u>

Worldwide, fungal infections affect agricultural crops, posing a serious danger to their output. 70% of plant illnesses are caused by fungus. Crop production decline has a significant impact on a country's economy. To resist the fungal diseases in plants, different fungicides of broad and narrow spectrum are synthesized which are not commonly used or are not successful enough. Because the types of fungal pathogens vary throughout their life cycles, effective crop protection methods are necessary for disease control. [52].

Table 8. List of nanomaterials as antimicrobial agents for disease control

Sr.#	Nanomaterials	Host and disease	Effect	Application Dose	Toxicity toward non-target organisms	Target pathogen	Reference
1	CuO, Cu_2O, Cu/Cu_2O NPs	Tomato; late light	Lesions of the Leaf were substantially repressed with Cu-based nanoparticles in the field settings	27.78– 43.87 ghl–1	No phytotoxicity	*Phytophthora infestans*	[53]
2	Ag NPs	Chickpea; Wilt- disorder	Silver nanoparticles exhibited excessive antifungal action (95%) against FOC. 73.33% decrease in wilt incidence was exhibited by Pot experiments	100 µg ml−1	No phytotoxicity as well as no adverse effect was seen on the soil community	*Fusarium oxysporum, f. sp. ciceri*	[54]
3	GO	Infection to various Triticum (genera)	Graphene oxide showed a strong influence on reproduction of entire 4 pathogens, which inhibited 80% germination of macroconidia, destroyed around 90% of the bacteria along with partial cell lysis and swelling	500 µg ml−1	NA	*Fusarium oxysporum, Xanthomonas campestris pv. undulosa, Pseudomonas syringae, Fusarium graminearum*	[55]

4	Chitosan NPs	Tomato; Fusarium Wilt disease	The synthesized chitosan nanoparticles show outstanding antifungal action in the in vitro settings. The foliar appliance of chitosan nanoparticles to the plants of tomato challenged with pathogen exhibited slowdown in wilt disease symptom appearance as well as lead to 81% safety of the plants of tomato from the wilt disease	0.1% (w/v) for foliar application and 0.0005% (w/v); for in vitro appliance	Plant growth and yield promoting	*Fusarium oxysporum, f.sp. lycopersici*	[56]
5	Ag-dsDNA-GO composite	Tomato; bacterial spot	Silver nanoparticles composites efficiently reduce cell viability of *X. perforans* on plants and in culture Considerable decrease in harshness of bacterial spot disorder in a greenhouse test	100 ppm	No phytotoxicity	*Xanthomonas perforans*	[57]
6	ZnO/nanocopper composite (ZnO-nCuSi)	Citrus; canker disorder	ZnO-n CuSi exhibited intense antimicrobial characteristics (in vitro) against microbes ZnO-n CuSi was valuable in restraining citrus canker disorder at below half the metallic speed of the corresponding commercial pesticide in field	0.22 kg ha–1 metallic Cu	No phytotoxicity	*Xanthomonas citri subsp. Citri*	[58]

7	Ag NPs	Multitudinous diseases in several crops	Silver nanoparticles are capable to prevent the growth of fungus in PDA agar	3 mg l−1	No phytotoxicity	*Aspergillus niger, Rhizopus sp., Penicillium expansum, Botrytis cinerea, Alternaria sp.*	[59]
8	C60, MWCNTs, Fe_2O_3, TiO_2	Tobacco; Turnip mosaic virus infection	The shoot biomass extensively enhanced by ~50% by experience with both metal- and carbon based nanomaterials. Nanomaterials appreciably restrained viral spreading, 15–60% reductions in the comparative quantity of TuMV coated proteins	50 mg l−1	Plant growth promoting.	*Turnip mosaic virus*	[60]
9	FQ-Cu, MV-Cu, CS-Cu nanocomposite	Tomato; bacterial spot disease	Cu-based nanocomposites eradicated the copper-tolerant *X. perforans* strain (in vitro), in the 60 minutes of treatment Greenhouse researches established that every copper composites appreciably lessened the seriousness of bacterial spot disease	100 μg ml−1	No phytotoxicity	*Xanthomonas perforans*	[61]

Abbreviations: FOC, *Fusarium oxysporum f. sp. Cubense*; GO, graphene oxide; MWCNTs, multi-wall carbon nanotubes; FQ-Cu, fixed quaternary ammonium copper; MV-Cu, multivalent copper; CS-Cu, core-shell copper

Therefore, nanofungicides containing nanoparticles or an active nano formulation ingredient are becoming more popular for disease recovery in plants than agrochemicals. They can destroy the undesired and fatal microorganisms from plants [62]. Scientists have synthesized several different forms of nanofungicides that are involved in plant disease control strategies (due to having a large surface area and high affinity for the target), which include metallic nanoparticles, nanospheres, metal-oxide-based NPs, nanogels, and nanoemulsions. Silver nanoparticles have also been reported to possess fungicidal activities against *Rhizoctonia solani, Sclerotinia sclerotiorum,* and *Sclerotinia minor*. Significant reductions in sclerotic germination as well as fungal growth were described by Min et al. Besides this, AgNPs had phytotoxic and suppressive reactions on conidial growth and also have substantial antifungal properties in the case of powdery mildew pathogens in cucumbers, cucurbits and roses. Furthermore, when nanoparticles were used in the field, a positive disease protection was reported. Early blight and wilt diseases in tomatoes and apple scab produced by *Fusarium solani* and *Venturia inaequalis* have been demonstrated to be resistant to sulphur [63].

Carbon nanoparticles have been found to have potent antifungal properties against *Fusarium graminearum* and *Fusarium poae* infections. Because of their tiny size, low viscosity, optical transparency, and higher kinetic stability, nanoemulsions are a desirable alternative for nanofungicides. They improve the solubility and bioavailability of active compounds in agrochemicals. Nanocapsules have active components of fungicide in the membrane-covered core and have the potential to be used in the formulation of nanofungicides [64].

6. Future Perspective

Nanotechnology is an auspicious approach in the recovery of plant diseases, having great advantages as compared to traditional methods due to fewer inputs, increased efficiency and lesser environmental toxicity. According to literature, nanoparticle has environmental effects and in soil, they upset the microflora. They may be transmitted from plants to animals, and people who consume and absorb food from them impact the food chain as a consequence. As a consequence, methods for defining appropriate standards for nanoparticle production and use, as well as their environmental implications, are required. Therefore, the physicochemical features of NPs that affect plant diseases must be determined without causing harm to ecosystems. Nanomaterials cannot only operate as a delivery route for active compounds to reduce phytopathogens, but they will also protect bio-stimulants and antimicrobial agents. Before they are used extensively in agriculture, the environmental concerns of nanomaterials (NMs) should be thoroughly assessed because of the limited knowledge about their fate in the environment. So, it is preferred to use accurate biosynthetic processes for the synthesis of NMs. Furthermore, investigations into optimizing the efficiency of NMs by modifying shape, size, and surface functionalization should be done to avoid environmental impact. One difficulty is that NM-based results must be examined on a range of plant pathogens in order to elucidate suppressive activity against diseases and to broaden their applicability for disease management.

7. Conclusion

The multifaceted investigation of nanoparticles demonstrated in this chapter accentuates their vast potential as transformative agents in agricultural and scientific domains. By categorizing nanoparticles in different variants (metallic, metal oxide, bimetallic, doped, and conjugated forms) we have illuminated the intrinsic structural diversity that dictates their functional performance and physiochemical attributes. The evaluation of fabrication techniques (Chemical, green synthesis and coprecipitation method) further reinforces the necessity for scalable, sustainable and application-oriented production strategies. Advanced Characterization techniques (UV-Vis, XRD, FTIR, Raman, and XPS) not only depict deep insight into surface chemistry, crystallinity and morphology of nanoparticles but also serve as integral tools for validating their efficacy, quality and stability. These analytical approaches are foundational for closing the gap between laboratory manufacturing and field-scale applications. Moreover, nanoparticles' integration into plant-based systems has yielded verified positive outcomes. From germination enhancement, nutrient uptake and photosynthetic efficiency, to alleviating biotic and abiotic stressors, nanoparticles have emerged as potent stress modulators and biostimulants. Their contribution as nanocarriers for agrochemicals validates improved crop resilience, precision delivery, and reduced environmental burden. Besides this, the intrinsic anti-microbial and anti-fungal attributes of specific nanoparticles provide a viable alternative to chemical pesticides (conventional), aligning with universal goals for sustainable agriculture. In essence, the chapter reasserts that nanoparticles, if judiciously synthesized, utterly characterized, and aptly applied, can catalyze a new epoch of environmental stewardship and agricultural innovation. The confluence of plant science and nanotechnology proffers a compelling roadmap towards accomplishing ecological sustainability, global food security, and enhanced productivity.

Author Contributions

Conceptualization, Design, Writing, Data curation, Results interpretation, Editing, Original draft preparation & Final approval, H.S; Design, Writing and Data Analysis, Z.A; Writing & Data Analysis, R.K, F.A and S.S; Data Compilation & Visualization, M.Q.F; Writing, K.T, A.L, B.G, S.G, H.A, A.S and F.F; Visualization & Final Approval, S.H & Z.K

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Conflicts of Interest

None of the authors have any conflicts of interest to declare.

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