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Nanoparticle Chemistry: The Synthesis, Properties and Applications of Polymer and Macromolecule-Based Nanoparticles and Their Composites

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Abstract

Nanoparticles have arisen as a transformative branch of materials in chemistry, owing to their unique physicochemical and biological properties that vary from their bulk materials. Various synthesis techniques, including physical (e.g., laser ablation), chemical (e.g., sol-gel, co-precipitation) and biological (e.g., microbial or plant-mediated) approaches, offer control over particle size, shape and surface characteristics. These methods influence the optical, electronic, catalytic and mechanical properties of nanoparticles. Nanoparticles can exhibit high surface area-to-volume ratios and quantum effects, making them highly reactive and efficient in roles such as drug delivery, catalysis, environmental remediation, and sensing technologies. A key example is a polymer composite, which leverages these properties for enhanced performance. Similarly, the properties of a single macromolecule or a larger polymer can be finely tuned to create nanoparticles with specific functions. Continued research in nanoparticle chemistry aims to develop safer, more sustainable synthesis routes and multifunctional materials tailored for biomedical, industrial, and technological innovations. This evolving field stands at the forefront of scientific advancement, bridging fundamental research and real-world applications, particularly in the realm of advanced polymer materials.

Keywords: Biomedical applications, chemical properties, drug delivery, nanoparticles, polymer nanomaterial composites, synthesis methods

INTRODUCTION

Nanotechnology is indeed the scientific field dedicated to constructing and controlling matter at the nanoscale, generally defined as structures between 1 and 100 nanometers (nm) [1]. The core principle of this discipline revolves around altering particle size and structure at this minute level. Because of their extremely small dimensions and large surface area-to-volume ratio, these resulting nanoparticles exhibit distinctive characteristics, making them highly valuable across various fields, notably in materials science. While the scientific understanding of these properties is relatively modern, human application of nanoscale materials dates back more than 4,000 years [2]. Scientific investigation into this realm accelerated during the 19th century. A notable early contribution came in 1857 when Michael Faraday documented the optical behavior of nanoscale metallic particles. Later, Norio Taniguchi formally introduced the term nanotechnology to describe the meticulous fabrication of materials atom-by-atom or molecule-by-molecule. The capacity to see and manipulate matter at this level was dramatically enhanced by breakthroughs in microscopy. The Transmission Electron Microscope (TEM), credited to Max Knoll

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and Ernst Ruska in 1931, was instrumental. Further advancements in high-resolution imaging, like Erwin Wilhelm Müller's Field Ion Microscope (FIM) in 1951, Gerd Binnig and Heinrich Rohrer's Scanning Tunneling Microscope (STM) in 1981, and Gerd Binnig, Calvin Quate, and Christoph Gerber's Atomic Force Microscope (AFM) in 1986, helped accelerate the discovery of naturally occurring nanoparticles. A landmark moment was the 1996 Nobel Prize in Chemistry awarded for the discovery of fullerene. This finding proved that carbon could assume novel allotropes, which directly led to the subsequent identification of carbon nanotubes and significantly broadened the potential of nanotechnology, especially for developing advanced composite materials.

CLASSIFICATION OF NANOPARTICLES

Nanoparticles are essentially classified according to their shape, form, and size, as well as by their dimensions, chemical composition, and unique size-dependent properties. This section focuses on the types of nanoparticles most relevant to polymer composites [3].

Organic Nanoparticles

Organic nanoparticles or organic polymeric nanoparticles are nanoscale particles primarily composed of organic compounds or polymeric macromolecules. They are typically synthesized using methods like miniemulsion or reprecipitation. Organic nanoparticles, such as ferritin, micelles, dendrimers, liposomes, nanogels, various polymeric natural polymers, and layered polymers, are frequently utilized in targeted drug delivery systems, commonly adopting nanosphere or nanoscale shapes. A key advantage for biomedical uses is that many of these particles exhibit low toxicity and biodegradability. Notably, structures like liposomes and micelles often feature a hollow spherical architecture.

Inorganic Nanoparticles

These are generally quite non-toxic simple molecules derived from non-living components, such as metals, metal oxides, or metal salts, lacking carbon-hydrogen bonds [4]. They are typically biocompatible, hydrophilic, and exhibit higher stability compared to organic nanoparticles. Inorganic nanoparticles possess diverse optical, electrical, chemical, colloidal, and magnetic characteristics, which can be tailored by controlling their size and shape during synthesis. The types of inorganic nanoparticles are classified into carbon, metal oxide, and metal-based nanoparticles [5]. Many of these can be integrated into polymer matrices to form polymer nanocomposites with enhanced properties.

Carbon-Based Nanoparticles

These nanoparticles are fundamentally and predominantly composed of carbon atoms and are often found in hollow spheres, ellipsoids, or tube-like structures. These are broadly classified into carbon quantum dots, carbon nanotubes, fullerenes, nanodiamonds, graphene, and their derivatives [6]. Drug molecules can be attached to the functionalized surfaces of carbon nanoparticles through covalent and non-covalent bonds. Pure carbon-based nanoparticles offer high stability, low toxicity, environmental friendliness, and exhibit excellent electrical conductivity, thermal conductivity, and mechanical properties [7].

Fullerenes

Fullerenes are unique allotropes of carbon that form spherical, cage-like molecules. These structures are composed of carbon atoms arranged in a polyhedral framework of pentagonal and hexagonal rings, giving them a striking resemblance to a soccer ball. The most well-known fullerene, C_{60}, is often called a buckyball, named after Buckminster Fuller, who popularized the geodesic dome, which shares a similar structural pattern. A minimum of 60 carbon atoms is required to form a fullerene molecule. The C_{60} fullerene specifically features an icosahedral symmetry with 20 hexagonal and 12 pentagonal rings. In this structure, each carbon atom is sp^2-hybridized and covalently bonded to three neighboring carbons. The molecule exhibits two distinct bond lengths: the shorter double bonds connecting two hexagonal rings (6:6 bonds) and the longer single bonds where a hexagon and a pentagon meet (6:5 bonds). This difference results in limited electron delocalization across the cage. Fullerenes are notable for their desirable material properties, including exceptional tensile strength, good electrical conductivity and ductility, high heat resistance, and considerable chemical inactivity.

Carbon Nanotubes (CNTs)

These are nanostructures directly derived from rolling up of graphene sheets, possessing various interesting and physicochemical properties that make them extensively useful in biomedicine. Their discovery using high-resolution electron microscopy (HREM) spurred intense experimental and theoretical studies [8]. CNTs are allotropes of carbon exhibiting a nanoscopic structure characterized by an extremely high length-to-diameter ratio, often surpassing 10^6:1. They exist as single-walled and multi-walled CNTs structures. CNTs offer numerous advantages, including biocompatibility, resistance to degradation and lack of immune response, high elasticity, potential for intracellular delivery, minimal cytotoxicity, and efficient excretion (96% via urine, 4% via feces). They are ultra-lightweight, do not break down during processing, and can enter cells through spontaneous mechanisms [9].

Graphene

It originates from graphite and is made entirely of pure carbon. This unique material is celebrated for its exceptional combination of strength, flexibility, and low weight, along with high durability. Structurally, it's a two-dimensional allotrope of crystalline carbon. It features a single atomic layer where the carbon atoms are precisely organized into a honeycomb lattice which is a planar, hexagonal arrangement with a thickness of about 1 nanometer (nm) [10].

Carbon Nanofibers

Carbon nanofibers are one-dimensional, cylindrical or conical nanostructures with diameters ranging from a few to hundreds of nanometers and lengths from less than a micron to millimeters. They are conductive materials with electronic structures like graphite. In some cases, graphene nano foils can be transformed into carbon nanofibers, like carbon nanotubes, but with the nano foils wound into cup or cone shapes instead of the elongated cylindrical tubes.

Carbon Black

Carbon black nanoparticles are a porous, amorphous form of carbon produced from the incomplete combustion of hydrocarbons. They may contain small amounts of other elements like hydrogen and oxygen. Because of their huge surface area, they can adsorb toxic substances, such as polycyclic aromatic hydrocarbons (PAHs), which can make them toxic. Carbon black is fine powder like material with a spherical shape, typically ranging from 20 to 70 nm in diameter. High inter-particle interaction often leads to their aggregation [11].

Metal Oxide Nanoparticles

These include zinc oxide (ZnO), iron oxide (FeO), titanium oxide (TiO_2), and cerium oxide (CeO) nanoparticles [12]. Their synthesis often involves modifying the properties of their respective metal nanoparticles. Oxidation can transform metallic nanoparticles (NPs), such as iron nanoparticles, into metal oxide nanoparticles (, e.g., iron oxide nanoparticles), which typically demonstrate enhanced reactivity and greater efficiency. Further examples of metal oxide nanoparticles encompass silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and magnetite [12].

Metal-Based Nanoparticles

Metal-based nanoparticles (NPs) are a class of nanomaterials composed of a single metallic element or its compounds, such as oxides, hydroxides, sulfides, and chlorides. These particles can be made from a wide array of metals, including gold (Au), silver (Ag), platinum (Pt), copper (Cu), zinc (Zn), aluminum (Al) and nickel (Ni) [13] (Figure 1). Examples include nanogold and nanosilver, as well as metal oxides like ZnO, copper oxide (CuO), and TiO_2. The synthesis of metal nanoparticles involves converting metal precursors using either destructive (, e.g., mechanical) or constructive (, e.g., chemical) methods. Common techniques include chemical reduction, microemulsion, and thermal decomposition of metal salts. All of which allow for the crucial control of the NP's shape, facet, and size. For instance, Cu-based nanocatalysts can adopt various morphologies (Cu, CuO, Cu_2O, and Cu_3N). In liquid media, a high growth rate can lead to anisotropic shapes, such as branched structures. The unique properties of metal NPs make them valuable in various fields. In chemical synthesis, metal nanoparticles, particularly Cu salts, are successfully employed as catalysts for C-C, C-N, C-O, and C-S cross-coupling reactions [14].

Silver Nanoparticles (AgNPs)

These are distinguished by their unique physicochemical characteristics, stemming from their small dimensions, a high surface area-to-volume ratio, and their capacity to absorb and scatter light across the visible and near-infrared spectrum. AgNPs have diverse uses, including protection against UV-induced DNA damage, targeted delivery to cancerous cells, implementation in Surface-Enhanced Raman Spectroscopy (SERS), and functioning as cathodes in silver-oxide batteries. Notably, these particles also display antimicrobial efficacy, capable of eliminating microorganisms in as little as six minutes while remaining non-toxic to human tissues.

Zinc Nanoparticles

These are tiny particles of Zn, with ZnO being a common form. They ZnO NPs can be fabricated into various morphologies, including hexagonal, spherical, cylindrical, and cuboidal shapes, typically within a 1 to 100 nm size range [15]. Due to their wide band gap of 3.37 eV, ZnO nanostructures are highly suitable for use in catalytic reactions. Several production techniques exist for ZnO NPs, such as laser ablation, hydrothermal synthesis, electrochemical deposition, the sol-gel method, chemical vapor deposition, ultrasound, microwave-assisted combustion and co-precipitation.

Copper Nanoparticles

The fluorescence of copper and gold metals has been long recognized. Copper nanoparticles, with their excellent catalytic activities, find applications in biosensors and electrochemical sensors. Copper nanoparticles typically exhibit a sphere-shaped and crystal-like nature, with a size range around 42–90 nm. Their elemental and chemical alignment is often characterized by Fourier-transform infrared (FTIR). These nanoparticles can be synthesized using copper chloride, sodium oleate and phenyl ether as solvent agents [16].

Gold Nanoparticles (AuNPs)

These are nanoscale particles made of Au, possessing unique physicochemical properties that allow them to absorb and emit light in the visible and near-IR range. Zsigmondy noted in his 1909 book that gold nanoparticles ‘are not always spherical when their size is 40nm or lower’ and also found anisotropic Au particles of different colors [17]. He won the Nobel Prize in 1925 for method used signifying the heterogeneous property of colloidal solutions, and for developing the ultra-microscope, which allowed him to visualize the forms of Au particles. He observed that gold frequently crystallized into a six-sided leaf shape.

Aluminum Nanoparticles

Aluminum nanoparticles are composed of aluminum. Their strong reactivity makes them suitable for applications in high-energy compositions, hydrogen generation in water processes, and the synthesis of alumina two and three dimensional structures. Aluminum nanoparticles are generally produced by evaporating the metal from its molten state inside a chamber filled with an inert gas; the metal vapor then condenses to form the particles.

Iron Nanoparticles (FeNPs)

Their functional diversity allows for several applications viz., they are investigated as catalysts, in drug delivery systems, and as sensors, alongside roles in energy conversion/storage. They also show promise in environmental remediation and water purification [18]. Furthermore, their magnetic properties make them useful as contrast agents in MRI and as components in magnetic recording media, such as hard disk drives [19].

CHARACTERIZATION OF NANOPARTICLES (NPS)

Understanding the various physicochemical properties of NPs is typical for their application in polymer composites. A range of characterization methods are applied to analyze their morphology, structure, size, and optical properties [20].

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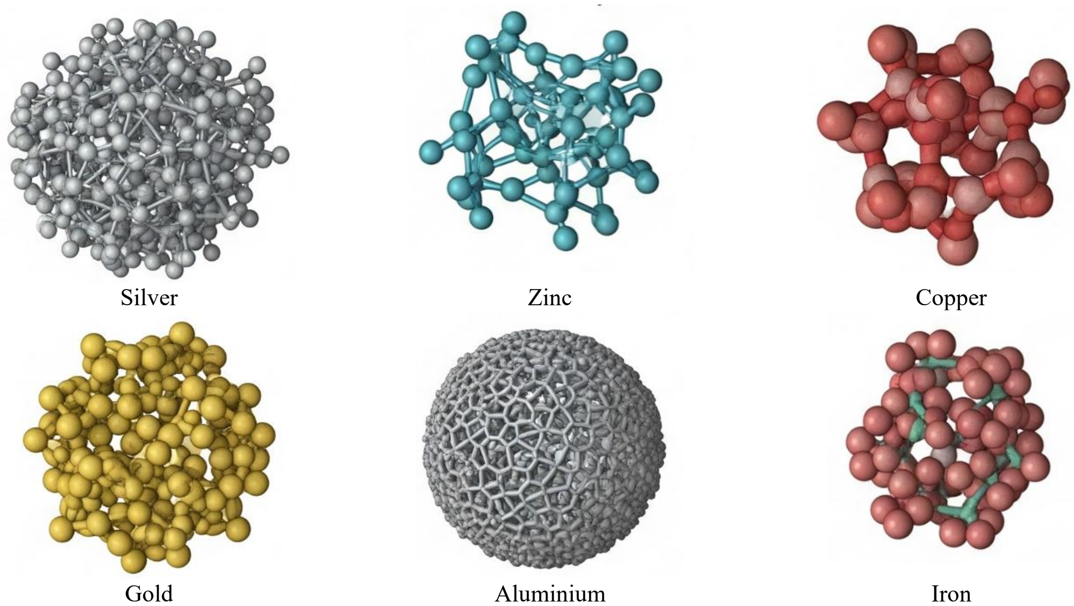

Figure 1. Silver, zinc, copper, gold, aluminum, iron nanoparticles.

Morphological Characterization

Microscopic techniques, particularly Scanning and Electron Microscopic (SEM and TEM) techniques are paramount for studying NPs morphology. SEM offers detailed information of the surface topography and nanoscale features of NPs. In contrast, TEM utilizes electron transmittance, allowing for high-resolution imaging of bulk materials and internal structures, which is critical for visualizing the dispersion and morphology of nanoparticles within a polymer matrix [21]. For example, TEM micrographs can reveal the diverse morphologies of nanoparticles and their interaction with polymer chains [22].

Structural Characterization

Structural characterization methods are important for understanding the composition and bonding nature of NP materials and their composites. Common methods include X-ray diffraction (XRD), energy-dispersive X-ray spectroscopy (EDX), X-ray photoelectron spectroscopy (XPS), Infrared (IR) spectroscopy, Raman spectroscopy and Brunauer-Emmett-Teller (BET) analysis. XRD is a cornerstone technique for revealing the structural properties of NPs, providing crucial information about their crystallinity and phase, which can be affected by their incorporation into a polymer matrix [23]. FTIR and Raman spectroscopies are used to study the vibrational properties of nanoparticles, which can help identify functional groups and confirm the successful integration of nanoparticles into a composite [24].

Particle Size and Surface Area Characterization

Several procedures can be employed to estimate NPs size, including SEM, TEM, XRD, Atomic Force Microscopy (AFM) and Dynamic Light Scattering (DLS). For materials designed for composites, the distribution of nanoparticle sizes is a key parameter affecting the final material's properties. Surface area characterization, often performed using the BET method, is depends on the principle of adsorption and desorption and is particularly useful for studying porous materials and nanoparticles that will be integrated into a polymer [25].

Optical Characterization

Optical characterization techniques are founded on the Beer-Lambert law and fundamental principles of light interaction. These methods provide information about the adsorption, reflectance, and phosphorescence properties of NPs. It's well-known that NPs, especially metallic and semiconductor NPs, exhibit diverse colors, making them ideal for photo-related applications [26]. Ultraviolet-Visible (UV-Vis) spectroscopy, photoluminescence (PL) spectroscopy, and ellipsometry are well-known optical instruments used to study the optical properties of NP materials. For example, carbon nanodot-carbon nitride composites have been identified as metal-free photocatalysts for water splitting [27].

CHARACTERIZATION TECHNIQUES FOR SYNTHESIZED NANOPARTICLES

The rapid advancement of nanotechnology across diverse scientific disciplines has necessitated the use of analytical techniques for the comprehensive characterization of NPs. Characterization is a crucial step in understanding the reaction mechanisms, physicochemical properties, and potential applications of synthesized nanoparticles. Commonly employed techniques include UV-Vis spectroscopy, XRD, SEM, BET surface area analysis, and TEM. These methods are essential for determining the shape, size, crystallinity, surface area, and other key attributes of nanoparticles.

UV-Visible Spectroscopy

UV–Vis spectroscopy is a simple, cost-effective, and widely used technique for analyzing nanomaterials. It measures the optical absorbance of a sample across the UV–Visible spectrum, offering insights into the electronic structure and optical properties of nanoparticles [28]. For instance, in the synthesis of ZnO nanoparticles, a shift in the absorption maximum from 300 nm ($Zn(NO_3)_2$) to 340–370 nm indicates successful conversion to ZnO [29].

XRD Analysis

XRD is a powerful method used to determine the crystal-like structure, phase configuration, and average crystallite size of nanoparticles. It provides vital chemical and structural information, including lattice parameters, crystallinity, and phase purity. XRD can be applied to various sample types, such as powders, crystals, and even fluids. The technique is also instrumental in stress analysis and texture evaluation. In nanoparticle research, XRD confirms the crystalline nature and identifies the phases present in the synthesized material [30].

BET Surface Area Analysis

BET analysis is commonly used to measure the specific surface area of porous materials and nanoparticles. Nitrogen gas is typically employed as the adsorbate due to its availability and compatibility with most materials. Because gas–solid interactions are weak at room temperature, the sample surface is cooled using liquid nitrogen to enhance adsorption. The BET method is particularly useful for studying metal–organic frameworks (MOFs) and other porous materials. It provides quantitative data on surface area, pore size distribution, and total pore volume, which are critical for applications in catalysis, adsorption, and energy storage [31].

FTIR Spectroscopy

FTIR spectroscopy is a method based on the absorption of mid-IR radiation (4000–400 cm^{-1}) by molecules, which causes vibrational transitions in their bonds. This method is used to identify functional groups and chemical bonds on the nanoparticle surface [32]. For a molecule to absorb IR radiation, it must exhibit a change in dipole moment, making it IR-active. The FTIR spectrum of nanoparticles typically shows characteristic absorption bands that correspond to capping agents or other surface-bound species.

TEM Analysis

TEM is a high-resolution method used to visualize the morphology, size, and internal structure of nanoparticles. Based on the transmission of electrons through an ultra-thin sample, TEM provides detailed images at the atomic or nanometer scale [33]. The electron source, typically a thermionic or field emission filament, generates high-energy electrons that are accelerated through the sample. TEM is capable of analyzing particle shape, grain size, and crystallographic features with exceptional precision. It is an essential tool for investigating the fine structural properties of nanomaterials.

NANOPARTICLES SYNTHESIS METHODS

Nanoparticles can be synthesized using a variety of methods, generally divided into two broad categories viz., Top-down and Bottom-up means. The top-down approach involves dividing down bulk materials into nanoscale particles, by means of methods like milling, grinding, laser ablation, and nanolithography [34]. While effective, this approach may introduce internal stress, structural defects, and contaminants. The bottom-up approach constructs nanoparticles atom-by-atom or molecule-by-molecule, often resulting in more homogeneous particles with fewer defects. This is a common method for creating nanoparticles for use in polymer composites, as it allows for precise control over size and surface chemistry. Commercial and industrial nanoparticle synthesis typically falls into four main categories: gas-phase processes, liquid-phase methods, sol-gel techniques, and solid-phase mechanical processes. Liquid-phase methods and sol-gel techniques are particularly relevant for producing nanoparticles that can be easily incorporated into polymer solutions or melts [35].

Physical Methods of Nanoparticle Synthesis

These methods utilize heat energy or high-energy radiation to induce condensation, evaporation, abrasion or melting [36]. These solvent-free techniques, generally categorized under the top-down approach, can yield monodisperse nanoparticles. Common methods include laser ablation, laser pyrolysis, physical vapor deposition, and inert gas condensation [37].

Insert Gas Condensation (IGC)

IGC is a versatile method for producing metallic and oxide nanoparticles, composites, semiconductors, and ceramics. Key factors like, chamber pressure, inert gas flow and temperature influence particle size and quality [38]. This method has been effectively used to synthesize size-controlled silver and copper nanoparticles, as well as multi-core shell nanoparticles, making it highly effective for producing high-quality nanomaterials [39].

Laser Ablation

It is also known as Pulsed Laser Deposition (PLD) and it is used to high-energy laser to evaporate material from a solid target. It is a vacuum-based PVD technique, used to create colloidal zinc nanoparticles and photoluminescent Pbs nanoparticles in an amorphous SiO_2 matrix [40]. The wavelength of the laser plays a critical role in controlling particle size and distribution. This method can also synthesize carbon nanotubes [41].

Physical Vapor Deposition (PVD)

PVD is an atomic-level thin-film coating process involving material vaporization and re-deposition. As a “green engineering” process, it generates minimal pollution [41]. PVD methods are widely used to enhance metal rigidity, oxidation and wear resistance and also, to fabricate quantum dots and nanoparticles for electronics and optoelectronics [42].

Laser Pyrolysis

It is a vapor-phase method where a CO_2 laser decomposes gaseous or liquid reactants to form nanoparticles. As the solvent in sprayed droplets evaporates, solute concentration rises, forming solid nanoparticles. It has been used to produce molybdenum disulfide, silicon carbide, TiO/SiO_2, and other oxide, carbide, nitride, and composite nanoparticles for energy and conservation applications [43].

Chemical Methods of Nanoparticle Synthesis

These methods involve reducing agents to form metallic colloids. Stabilizing agents like PEG, PVP, PMMA and PMAA are essential to prevent agglomeration. Techniques under this method include, microwave-assisted or solvothermal or hydrothermal synthesis, polyol process, microemulsion method, sol-gel method and chemical vapor synthesis. These are considered bottom-up approaches [44].

Chemical Vapor Synthesis (CVS)

This is a high-temperature process forms thin films or ultrafine particles from vapor-phase precursors. Metal-Organic-CVD enables the controlled formation of Ni/NiO nanostructures. Advantages include low equipment cost and tunable parameters, such as temperature, precursor concentration and residence time, typically yielding particles around 20 [45].

Hydrothermal Synthesis

Hydrothermal synthesis produces hydrophilic or hydrophobic nanoparticles with controlled morphology. This can be done in batch or continuous systems. At temperatures like 150 °C, nanoparticles smaller than 10 nm have been created. The method allows control over particle size, surface chemistry, morphology and crystalline phase by adjusting temperature, pressure and solution composition [46].

Sol-Gel Method

This method creates metal oxides from chemical precursors, such as metal chlorides and alkoxides. It involves hydrolysis and polymeric condensation reactions to form a gel. The method allows for film deposition via dip or spin coating, or formation of microspheres or nano powders. Fe_3O_4 nanoparticles with near-spherical morphology were successfully synthesized under vacuum using this method [47].

Solvothermal Synthesis

It is like hydrothermal synthesis but allows solvents other than water [48]. It offers fine control over size, shape and crystallinity. The technique has been used to produce nanoparticles like $MgMn_2O_4$ spinel for battery applications and nickel nanoparticles at low temperatures [49].

Microemulsion Technique

This technique is used to create inorganic nanoparticles, such as metal and its oxide, and semiconducting nanoparticles. Microemulsions are thermally stable, optically transparent, and isotropic dispersions [50]. Using water-in-oil or oil-in-water systems, ZnO nanoparticles with Wurtzite structure and stable SiO_2 nanoparticles have been synthesized. Combining reverse microemulsion and calcination yields well-crystallized, size-controlled nanoparticles [51].

Biological Methods

These methods due to their environmental friendliness utilize lower energy consumption and produce potential for scalability. These green approaches leverage biological entities to drive the reduction and stabilization processes required to form the nanoparticles or the composite matrix. The biological synthesis route specifically utilizes microorganisms, such as bacteria, fungi, and algae, or plant extracts rich in biomolecules like polyphenols, flavonoids, and proteins [52–55]. These methods are increasingly favored for producing biocompatible composites for biomedical applications like drug delivery or antimicrobial coatings.

APPLICATIONS OF NANOPARTICLES IN POLYMER COMPOSITES

Nanoparticles have a wide range of uses across multiple fields due to their specific properties at the nanoscale (Table 1). Their integration into polymer and macromolecule-based composites leverages these properties to enhance material performance.

Drug Delivery

Organic nanoparticles, such as liposomes and polymeric nanoparticles, are used to encapsulate therapeutic agents for targeted drug delivery, minimizing side effects and increasing treatment efficacy. Their biocompatibility and biodegradability make them ideal for creating drug-loaded polymer composites for controlled release [63].

Materials Science

The integration of nanoparticles into composite materials improves mechanical strength, thermal conductivity and optical properties, driving innovation in material design. For example, carbon-based nanomaterials like carbon nanotubes and graphene are added to polymers to create composites with improved electrical conductivity and tensile strength [64].

Table 1. Comparative analysis of nanoparticles: physical dimensions, structural characteristics and functional applications.

Nanoparticles	Size (nm)	Structural properties	Applications	References
Carbon Nanotube	2-100	Single-walled nano tube and multi-walled nanotubes	Drug delivery and anti-cancer, high thermal conductivity etc	[56]
Liposomes	100-200	Lipid bi-layer globules	Hydrophilic and hydrophobic drug delivery	[57]
Nanosphere	100-150	Spherical shape	Tissue regeneration and drug delivery, Anti Alzheimer activity etc	[56]
Polymeric Nanoparticles	1-1000	Polymers as chitosan, PLGA	Biocompatibility, biodegradability and non-toxicity, Tissue regeneration etc	[58]
Fullerene	1	Cage structure, including spherical, ellipsoidal structure	Medicine, catalysis and anti-oxidants	[59]
Graphene	0.345	Carbon atom form layer of hexagonal rings in a single layer	Composites, polymer additives and sensors	[60]
Carbon Nanofibers	50-500	Nano Fiber wall density, catalyst, outer Diameter and inner diameter	Photocatalytic, Nanocomposites, sensors and drug delivery	[61]
Carbon black	10-500	Amorphous carbon, high surface area	Colouring, reinforcing and conductive property	[62]

Electronics

Nanoparticles contribute to smaller, faster, and more efficient electronic devices. When incorporated into polymer matrices, metallic nanoparticles can enhance sensor sensitivity due to their electrical conductivity.

Catalysis

The wide surface area and tunable catalytic activity of nanoparticles make them critical for accelerating chemical reactions. Nanoparticles embedded in a polymer matrix can act as stable and recoverable catalysts for industrial processes. The continued advancement in nanoparticle synthesis and characterization is expanding their potential, promising further breakthroughs across science and industry, particularly in the development of advanced polymer composites.

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