International Journal of Pharmacy and Pharmaceutical Research (IJPPR)
Volume 32, Issue 5, May 2026 **ijppr.humanjournals.com** ISSN: 2349-7203

Emerging Trends in Nanotechnology: Nanoparticles for Drug Delivery and Beyond

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Received: 22 March 2026 Revised: 15 April 2026 Accepted: 23 April 2026

ABSTRACT:

Nanoparticles are nanoscale carriers widely explored for targeted and controlled drug delivery due to their unique physicochemical properties and high drug-loading potential. They enable site-specific delivery, protect therapeutic agents from degradation, and allow programmable release profiles to enhance treatment efficacy while reducing systemic toxicity. Nanoparticles are broadly classified into organic, inorganic, and carbon-based systems, each offering distinct structural and functional advantages. Their synthesis involves top-down and bottom-up approaches, including sol–gel, chemical vapor deposition, biosynthesis, and mechanical milling. Polymeric carriers and suitable adjuvants play a crucial role in nanoparticle formulation and stability. Advanced characterization techniques are employed to evaluate size, morphology, surface charge, and hydrophobicity. Despite advantages such as sustained release and multi-route compatibility, challenges including aggregation and toxicity remain. Overall, nanoparticles demonstrate extensive applications across medicine, cosmetics, environmental remediation, energy, food packaging, and electronics, highlighting their significance in modern nanotechnology.

Keywords: Nanoparticles, Nanocarriers, Organic nanoparticles, Inorganic nanoparticles, Carbon-based nanoparticles, Synthesis methods, Characterization techniques, Biocompatible polymers, Nanotechnology applications, Toxicity and safety.

INTRODUCTION:

Nanoparticles are particulate dispersions or solid structures typically ranging in size from 10 to 1000 nm. Within these systems, a drug may be dissolved, entrapped, encapsulated, or bound to the nanoparticle matrix. The primary objectives in the design of nanoparticle-based drug delivery systems are to regulate particle size, surface characteristics, and drug release profiles, thereby enabling site-specific delivery of therapeutically active agents at an optimal rate and dosage[1].

Despite their nanoscale size and invisibility to the naked eye, nanoparticles can effectively protect drugs from degradation while enabling controlled release. Nanoparticle-based delivery systems facilitate targeted transport of therapeutic agents to specific tissues and organs. Moreover, drugs encapsulated within nanoparticles can be released in predefined patterns, such as immediate, sustained, burst, pulsatile, or modulated release, allowing precise control over delivery rates[2].

Nanoparticles play a significant role in targeted drug delivery, as they share several advantages with liposomes, particularly their favourable particle size. However, unlike liposomes, nanoparticles exhibit greater physicochemical stability, longer shelf life, and generally possess a higher drug-loading capacity[3].

Nanoparticles exhibit greater stability compared with liposomes. Owing to their small particle size, nanoparticle-based colloidal systems are well suited for parenteral administration and can function as sustained-release injectable formulations for targeted delivery to specific organs or sites of action. Targeted drug delivery enhances therapeutic efficacy while allowing a reduction in the administered dose required to achieve the desired therapeutic effect, thereby minimizing systemic toxicity and adverse effects[4].

On the basis of dimensions NPs can be classified into[5]:

TABLE 1: Classification of NPs

Dimensionality	Description	Representative Example
Zero-dimensional (0D)	All three dimensions (length, breadth, and height) are confined to a single point	Nanodots
One-dimensional (1D)	One dimension is extended, while the other two are confined	Graphene
Two-dimensional (2D)	Two dimensions (length and breadth) are extended	Carbon nanotubes
Three-dimensional (3D)	All three spatial dimensions (length, breadth, and height) are well defined	Gold nanoparticles

Nanoparticles (NPs) can exist in a wide range of sizes, shapes, and structural forms, including spherical, cylindrical, tubular, conical, hollow-core, spiral, planar, and wire-like morphologies, and may also exhibit irregular geometries. The surface characteristics of NPs can be either uniform or heterogeneous. Additionally, nanoparticles may occur in crystalline or amorphous states, existing as single-crystalline or polycrystalline solids; polycrystalline structures may be loosely aggregated or densely agglomerated. The physicochemical properties of nanoparticles are largely governed by variations in their size and shape. Owing to their distinctive physical and chemical characteristics, NPs have found extensive applications across diverse fields, including medicine, environmental science, energy research, imaging, chemical and biological sensing, and gas sensing technologies. Consequently, nanotechnology has attracted considerable research interest and is widely regarded as a key contributor to a clean and sustainable future[6].

STRUCTURE OF NANOPARTICLES:

Nanoparticles (NPs) possess a complex, multilayered structure typically consisting of two or three distinct components:

(i) A surface layer, which may be functionalized with various small molecules, metal ions, surfactants, or polymers.

(ii) A shell layer, which can be intentionally introduced and is chemically distinct from the core.

(iii) The core material, which forms the central region of the nanoparticle. The characteristic properties of NPs are primarily governed by the core material[7].

Consequently, nanoparticles are commonly referred to according to their core composition[8].

CLASSIFICATION OF NANOPARTICLES:

The nanoparticles are generally classified as organic, inorganic, and carbon-based.

A. Organic Nanoparticles:

Organic nanoparticles are the solid particles composed of organic compounds such as lipids or polymers with a diameter in the range of 10 nm to 1 μm[6].

Dendrimers, micelles, liposomes, ferritin, and related systems are commonly classified as organic or polymer-based nanoparticles. These nanoparticles are generally biodegradable and non-toxic. Certain nanostructures, such as micelles and liposomes, possess a hollow core (Figure 1) and are therefore referred to as nanocapsules. Additionally, these nanoparticles are sensitive to thermal and electromagnetic stimuli, including heat and light. These properties make organic nanoparticles well suited for drug delivery applications. Their drug-loading capacity, stability, and mode of drug incorporation (encapsulation or surface adsorption), together with intrinsic characteristics such as size, composition, and surface morphology, govern their performance and application potential. Consequently, organic nanoparticles are extensively used in biomedical fields, particularly for targeted drug delivery, enabling efficient and site-specific drug administration[8](Table1).

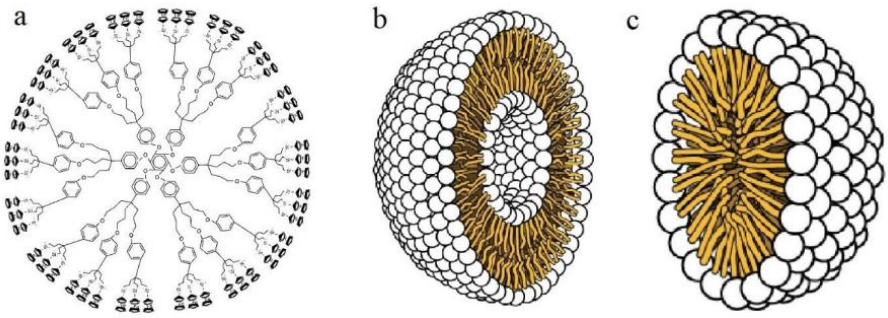


Figure 1. Organic nanoparticles: a- Dendrimers, b- Liposomes and c- miscelles[8].

B. Inorganic Nanoparticles:

Inorganic nanoparticles are nanostructures that do not contain carbon as a primary component. They are typically composed of metals or metal oxides and are therefore commonly classified as metal and metal-oxide based nanoparticles.

Metal based:

Metal-based nanoparticles are produced by reducing bulk metals to the nanometer scale using either top-down (destructive) or bottom-up (constructive) synthesis approaches. Nearly all metals can be fabricated in nanoparticulate form. Commonly utilized metals for nanoparticle synthesis include aluminium (Al), cadmium (Cd), cobalt (Co), copper (Cu), gold (Au), iron (Fe), lead (Pb), silver (Ag), and zinc (Zn).

Metal oxides based:

Metal oxide–based nanoparticles are synthesized to enhance or modify the properties of their corresponding metal nanoparticles. Common examples include aluminum oxide (Al_2O_3), cerium oxide (CeO_2), iron oxide (Fe_2O_3), magnetite (Fe_3O_4), silicon dioxide (SiO_2), titanium dioxide (TiO_2), and zinc oxide (ZnO). Compared with their metallic counterparts, these nanoparticles exhibit superior and distinct physicochemical properties[9].

C. Carbon Based Nanoparticles:

Nanoparticles composed primarily of carbon are referred to as carbon-based nanoparticles. These nanoparticles can exist in various morphologies, including tubular, horn-like, spherical, and ellipsoidal forms. The two major classes of carbon-based nanoparticles are fullerenes and carbon nanotubes (CNTs). Additional carbon-based nanomaterials include graphene, carbon nanofibers, and carbon black[10].

1. Fullerenes:

Fullerenes (C_{60}) are spherical carbon nanostructures composed of carbon atoms bonded through sp^2 hybridization. These structures typically consist of approximately 28 to 1500 carbon atoms, forming closed cages with diameters of up to about 8.2 nm for single-layer fullerenes and ranging from approximately 4 to 36 nm for multilayered fullerenes.

2. Graphene:

Graphene is a two-dimensional allotrope of carbon consisting of a hexagonal honeycomb lattice of carbon atoms arranged in a planar structure. The thickness of a graphene sheet is approximately 1 nm.

3. Carbon Nano Tubes (CNT):

Carbon nanotubes (CNTs) are cylindrical nanostructures formed by rolling a graphene sheet with a hexagonal honeycomb lattice into hollow tubes. Single-walled CNTs typically have diameters as small as ~0.7 nm, while multi-walled CNTs can reach diameters of up to ~100 nm, with lengths ranging from a few micrometres to several millimetres. The tube ends may be either open or capped by hemispherical fullerene structures.

4. Carbon Nanofiber:

Carbon nanofibers are also derived from graphene nanofoils, similar to carbon nanotubes; however, in this case, the graphene sheets are arranged in conical or cup-like structures rather than forming uniform cylindrical tubes.

5. Carbon black:

This amorphous carbon material consists of spherical particles with diameters ranging from approximately 20 to 70 nm. Owing to strong interparticle interactions, these particles readily bind together, forming aggregates and agglomerates with sizes of up to about 500 nm[11].

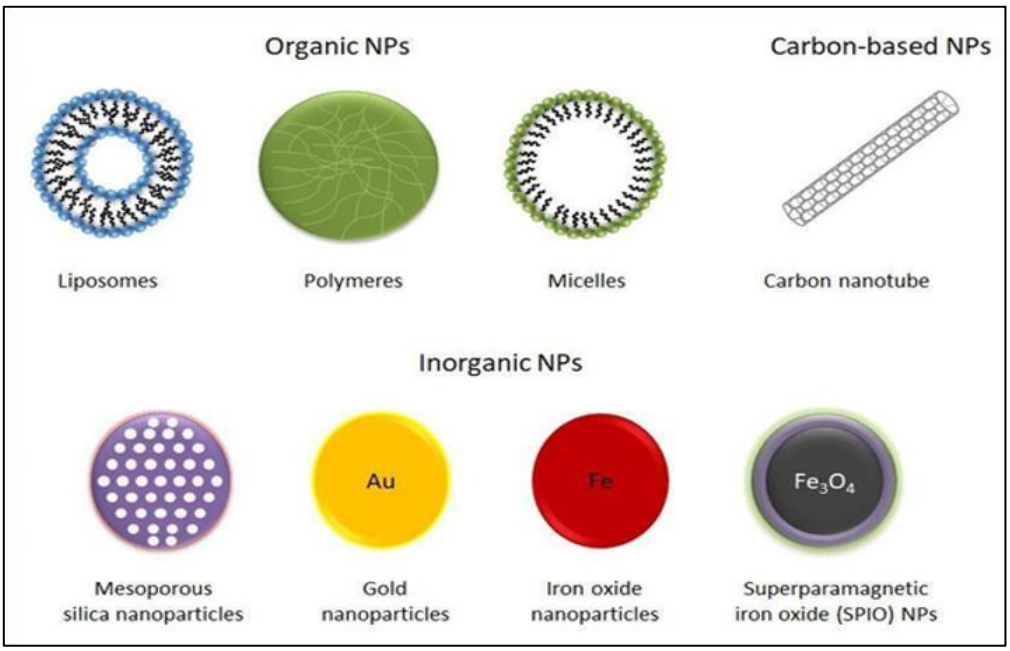


Figure 2: Types of Nanoparticles.

SYNTHESIS OF NANOPARTICLES:

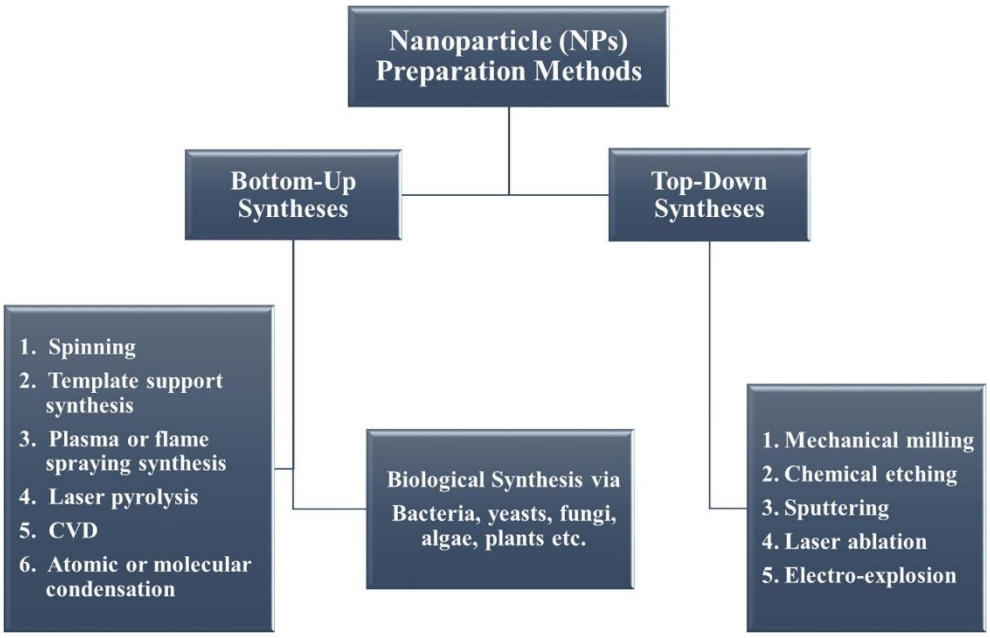
Various techniques are available for the synthesis of nanoparticles (NPs), which are broadly classified into two main categories:

(i) Bottom-up

(ii) Top-down approaches.

These approaches are further subdivided into several subclasses depending on the operational methods, reaction conditions, and synthesis protocols employed[12].

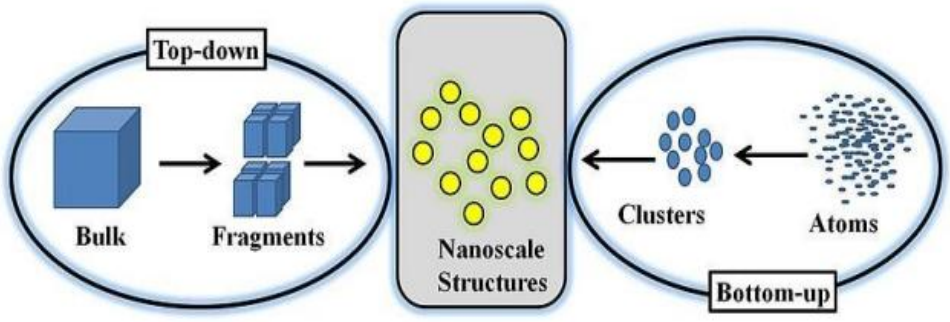
International Journal of Pharmacy and Pharmaceutical Research (IJPPR)
Volume 32, Issue 5, May 2026 ijppr.humanjournals.com ISSN: 2349-7203



Scheme 1. Typical synthetic methods for NPs for the (a) top-down and (b) bottom-up approaches[13].

A. Top-Down Approach:

The top-down approach involves the reduction of bulk materials into nanoscale particles and is therefore considered a destructive method. This approach is relatively simple and relies on the removal, division, or miniaturization of bulk materials or fabrication processes to obtain nanostructures with desired properties. Common top-down techniques for nanoparticle synthesis include mechanical milling, nanolithography, laser ablation, sputtering, and thermal decomposition.



Scheme 2. Schematic representation of Top- down approach & Bottom-up approach.

B. Bottom- Up Approach:

The bottom-up, or constructive, approach is an alternative synthesis strategy in which nanoparticles are assembled from atomic or molecular precursors through the formation of clusters. This approach typically involves processes such as reduction and sedimentation. Compared with top-down methods, the bottom-up approach is generally more economical, as it has the potential to generate less material waste. Commonly employed bottom-up techniques include sol–gel processing, spinning methods, green synthesis, chemical vapor deposition (CVD), pyrolysis, and biosynthesis[6].

Bottom-up method:

The bottom-up or constructive approach involves assembling materials starting from individual atoms, progressing through clusters, and finally forming nanoparticles. Commonly used bottom-up techniques for nanoparticle synthesis include sol-gel processing, spinning, chemical vapor deposition (CVD), pyrolysis, and biosynthesis.

Sol-gel:

A *sol* is a colloidal suspension in which solid particles are dispersed in a liquid medium, whereas a *gel* is a semi-solid network structure in which a liquid is trapped within a solid matrix. The sol-gel method is one of the most widely used bottom-up techniques due to its simplicity and versatility, allowing the synthesis of a wide range of nanoparticles. This wet-chemical process uses a precursor solution to form an interconnected system of fine particles. Metal oxides and chlorides are commonly employed as precursors in the sol-gel process. The precursor is dispersed in a suitable solvent through stirring, shaking, or sonication, resulting in a mixture containing both liquid and solid phases. Nanoparticles are then separated using techniques such as sedimentation, filtration, or centrifugation, followed by drying to remove residual moisture[15].

Spinning.:

Nanoparticle synthesis using the spinning method is typically performed in a spinning disc reactor (SDR). This system consists of a rotating disc housed within a reaction chamber, where key operating parameters such as temperature can be precisely controlled. The reactor environment is commonly purged with nitrogen or other inert gases to eliminate oxygen and prevent unwanted chemical reactions during the synthesis process[16]. The disc is rotated at controlled speeds while the liquid reactants, including the precursor solution and water, are continuously introduced. The centrifugal forces generated during rotation promote molecular interactions and nucleation, leading to particle formation. The resulting nanoparticles are subsequently precipitated, collected, and dried. Key operational parameters such as liquid flow rate, disc rotational speed, precursor-to-solvent ratio, feed injection position, and disc surface properties play a crucial role in determining the size, morphology, and overall characteristics of nanoparticles synthesized using the SDR system[17].

Chemical Vapour Deposition (CVD):

Chemical vapor deposition (CVD) is a process in which thin films are formed by depositing gaseous reactants onto a substrate surface. The deposition takes place within a reaction chamber, where gas-phase precursors are introduced and transported to the substrate. When these combined gases come into contact with a heated substrate, a chemical reaction is initiated, resulting in the formation of a solid film on the substrate surface[18]. This reaction results in the formation of a thin product film on the substrate surface, which is subsequently collected for further use. Substrate temperature is a critical parameter influencing the efficiency and quality of the CVD process. The major advantages of CVD include the production of highly pure, uniform, mechanically robust, and structurally stable nanoparticles. However, the process requires specialized equipment, and the gaseous by-products generated during deposition are often hazardous and toxic in nature[19].

Pyrolysis:

Pyrolysis is one of the most widely employed industrial techniques for the large-scale production of nanoparticles. This method involves the thermal decomposition of a precursor using a high-temperature flame. The precursor, supplied in either liquid or vapor form, is injected into a furnace under high pressure through a narrow inlet, where it undergoes combustion[20]. The resulting product and by-product gases are subsequently subjected to air classification to recover the synthesized nanoparticles. In some systems, alternative heat sources such as lasers or plasma are used instead of conventional flames to achieve the high temperatures required for efficient precursor evaporation. Pyrolysis offers several advantages, including operational simplicity, high efficiency, cost-effectiveness, continuous processing capability, and high production yield[21].

Biosynthesis:

Biosynthesis is a sustainable and environmentally friendly approach for nanoparticle production, offering the advantages of non-toxicity and biodegradability[22]. This method employs biological resources such as bacteria, plant extracts, and fungi in combination with precursor materials to facilitate nanoparticle formation, replacing conventional chemical agents used for bio-reduction and stabilization. Biosynthesized nanoparticles exhibit unique and enhanced physicochemical properties, making them particularly suitable for various biomedical applications[23].

Top-down method:

The top-down, or destructive, approach involves the breakdown of bulk materials into particles with nanometer-scale dimensions. Commonly employed top-down techniques for nanoparticle synthesis include mechanical milling, nanolithography, laser ablation, sputtering, and thermal decomposition[8].

Mechanical milling:

Among the various top-down techniques, mechanical milling is the most widely utilized method for the synthesis of different types of nanoparticles. This process involves the milling and post-annealing of materials under an inert atmosphere, during which multiple elemental components are mechanically processed to form nanoparticles. Key mechanisms influencing the milling process include plastic deformation, which affects particle morphology; fracture, which contributes to particle size reduction; and cold welding, which can lead to an increase in particle size[24].

Nanolithography:

Nanolithography refers to the fabrication of structures at the nanometer scale, with at least one dimension ranging between 1 and 100 nm. Several nanolithography techniques have been developed, including optical lithography, electron-beam lithography, multiphoton lithography, nanoimprint lithography, and scanning probe lithography[25]. Lithography is a patterning technique in which predefined shapes or structures are transferred onto a light-sensitive material, enabling selective material removal to achieve the desired geometry. One of the key advantages of nanolithography is its ability to fabricate individual nanoparticles or nanoparticle assemblies with precise control over shape and size. However, the method is limited by the need for sophisticated instrumentation and the high operational and fabrication costs involved[26].

Laser ablation:

Laser Ablation Synthesis in Solution (LASiS) is a widely used technique for producing nanoparticles in various solvent environments. In this process, a laser beam irradiates a metal target submerged in a liquid medium, generating a plasma plume that subsequently cools and condenses to form nanoparticles. LASiS is a reliable top-down approach that serves as an alternative to conventional chemical reduction methods for the synthesis of metal-based nanoparticles[27]. Furthermore, the method enables stable nanoparticle formation in both organic solvents and aqueous media without the need for additional stabilizing agents or chemical additives, making it an environmentally friendly or “green” synthesis technique.

Sputtering:

Sputtering is a physical vapor deposition technique in which atoms are ejected from a target material through ion bombardment and subsequently deposited onto a substrate surface to form nanoparticles. The process generally involves thin-film deposition followed by thermal annealing to promote nanoparticle formation and structural reorganization[28]. Critical parameters, including deposited film thickness, annealing temperature and duration, substrate type, and processing conditions, strongly influence the size, shape, and distribution of the resulting nanoparticles.

Thermal decomposition:

Thermal decomposition is an endothermic process in which chemical compounds are broken down into simpler components through the application of heat[9]. The temperature at which a compound undergoes chemical breakdown is referred to as its decomposition temperature. In nanoparticle synthesis, metal precursors are thermally decomposed at specific temperatures, leading to chemical reactions that generate nanoparticles along with secondary by-products. Table 2 summarizes selected nanoparticles synthesized using these methods.

Table 2. Categories of the nanoparticles synthesised from the various methods.

Category	Method	Nanoparticles
Bottom-up	Sol-gel	Carbon, metal and metal oxide based
	Spinning	Organic polymers
	Chemical Vapour Deposition (CVD)	Carbon and metal based
	Pyrolysis	Carbon and metal oxide based
	Biosynthesis	Organic polymers and metal based
Top-down	Mechanical milling	Metal, oxide and polymer based
	Nanolithography	Metal based
	Laser ablation	Carbon based and metal oxide based
	Sputtering	Metal based
	Thermal decomposition	Carbon and metal oxide based

CARRIERS USED IN PREPARATION OF NANOPARTICLES:

Polymers used in drug delivery systems must exhibit physiological compatibility, including non-toxicity and non-antigenicity, and should possess biodegradable and biocompatible properties. Polymeric drug carriers facilitate targeted drug delivery to tissue sites through several physicochemical mechanisms. These include:

(1) Hydration-induced swelling of polymer nanoparticles followed by drug release via diffusion.

(2) Enzymatic degradation or cleavage of the polymer matrix at the delivery site, leading to the release of the encapsulated drug from the core.

(3) Dissociation of the drug from the polymer matrix and subsequent desorption or release from the swollen nanoparticles[30].

Polymers employed in nanoparticle fabrication are macromolecular materials that may be derived from natural amphiphilic sources, synthetic hydrophobic polymers, or chemically synthesized compounds. Many of these polymers were initially developed for biomedical applications and have therefore been extensively evaluated for their safety, biocompatibility, and biodegradability. Both natural hydrophilic and synthetic hydrophobic polymers are widely utilized in nanoparticle preparation. Among natural polymers, biopolymers—particularly polysaccharides—have attracted significant interest in drug delivery applications due to their favourable biocompatibility, biodegradability, hydrophilicity, and protective properties (Barichello JM, 1999). Furthermore, interactions between biodegradable cationic and anionic biopolymers result in the formation of polyelectrolyte hydrogels, which exhibit advantageous characteristics for efficient drug encapsulation and controlled release (Chella F, 2000). Notably, chitosan and alginate have received considerable attention owing to their ability to preserve structural integrity, retain biological activity, and protect encapsulated compounds from enzymatic degradation[31].

Table 3: Polymers used for the preparation of nanoparticles

Sl/No	Synthetic polymers	Natural polymers
1.	Poly (E caprolactone) (PECL)	Gelatin
2.	Poly (Lactic acid) (PLA)	Albumin
3.	Poly (Lactide-co-glycolide) (PLGA)	Lectins
4.	Polystyrene	Alginate
5.	Poly hexyl cyanoacrylate (PHC)	Dextran
6.	Poly butyl cyanoacrylate (PBC)	Chitosan
7.	Poly methyl methacrylate (PMM)	Agarose

ADJUVANT USED IN THE PREPARATION OF NANOPARTICLES:

- Cross linking agent – gluteraldehyde
- Desolvating agents – sodium sulphate, ethanol, isopropyl alcohol
- Counter ions – tripolyphosphate Surfactants – tween-80, span-80

- Stabilizer – poly vinyl alcohol
- Solvents – methanol, isopropyl alcohol, chloroform, dichloromethane, water etc[32].

CHARACTERIZATION OF NANOPARTICLES:

Nanoparticles are routinely characterized based on key physicochemical properties such as particle size, density, electrophoretic mobility, contact angle, and specific surface area using advanced analytical techniques including scanning electron microscopy (SEM), transmission electron microscopy (TEM), and atomic force microscopy (AFM). Parameters such as particle size distribution, mean particle diameter, and surface charge strongly influence the physical stability, dispersion behaviour, and in vivo performance of nanoparticle systems. In particular, surface charge plays a critical role in colloidal stability, redispersibility of polymeric formulations, and biological interactions. Furthermore, electron microscopy techniques provide valuable insights into nanoparticle morphology, which is an important determinant of cellular uptake and potential toxicity.

1. **Size and Morphology:**

Particle size is one of the most critical characteristics influencing nanoparticle performance, biodistribution, and cellular interaction. Photon correlation spectroscopy and electron microscopy are the primary techniques used to determine particle size distribution. Electron microscopy methods include SEM, TEM, and freeze-fracture analysis. AFM has also been widely applied for nanoscale surface imaging and morphological characterization of polymeric nanoparticles such as poly(lactic acid) (PLA) nanospheres. In addition, mercury porosimetry is employed for estimating the size and porosity of nanoparticulate systems.

2. **Surface Charge and Electrophoretic Mobility:**

The surface charge of nanoparticles significantly affects their interaction with biological environments and electrostatic binding with therapeutic molecules. Surface charge is commonly evaluated by measuring particle velocity under an applied electric field. Laser Doppler velocimetry, a laser light scattering technique, enables rapid and high-resolution measurement of electrophoretic mobility. This parameter is typically determined in phosphate-buffered saline (PBS, pH 7.4) and human serum to simulate physiological conditions. The zeta potential is subsequently calculated using the Helmholtz–Smoluchowski equation and serves as a key indicator of colloidal stability and nanoparticle biodistribution.

3. **Density:**

Nanoparticle density is measured using gas pycnometry, with helium or air commonly employed as displacement gases. Variations between density values obtained using different gases are attributed to differences in nanoparticle surface area and internal porosity.

4. **Surface Hydrophobicity:**

Surface hydrophobicity is an important parameter influencing protein adsorption, cellular interaction, and biological performance of nanoparticles. It can be evaluated using methods such as biphasic partitioning, hydrophobic interaction chromatography, contact angle measurements, and probe adsorption techniques. In addition, X-ray photoelectron spectroscopy allows identification of specific chemical functional groups present on nanoparticle surfaces, providing valuable information regarding surface composition and functionality[33].

ADVANTAGES OF NANOPARTICLES:

The use of nanoparticles as drug delivery systems offers several significant advantages.

a) The particle size and surface properties of nanoparticles can be precisely engineered to enable both passive and active targeting following parenteral administration.

b) Nanoparticles provide controlled and sustained drug release during circulation and at the target site, thereby modifying drug biodistribution and clearance profiles, which enhances therapeutic efficacy while minimizing adverse effects.

c) Site-specific targeting can be further improved by functionalizing nanoparticle surfaces with targeting ligands or by employing magnetic guidance strategies.

d) Drug release kinetics and particle degradation behaviour can be effectively tailored through appropriate selection of matrix materials. In addition, nanoparticles allow high drug loading capacity, and therapeutic agents can be incorporated without chemical modification, thereby preserving their biological activity.

e) These delivery systems are compatible with multiple routes of administration, including oral, nasal, parenteral, intraocular, and other localized delivery pathways[45].

LIMITATIONS OF NANOPARTICLES:

The small particle size and high surface area of nanoparticles can promote aggregation, which complicates handling and formulation stability in both liquid and dry forms. Moreover, these characteristics may lead to reduced drug loading efficiency and undesirable burst release profiles. Such formulation- and stability-related challenges must be addressed before nanoparticle-based delivery systems can be widely adopted for clinical use and commercial development[46].

TOXICITY:

Due to their extremely small size, nanoparticles can readily enter the body through the skin, respiratory system, or gastrointestinal tract and subsequently accumulate in various organs. This accumulation may induce adverse biological effects by altering the physicochemical properties of tissues. In particular, the use of non-biodegradable nanoparticles for drug delivery can result in prolonged retention at the administration site, potentially triggering chronic inflammatory responses. Most nanoparticle-associated toxicological effects have been reported following inhalation exposure, which has been linked to respiratory and cardiovascular complications[47].

APPLICATIONS OF NANOPARTICLES:

Nanoparticles exhibit distinctive physicochemical properties, including electronic and optical characteristics, mechanical strength, magnetic behaviour, and thermal conductivity. These unique features have enabled their widespread application across various fields. Some of the major applications of nanoparticles are discussed in the following sections:

A. Cosmetics and Sunscreens:

Conventional ultraviolet (UV) protection sunscreens often exhibit limited long-term stability during use. In contrast, the incorporation of nanoparticles, particularly titanium dioxide and zinc oxide, offers several advantages. These nanoparticles provide effective UV protection by absorbing and reflecting ultraviolet radiation while remaining transparent to visible light, thereby maintaining cosmetic appeal. As a result, they have been widely incorporated into sunscreen formulations. In addition, iron oxide nanoparticles are commonly used as pigments in cosmetic products such as lipsticks[34].

B. Medicine:

Nanoparticles have made significant contributions to clinical medicine, particularly in medical imaging and drug and gene delivery applications. Iron oxide nanoparticles, such as magnetite (Fe_3O_4) and its oxidized form hematite (Fe_2O_3), are among the most widely used nanomaterials in biomedical applications due to their favorable magnetic properties and biocompatibility. Silver nanoparticles are increasingly incorporated into wound dressings, catheters, and various household products owing to their strong antimicrobial activity. In addition, gold nanoparticles have emerged as promising platforms for cancer therapy, serving as drug delivery vehicles, photothermal agents, imaging contrast enhancers, and radiosensitizer[35]. Over the past few decades, significant interest has been directed toward the development of biodegradable nanoparticles as efficient drug delivery systems. A wide range of polymers have been explored in drug delivery research due to their ability to facilitate targeted drug transport, enhance therapeutic efficacy, and minimize adverse side effects.

C. Environmental Remediation:

Nanoparticles are widely utilized in environmental remediation due to their high versatility in both *in situ* and *ex situ* treatment processes, particularly in aqueous systems. Silver nanoparticles (AgNPs), owing to their strong antibacterial, antifungal, and antiviral activities, have been extensively employed as water disinfectants[36] and in self-cleaning surface applications[37]. In addition, their low cost, low toxicity, semiconducting behaviour, photocatalytic activity, electronic properties, gas-sensing capability, and energy conversion potential further enhance their suitability for environmental and industrial applications.

D. Mechanical Industries:

Due to their excellent Young's modulus and enhanced stress–strain characteristics, nanoparticles have found widespread applications in the mechanical industry, particularly in coatings, lubricants[38], adhesives[39], and the fabrication of mechanically robust nanodevices[40]. For example, a two-step dip-coating approach employing silver nanoparticles (AgNPs) in combination with a fluorine-free silane monomer, 3-(Trimethoxysilyl) propyl methacrylate (TMSPM), has been reported for the fabrication of hydrophobic coatings on cotton fabrics.

E. Food:

Nanoparticles have been increasingly incorporated into food packaging systems to regulate the surrounding atmosphere of packaged products, thereby enhancing freshness and protecting against microbial contamination[41]. In recent years, inorganic and metal nanoparticles have been widely explored as alternatives to conventional petroleum-based plastics in the food packaging industry, as they enable the direct incorporation of antimicrobial agents onto coated film surfaces, improving food safety and shelf life[42].

F. Electronics:

The unique structural, optical, and electrical properties of one-dimensional semiconductor and metallic nanostructures make them fundamental building blocks for the development of next-generation electronic, sensing, and photonic materials.

G. Energy Harvesting:

Due to the increasing scarcity of fossil fuel resources, significant research efforts have been directed toward developing alternative strategies for renewable energy generation using abundant and cost-effective resources. Nanoparticles have emerged as promising candidates for such applications owing to their large surface area, unique optical properties, and high catalytic activity. They are widely employed in photoelectrochemical (PEC) and electrochemical water-splitting systems for sustainable energy production[43]. In addition, advanced energy conversion technologies such as electrochemical CO_2 reduction to fuel precursors, solar cells, and piezoelectric generators have also benefited from nanoparticle-based materials[44]. Furthermore, graphene has been extensively investigated for its potential in energy generation and as a key component in next-generation smart energy storage devices.

CONCLUSION:

Nanoparticles have emerged as highly versatile and efficient platforms for drug delivery and multifunctional applications due to their unique structural, physicochemical, and biological properties. Their ability to enable targeted delivery, controlled release, and enhanced therapeutic efficacy makes them valuable tools in modern medicine. The wide range of nanoparticle types, synthesis techniques, carrier systems, and characterization methods provides flexibility in designing tailored nanocarriers for specific applications. However, challenges such as formulation stability, aggregation, and potential toxicity must be carefully addressed to ensure safe clinical translation. Continued advancements in green synthesis methods, biocompatible materials, and surface functionalization strategies are expected to further improve nanoparticle performance. Overall, nanoparticles hold immense potential to revolutionize healthcare, environmental sustainability, and industrial technologies, contributing significantly to future scientific and technological progress.

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How to cite this article:
Druti S N et al. Ijppr.Human, 2026; Vol. 32 (5): 19-31.
Conflict of Interest Statement: All authors have nothing else to disclose.