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NANOPARTICLES IN CHEMISTRY: A COMPREHENSIVE REVIEW SYNTHESIS, PROPERTIES, CHARACTERIZATION, AND APPLICATIONS

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Abstract
Nanoparticles (NPs) materials with at least one dimension between 1 and 100 nanometers have emerged as one of the most transformative fields in modern chemistry and materials science. Their exceptional and often size-tunable physicochemical properties, arising from quantum confinement effects and dramatically increased surface-to-volume ratios, distinguish them fundamentally from their bulk counterparts. This review provides a comprehensive overview of nanoparticle science, encompassing their classification by composition and morphology, the principal synthetic routes (top-down and bottom-up), key characterization techniques, and the broad spectrum of chemical applications including catalysis, drug delivery, environmental remediation, sensing, and energy conversion. We also critically examine the challenges surrounding nanoparticle stability, scalability, toxicity, and regulatory concerns. Emerging trends in green synthesis, smart nanomaterials, and theranostic platforms are highlighted, and future directions are discussed. This review aims to serve as a reference for chemists, materials scientists, and engineers working at the nanoscale frontier.

1. Introduction

The nanoscale regime, broadly defined as the size range of 1–100 nm, represents a unique intersection of classical physics, quantum mechanics, and chemistry. At these dimensions, materials exhibit properties that deviate substantially from those of both individual atoms and bulk solids. The term "nanoparticle" encompasses an extraordinarily diverse range of structures from metallic and metal oxide clusters to polymeric assemblies, carbon allotropes, and semiconductor quantum dots all unified by their nanoscale dimensions and the profound influence of surface effects on their behavior (Alivisatos, 1996).

The modern era of nanoscience is often traced to Richard Feynman's visionary 1959 lecture "There's Plenty of Room at the Bottom," in which he speculated about the manipulation of matter at the atomic scale. However, the practical and deliberate engineering of nanoparticles for chemical applications accelerated only in the 1980s and 1990s, catalyzed by advances in electron microscopy, atomic force microscopy, and colloidal synthesis. Today, nanoparticle research spans materials chemistry, biochemistry, environmental science, medicine, and energy engineering (Barrán-Berdón et al., 2013).

The global nanomaterials market has grown exponentially, driven by applications ranging from heterogeneous catalysis and photovoltaics to targeted cancer therapy and antimicrobial coatings. Understanding the fundamental chemistry of nanoparticles how they are made, what governs their properties, and how they interact with their environment is therefore essential knowledge for the contemporary chemist.

2. Classification of Nanoparticles

Nanoparticles may be classified along several axes: chemical composition, physical morphology, surface functionalization, and intended application. The most common taxonomies are based on composition (Brust et al., 1994).

2.1 Metallic Nanoparticles

Metallic nanoparticles (MNPs) particularly those of gold (Au), silver (Ag), platinum (Pt), and palladium (Pd) are among the most extensively studied. Gold nanoparticles (AuNPs) exhibit localized surface plasmon resonance (LSPR), a collective oscillation of conduction electrons that gives rise to intense absorption and scattering of light. The LSPR peak is highly sensitive to particle size, shape, and local dielectric environment, making AuNPs invaluable in biosensing and surface-enhanced Raman scattering (SERS). Silver nanoparticles are prized for their potent antimicrobial activity and optical properties. Platinum and palladium nanoparticles serve as high-performance heterogeneous catalysts (Daniel & Astruc, 2004).

2.2 Metal Oxide Nanoparticles

Metal oxide nanoparticles include iron oxides (Fe_2O_3, Fe_3O_4), titanium dioxide (TiO_2), zinc oxide (ZnO), cerium oxide (CeO_2), and copper oxide (CuO), among many others. Iron oxide nanoparticles are superparamagnetic below a critical size, enabling their use in magnetic resonance imaging (MRI) contrast enhancement, magnetic hyperthermia, and magnetically guided drug delivery. TiO_2 and ZnO are widely used photo catalysts due to their wide bandgaps and strong oxidative power under UV irradiation (Feynman, 1960).

2.3 Semiconductor Nanoparticles (Quantum Dots)

Quantum dots (QDs) are semiconductor nanocrystals typically cadmium selenide (CdSe), cadmium sulfide (CdS), zinc sulfide (ZnS), or their core-shell composites whose electronic and optical properties are governed by quantum confinement. The bandgap of a QD increases as particle size decreases, enabling precise tuning of fluorescence emission across the visible and near-infrared spectrum simply by controlling size during synthesis. This property makes QDs powerful fluorescent labels in bio imaging and optoelectronics (Gao et al., 2007).

2.4 Carbon-Based Nanoparticles

Carbon nanoparticles encompass fullerenes (C_{60} and higher analogues), carbon nanotubes (single-walled, SWCNT, and multi-walled, MWCNT), graphene and graphene oxide (GO), and carbon dots (C-dots). Fullerenes are discrete, cage-like molecules with unique redox chemistry. Carbon nanotubes exhibit extraordinary mechanical strength and either metallic or semiconducting electrical conductivity depending on chirality. Graphene is a two-dimensional sp^2-hybridized carbon lattice with exceptional electron mobility and mechanical stiffness. Carbon dots are fluorescent, water-soluble nanoparticles emerging as non-toxic alternatives to heavy-metal QDs (Iijima, 1991).

2.5 Polymeric and Lipid-Based Nanoparticles

Polymeric nanoparticles, including those formed from poly(lactic-co-glycolic acid) (PLGA), chitosan, and polyethylene glycol (PEG)-based block copolymers, serve primarily as drug delivery vehicles. Lipid-based nanoparticles liposomes, solid lipid nanoparticles (SLNs), and lipid nanoparticle (LNP) systems are biocompatible carriers that have achieved major clinical success, most notably in mRNA vaccine delivery platforms (Laurent et al., 2008).

3. Physicochemical Properties

The extraordinary and often counterintuitive properties of nanoparticles arise from two primary nanoscale phenomena: the quantum confinement effect and the dramatic increase in surface-to-volume ratio.

3.1 Surface-to-Volume Ratio

As a particle shrinks to nanoscale dimensions, the fraction of atoms residing at or near the surface grows dramatically. For a spherical particle of diameter d, the surface-to-volume ratio scales as 6/d; halving the diameter doubles the ratio. Surface atoms have fewer nearest-neighbor bonds than bulk atoms and therefore higher free energy, greater reactivity, and different coordination chemistry. This enhanced surface reactivity underpins the superior catalytic activity of many nanoparticle systems compared to bulk materials (Chandra et al., 2026; Kim et al., 2021).

3.2 Quantum Confinement

When the size of a semiconductor nanocrystal becomes comparable to or smaller than the exciton Bohr radius of the material, electrons and holes are spatially confined, and the continuous energy bands of bulk semiconductors split into discrete, quantized energy levels. The energy gap between the highest occupied and lowest unoccupied level increases with decreasing particle size, shifting optical absorption and emission to higher energies (blue shift). This quantum size effect enables size-tunable photoluminescence in quantum dots (García de Arquer et al., 2021).

3.3 Optical Properties: Surface Plasmon Resonance

Noble metal nanoparticles (Au, Ag, Cu) support localized surface Plasmon resonances collective oscillations of the free electron gas driven by incident electromagnetic radiation. The resonant frequency depends sensitively on particle size, shape (sphere, rod, cube, triangle, cage), composition, and surrounding medium. Anisotropic particles such as gold Nano rods exhibit two LSPR modes (transverse and longitudinal), with the longitudinal mode tunable far into the near-infrared, which is valuable for photo thermal therapy (Chen et al., 2026; Correa-Duarte et al., 2025).

3.4 Magnetic Properties

Below a critical diameter (typically 20–30 nm for magnetite Fe_3O_4), magnetic nanoparticles exist as single magnetic domains rather than the multi-domain structures of bulk magnets. In this regime, thermal fluctuations can spontaneously reverse the magnetization direction a phenomenon called superparamagnetic. Superparamagnetic nanoparticles show zero eminence and coercively in the absence of a field, preventing agglomeration, but respond strongly to an applied field, enabling magnetic separation and hyperthermia applications (Laurent et al., 2008).

4. Synthesis of Nanoparticles

Nanoparticle synthesis strategies are broadly categorized into top-down (physical) and bottom-up (chemical) approaches.

Method	Category	Key Feature	Example Products
Ball Milling	Top-Down	Mechanical grinding of bulk	Metal, alloy NPs
Laser Ablation	Top-Down	Laser pulse on target in liquid	Au, Ag, C NPs

Chemical Reduction	Bottom-Up	Reducing agent + metal salt	AuNPs, AgNPs
Sol-Gel	Bottom-Up	Hydrolysis + condensation	TiO_2, SiO_2 NPs
Hydrothermal	Bottom-Up	High T/P aqueous reaction	Fe_3O_4, ZnO NPs
Green Synthesis	Bottom-Up	Plant extracts as reductant	AgNPs, AuNPs
Micro emulsion	Bottom-Up	Reverse micelle template	CdSe QDs, Pt NPs

4.1 Top-Down Methods

Top-down methods start with bulk material and progressively reduce it to nanoscale dimensions. Ball milling uses high-energy impacts to fracture bulk powders into nanoparticles, though the resulting size distribution is often broad and contamination from milling media is a concern. Laser ablation in liquid (LAL) involves focusing intense laser pulses on a solid target submerged in a solvent; the resulting plasma plume condenses into nanoparticles of controllable size through choice of laser fluence, pulse duration, and solvent composition. LAL produces surfactant-free nanoparticles with clean surfaces, advantageous for catalytic applications (Chandra et al., 2026).

4.2 Chemical Reduction

Chemical reduction is the most widely practiced bottom-up route for metallic nanoparticles. A metal salt precursor (e.g., $HAuCl_4$ for gold, $AgNO_3$ for silver) is reduced by a chemical reductant such as sodium borohydride ($NaBH_4$), citrate, or ascorbic acid. The Turkevich method, developed in 1951, uses trisodium citrate to simultaneously reduce and stabilize gold nanoparticles, yielding near-monodisperse spheres of 15–20 nm. The Brust-Schiffrin method uses $NaBH_4$ in a two-phase system with thiol ligands to produce smaller, exceptionally stable AuNPs. Nucleation and growth kinetics govern final particle size and distribution, as described by LaMer's burst nucleation model (Chandra et al., 2026).

4.3 Green Synthesis

Green synthesis exploits biological systems plant extracts, microorganisms, fungi, and algae as reducing and capping agents, replacing toxic chemical reductants and stabilizers. Plant extracts contain polyphenols, flavonoids, Terpenoids, and alkaloids that act as electron donors to reduce metal ions. This approach is low-cost, scalable, and environmentally benign, though reproducibility and mechanistic understanding remain challenges. Silver and gold nanoparticles synthesized via leaf extracts of Aloe vera, *Azadirachta indica* (neem), and *Camellia sinensis* (green tea) have been extensively studied (Ansari et al., 2021; Jain et al., 2025).

4.4 Hydrothermal and Solvothermal Synthesis

Hydrothermal synthesis conducts reactions in sealed autoclaves at temperatures above 100°C under autogenous water vapor pressure. These conditions favor controlled nucleation and crystallization, yielding highly crystalline nanoparticles with narrow size distributions. Iron oxide, titanate, and zeolitic nanostructures are routinely prepared hydrothermally. Solvothermal synthesis uses non-aqueous solvents (e.g., ethanol, ethylene glycol) and enables the preparation of nanoparticles with compositions or phases inaccessible in water (Chandra et al., 2026).

5. Characterization Techniques

Thorough characterization of nanoparticles requires a suite of complementary techniques addressing morphology, crystal structure, composition, surface chemistry, and colloidal stability (Mourdikoudis et al., 2018).

5.1 Transmission Electron Microscopy (TEM)

TEM provides direct, high-resolution imaging of nanoparticle size, shape, and crystalline structure. High-resolution TEM (HRTEM) resolves atomic lattice fringes, enabling identification of crystal phases and defects. Scanning TEM (STEM) coupled with energy-dispersive X-ray spectroscopy (EDS) or electron energy loss spectroscopy (EELS) gives spatially resolved elemental maps, essential for characterizing core-shell and alloyed nanoparticles (Kim et al., 2021; Mourdikoudis et al., 2018).

5.2 X-Ray Diffraction (XRD)

Powder XRD determines the crystal phase and phase purity of nanoparticles. The Scherrer equation, $D = K\lambda/(\beta \cos\theta)$, relates the broadening (β) of diffraction peaks to mean crystallite size (D). While XRD measures volume-weighted crystallite dimensions rather than particle sizes per se, it is invaluable for confirming phase identity and monitoring phase transformations (Mourdikoudis et al., 2018).

5.3 Dynamic Light Scattering (DLS) and Zeta Potential

DLS measures the hydrodynamic diameter of nanoparticles in suspension by analyzing fluctuations in scattered laser light due to Brownian motion. It captures the solvation shell and any adsorbed ligands, so hydrodynamic diameters typically exceed TEM sizes. Zeta potential measured by electrophoretic light scattering quantifies the surface charge of colloidal nanoparticles. Nanoparticles with $|\zeta| > 30$ mV are generally considered colloidally stable, as electrostatic repulsion prevents aggregation (Mourdikoudis et al., 2018).

5.4 UV–Vis Spectroscopy

UV–Vis absorption spectroscopy is a rapid, non-destructive probe of nanoparticle optical properties. For gold and silver nanoparticles, the position, width, and intensity of the LSPR absorption band report on size, shape, and aggregation state. For quantum dots, the first excitonic absorption peak enables size estimation via empirical calibration curves. For semiconductor oxide nanoparticles, Tauc plots derived from UV–Vis data yield optical bandgap energies (García de Arquer et al., 2021; Mourdikoudis et al., 2018).

5.5 X-Ray Photoelectron Spectroscopy (XPS)

XPS probes the elemental composition and oxidation states of elements within the top ~10 nm of a nanoparticle surface. It is indispensable for confirming successful surface functionalization, identifying surface oxidation, and quantifying ligand coverage. The binding energy shifts of core-level peaks (e.g., Au 4f, Fe 2p) are sensitive to the chemical environment and charge transfer (Mourdikoudis et al., 2018).

6. Chemical Applications

6.1 Catalysis

Heterogeneous catalysis is one of the most commercially significant applications of nanoparticles. The high surface-to-volume ratio of metallic nanoparticles exposes a large fraction of active surface atoms, dramatically increasing turnover frequencies per unit mass of precious metal. Platinum and palladium nanoparticles are deployed in automotive catalytic converters and hydrogenation reactions. Gold nanoparticles, traditionally regarded as inert, are highly active catalysts for low-temperature CO oxidation when deposited on reducible metal oxide supports. The Mars-van Krevelen mechanism, in which lattice oxygen from the support participates in the reaction cycle, is widely invoked to explain this activity (Chadha et al., 2022).

Enzyme-mimicking nanoparticles (nanozymes) represent an emerging subfield. Iron oxide nanoparticles exhibit peroxidase-like activity, catalyzing the oxidation of chromogenic substrates such as TMB (3,3',5,5'-tetramethylbenzidine) in the presence of H2O2 a reaction exploited in colorimetric biosensors for glucose and H2O2 detection (Gao et al., 2007; Manoharan et al., 2024).

6.2 Drug Delivery and Nanomedicine

Nanoparticle-based drug delivery systems exploit the enhanced permeability and retention (EPR) effect in solid tumors, whereby defective tumor vasculature and impaired lymphatic drainage cause preferential accumulation of nanoscale carriers. Surface functionalization with polyethylene glycol (PEGylation) prolongs circulation half-life by reducing opsonization and phagocytic clearance. Active targeting is achieved by conjugating nanoparticles with ligands (antibodies, aptamers, peptides, small molecules) that recognize overexpressed receptors on target cells (Anchordoquy et al., 2024).

Liposomal doxorubicin (Doxil) and albumin-bound paclitaxel (Abraxane) are clinically approved nanoparticle formulations that exemplify the translational success of nanomedicine. More recently, lipid nanoparticles encapsulating mRNA have achieved unprecedented clinical impact as the delivery vehicles for COVID-19 vaccines (Pfizer-BioNTech BNT162b2 and Moderna mRNA-1273) (Anselmo & Mitragotri, 2021; Desai et al., 2025).

6.3 Environmental Applications

Nanoparticles offer powerful tools for environmental remediation. Nanoscale zero-valent iron (nZVI) is employed for in situ groundwater treatment, reductively dechlorinating chlorinated solvents such as trichloroethylene (TCE) and perchloroethylene (PCE). TiO_2 nanoparticles under UV irradiation generate reactive oxygen species (ROS) particularly hydroxyl radicals (•OH) that mineralize organic pollutants in wastewater photocatalytically. Silver and copper nanoparticles incorporated into water filtration membranes provide antimicrobial activity without chemical biocides (Rahman et al., 2023; Tabassum & Ahmad, 2022).

Magnetic nanoparticles enable magnetically assisted removal of heavy metal ions and organic dyes from contaminated water by adsorption followed by facile magnetic separation. Functionalized graphene oxide composites show exceptional adsorption capacities for Pb^{2+}, Cd^{2+}, and As^{3+} ions (Rahman et al., 2023).

6.4 Sensing and Detection

The extreme sensitivity of LSPR to the local refractive index makes gold and silver nanoparticles ideal transducers for chemical and biological sensing. In aggregation-based colorimetric assays, analyte-induced aggregation of AuNPs produces a red-to-blue color shift visible to the naked eye exploited in rapid tests for nucleic acids, proteins, and small molecules. SERS exploits the enormous electromagnetic field enhancement in the nanogaps between metal nanoparticles ("hot spots") to detect molecules at sub-femtomolar concentrations (Chen et al., 2026; Correa-Duarte et al., 2025).

Electrochemical sensors functionalized with metal nanoparticles exhibit enhanced electron transfer kinetics and catalytic activity toward target analytes. Carbon nanotube and graphene-based electrochemical sensors offer ultrasensitive detection of neurotransmitters, heavy metals, and disease biomarkers (Mourdikoudis et al., 2018).

6.5 Energy Applications

In photovoltaics, plasmonic nanoparticles embedded in or near the active layer of solar cells can enhance light absorption through near-field enhancement and far-field scattering. Quantum dot solar cells exploit the tunability of QD bandgaps and multiple exciton generation to potentially exceed the Shockley-Queisser efficiency limit. In electrocatalysis, platinum and platinum-group-metal nanoparticles on carbon supports serve as the cathode catalysts for the oxygen reduction reaction (ORR) in hydrogen fuel cells; ongoing research targets earth-abundant alternatives (Fe-N-C, Co-N-C catalysts) to reduce cost (Chadha et al., 2022; Kumar et al., 2026).

Nanostructured electrode materials including lithium iron phosphate ($LiFePO_4$), lithium manganese oxide ($LiMnO_2$), and silicon nanoparticles are central to next-generation lithium-ion and solid-state batteries, offering higher specific capacities and faster charge/discharge kinetics than their bulk counterparts (Kumar et al., 2026).

7. Challenges and Limitations

7.1 Stability and Aggregation

Colloidal nanoparticles are thermodynamically unstable with respect to aggregation and coalescence, driven by minimization of surface free energy. Aggregation fundamentally alters their properties and, in biological systems, can cause rapid clearance or toxicity. Stabilization strategies include electrostatic stabilization (surface charges), steric stabilization (polymer or ligand coatings), and combined electrosteric stabilization. However, ligand coatings may attenuate catalytic activity or alter pharmacokinetics in drug delivery applications, creating engineering trade-offs (Anchordoquy et al., 2024; Chandra et al., 2026).

7.2 Scalability and Reproducibility

Many nanoparticle syntheses that yield monodisperse, well-characterized products at the milligram scale become difficult to reproduce at kilogram scale due to changes in mixing efficiency, heat transfer, and reagent concentration gradients. Continuous flow reactors and microfluidic synthesis platforms offer improved reproducibility and scalability compared to batch processes, and are an active area of process chemistry research (Chandra et al., 2026; Desai et al., 2025).

7.3 Toxicology and Environmental Fate

The same properties that make nanoparticles technologically powerful small size, high surface reactivity, ability to penetrate biological barriers raise legitimate concerns about toxicity to living organisms and ecosystems. Nanoparticle toxicity depends on composition, size, shape, surface chemistry, and dissolution behavior. Silver nanoparticles release Ag^{+} ions, which are cytotoxic to bacteria and eukaryotic cells alike. Carbon nanotubes, depending on length and surface functionalization, can cause pulmonary inflammation resembling asbestosis. The environmental fate, bioaccumulation, and ecotoxicology of engineered nanoparticles remain incompletely understood, and risk assessment frameworks are still evolving (Kumah et al., 2023).

7.4 Regulatory and Ethical Considerations

The regulatory landscape for nanomaterials varies considerably across jurisdictions. In the European Union, the Nanomaterials Regulation and REACH framework require registration and safety assessment of nanomaterials. The U.S. FDA has issued guidance documents for nanotechnology in drugs, devices, and food contact materials but lacks a comprehensive nanomaterial-specific regulatory statute (Desai et al., 2025; Rodríguez-Gómez et al., 2025).

8. Future Perspectives

The trajectory of nanoparticle research points toward several exciting frontiers:

- Theranostics: Multifunctional nanoparticles that simultaneously diagnose and treat disease integrating imaging contrast (MRI, fluorescence, photoacoustic), therapeutic payloads (chemotherapy, gene therapy, photodynamic agents), and targeting moieties on a single platform represent the convergence of diagnostics and therapeutics.
- Stimuli-Responsive Nanomaterials: Smart nanoparticles that release drug cargo or change properties in response to pH, temperature, light, magnetic fields, or enzymatic activity enable spatiotemporally controlled therapy with reduced off-target effects.
- Machine Learning-Guided Design: High-throughput synthesis combined with machine learning and data-driven models is accelerating the discovery of nanoparticles with optimized properties, reducing the reliance on trial-and-error experimentation.
- Single-Nanoparticle Analysis: Advances in super-resolution microscopy, single-particle tracking, and cryo-electron tomography are revealing the heterogeneity within nanoparticle populations and the dynamics of individual nanoparticles in complex biological environments.
- Sustainable Nanochemistry: Increasing emphasis on life-cycle assessment, atom economy, and circularity is driving the development of biodegradable nanoparticles, toxicologically

benign compositions, and synthesis routes that minimize waste and energy consumption.

As the tools for synthesis, characterization, and computational modeling continue to mature, nanoparticles will increasingly transition from laboratory curiosities to engineered components of real-world chemical, biomedical, and energy systems. Meeting the challenges of safety, scalability, and sustainability will be as important as the science itself.

9. Conclusions

Nanoparticles occupy a uniquely productive intersection of chemistry, physics, biology, and engineering. Their emergent properties arising from quantum confinement, high surface-to-volume ratios, and collective electronic phenomena provide a rich palette for chemical innovation. This review has traced the major families of nanoparticles, from noble metals and metal oxides to quantum dots and carbon nanomaterials, surveyed the principal synthetic strategies from chemical reduction and hydrothermal methods to green synthesis, and outlined the characterization toolkit that modern Nano chemistry relies upon.

Critical challenges remain. The long-term environmental fate of engineered nanoparticles, the mechanistic basis of Nano toxicology, and the gap between laboratory-scale synthesis and industrial-scale production all demand sustained research effort. Interdisciplinary collaboration bridging synthetic chemistry, toxicology, regulatory science, and social science will be essential for realizing the full potential of nanoparticle science responsibly and equitably.

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