INTERNATIONAL JOURNAL OF RESEARCH AND SCIENTIFIC INNOVATION (IJRSI)
ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue IX September 2025

Nanoparticles: Classification, Synthesis, Characterization, and Applications

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DOI: https://doi.org/10.51244/IJRSI.2025.1208004120

Received: 08 Oct 2025; Accepted: 15 Oct 2025; Published: 24 October 2025

ABSTRACT

Objective: This review aims to present a comprehensive overview of nanoparticles, focusing on their classification, physicochemical properties, synthesis methods, characterization techniques, and diverse scientific applications.

Methods: Relevant studies and review articles were collected from major databases such as PubMed, ScienceDirect, SpringerLink, and Scopus. Various chemical, physical, and biological synthesis approaches were analyzed, along with modern characterization techniques such as electron microscopy, spectroscopy, and thermal analysis.

Results: Findings indicate that nanoparticles possess distinctive properties, including high surface-to-volume ratio and tunable morphology, which enhance their efficiency in drug delivery, imaging catalysis, and energy storage. Biologically synthesized nanopartilces demonstrated better biocompatibility and reduced toxicity compared to chemically prepared ones

Conclusion: Nanoparticles represent a rapidly advancing field with vast biomedical and industrial applications. However, biosafety, toxicity, and environmental concerns require further systematic investigation to ensure their safe and sustainable use.

Keywords: Nanoparticles, Synthesis, Characterization, Drug Delivery, Biomedical Applications, Toxicity

ABSTRACT

Nanoparticles, typically defined as particles within the size range of 1–100 nm, have emerged as a pivotal class of materials owing to their distinctive physicochemical characteristics. This review provides a comprehensive overview of nanoparticles, encompassing their classification, physicochemical attributes, methods of synthesis, and diverse applications across scientific and industrial domains. Their unique properties, largely attributed to their nanoscale dimensions and high surface-to-volume ratio, have significantly broadened their utility in fields such as medicine, electronics, energy, and environmental sciences.

Various synthesis approaches—including chemical, physical, and biologically mediated methods—are critically discussed, along with state-of-the-art characterization techniques such as electron microscopy, spectroscopy, and thermal analysis, which enable precise evaluation of nanoparticle structure, morphology, and functionality. While nanoparticles present numerous advantages, challenges related to toxicity, biosafety, and environmental impact remain key considerations that require systematic investigation.

In terms of applications, nanoparticles have demonstrated remarkable potential in drug delivery, diagnostic imaging, environmental remediation, catalysis, and energy storage technologies. Their ability to facilitate targeted therapeutic delivery, enhance imaging resolution, remove environmental pollutants, and improve energy efficiency underscores their transformative role in advancing modern science and technology.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue IX September 2025

In conclusion, nanoparticles represent a rapidly evolving research frontier with significant industrial and biomedical implications. However, continued interdisciplinary efforts are essential to fully exploit their potential while addressing associated safety and regulatory concerns.

INTRODUCTION

Nanotechnology is the branch of science that deals with the study and manipulation of materials at an extremely small scale. The term originates from the Greek word *nanos* (through the Latin *nanus*), meaning "dwarf" or "very small"[4]. Nanoparticles (NPs) exhibit unique physical and chemical characteristics because of their nanoscale size and high surface area. These properties make them highly suitable for diverse applications, including environmental protection, medical diagnostics and therapy, imaging, energy research, and catalysis[2]. Structurally, nanoparticles are complex and typically consist of two to three layers: a functionalized surface layer containing small molecules, polymers, surfactants, or metal ions; a shell layer that is chemically different and can be deliberately introduced; and a core, which represents the fundamental component of the nanoparticle[1]. Their synthesis can be achieved through both chemical and biological methods.

Chemical synthesis of nanoparticles often involves toxic reagents, which can lead to various harmful effects. In contrast, biological synthesis offers a safer and more eco-friendly approach. This method employs microorganisms, enzymes, fungi, or plants and their extracts for nanoparticle production[4].

Nanoparticles serve as the fundamental building blocks of nanotechnology, exhibiting dimensions within the range of 1–100 nm. Depending on their composition, nanoparticles can be derived from a variety of sources, including carbon-based materials, metals, metal oxides, and organic compounds. Their nanoscale size imparts unique structural and functional characteristics that distinguish them from their bulk counterparts and enables their application across diverse scientific and technological domains.

Nanoparticles can exist in multiple shapes and dimensions. Zero-dimensional structures, such as nanodots, are confined at a single point in all directions. One-dimensional materials, like graphene, extend only along one parameter. Two-dimensional structures, such as carbon nanotubes, possess both length and breadth, while three-dimensional nanoparticles, including gold nanoparticles, exhibit all three spatial dimensions.

Nanoparticles are available in a wide range of sizes, shapes, and structural configurations, including spherical, cylindrical, tubular, conical, hollow-core, spiral, and flat morphologies, among others[1]. These diverse geometries significantly influence their physicochemical properties, functionality, and potential applications in various fields.

Nanoparticles (NPs) can be synthesized using three main approaches: physical, chemical, and biological. The physical method is generally categorized as a top-down approach, whereas chemical and biological methods are grouped under the bottom-up approach. The biological route is also widely recognized as the green synthesis method of nanoparticles. Each of these approaches is further divided into specific techniques. Common examples include lithography, chemical vapor deposition, sol–gel process, co-precipitation, hydrothermal synthesis, electrospinning, laser ablation, sputtering, sonication, exploding wire method, and arc discharge technique[27].

Classification of Nanoparticles

Nanoparticles are broadly classified into three major types: organic, inorganic, and carbon-based.

1. Organic nanoparticles

Organic nanoparticles are formed from organic molecules and typically measure below 100 nm in size. They are often referred to as *nano capsules* and are generally non-toxic as well as environmentally friendly. Examples include **ferritin, liposomes, micelles, and dendrimers**, which act as highly sensitive polymers when exposed to heat or light[47].

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A. Dendrimers

Dendrimers are a novel class of polymers with controlled structures and nanometric dimensions. Commonly ranging from **10 to 100 nm**, they possess multiple functional groups on their surface, making them highly suitable for drug delivery and imaging applications. In the pharmaceutical field, dendrimers have been explored as **NSAIDs, antimicrobials, anticancer agents, prodrugs,** applications and as **screening tools in high-throughput drug development**[4].

B. Liposomes

Liposomes are spherical vesicles composed of one or more phospholipid bilayers and are widely explored as drug delivery systems (DDS) in chemotherapy. Their advantages include **easy functionalization, efficient drug encapsulation, biocompatibility,** and **size controllability**. However, despite the potential benefits, their **short circulation half-life** remains a major limitation for clinical, although surface modifications can help overcome this drawback[39]. The structural components of Liposome are illustrated in Figure 1[22]

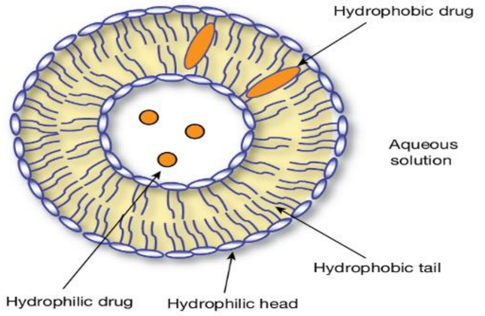

Figure 1 liposome and their structure

2. Inorganic nanoparticles

Inorganic nanoparticles are composed of non-carbon materials such as **metals, metal oxides, and metal salts**. Depending on atomic packing, they can exhibit diverse shapes—including **spheres, cylinders, ellipsoids, cubes, oblate forms, and stars**—while retaining the crystallinity of metal-based compounds[21].

A. Metal based nanoparticles

The synthesis of metal-based nanoparticles to nanometric dimensions can follow either a top-down (destructive) or bottom-up (constructive) approach[2].

B. Gold nanoparticles

Gold nanoparticles are nanometer-sized particles with unique physical and chemical properties that enable them to absorb and scatter visible as well as near-infrared light. They are considered highly stable, non-toxic, and easy to synthesize. Owing to their remarkable characteristics—such as the quantum size effect and the ability to assemble into diverse structures—gold nanoparticles serve as excellent model systems for scientific research[44].

C. Silver nanoparticles

The unique physicochemical properties of silver nanoparticles—such as **electrical and thermal conductivity, catalytic activity,** and **non-linear optical behaviour**—have led to the development of numerous innovative products and scientific applications.[48]

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D. Metal oxide-based nanoparticles

Metal oxide nanoparticles, owing to their small size and **high surface area**, are valuable in various applications such as **biosensors, bionanotechnology,** and **nanomedicine**. Common examples include **copper oxide (CuO), titanium dioxide (TiO_2),** and **zinc oxide (ZnO)**.[43]

E. zinc oxide nanoparticles

ZnO nanoparticles are safe and **biocompatible**, making them ideal for use in textiles and surfaces that contact human skin. They exhibit **antibacterial activity** against both Gram-positive and Gram-negative bacteria, as well as heat- and pressure-resistant spores.[46]

F. Titanium oxide nanoparticles

The antimicrobial activity of TiO_2 nanoparticles is influenced by their **crystal structure, shape, and size**. TiO_2 NPs are particularly responsive to oxidative stress due to the generation of **reactive oxygen species (ROS)**. They have been shown to enhance the effectiveness of antibiotics—such as **beta-lactams, cephalosporins, aminoglycosides, lincosamides,** and **tetracyclines**—against **MRSA**.[43]

3. Carbon-based nanoparticles

They are made of carbon atoms with Sp2 bonds. They include nano-diamonds, nano-horns, nano-onions, grapheme, fullerenes, and single- This includes multi-walled carbon nanotubes, carbon nanofibers, and nanographite. Carbon materials are synthesized using three techniques: chemical vapor deposition, laser ablation, and arch discharge.[21]

A. Carbon-nanotubes

CNTs have high specific surface area and oleophilic characteristics, making them ideal for developing an oil-removing membrane with high penetration flux [30]. Carbon nanotubes come in two sizes: single-walled (0.4–2 nm) and multi-walled (2–100 nm). Carbon nanotubes are composed of enrolled graphite sheets.[41]

B. Graphene

Carbon atoms are grouped hexagonally in a crystalline lattic that resembles A two-dimensional (2D) grapheme represents honeycomb structures with lateral diameters ranging from micro to millimetres. This material features high intrinsic strength, thermal conductivity, biocompatibility, and low toxicity. The most significant benefits for biosensing[49].

C. Fullerenes

Fullerenes are spherical carbon nanoparticles formed through Sp2 hybridization. The process produces round, mono-layered fullerenes up to 8.3 nm and poly-layered fullerenes with diameters ranging from 4-36 nm.[47]

Advantage of Nanoparticles[14]

1. Nanoparticle surface characteristics and particle size can be easily modified to target medicines passively or actively after parenteral administration.

2. Nanosized quantum dots based on immunofluorescence label specific germs for easy identification and removal.

3. Nanotechnology is expanding throughout industries, including aquaculture, with numerous uses in nutrition.

4. Applications include reproduction, water purification, fishing, illness management, and reduced toxicity and negative consequences.

5. Biodegradable nanoparticles allow for prolonged medication release at the target site over days or weeks.

6. Nanoparticles are small enough to pass through tiny capillaries and be absorbed by cells, allowing for effective drug accumulation at target areas.

7. Nanotechnology can improve fabric durability by increasing surface energy and area to volume ratio.

Disadvantage of Nanoparticles[14]

1. Nanoparticles' small size and large surface area make them extremely reactive in the cellular environment.

2. Non-biodegradable particles can collect at drug delivery sites, leading to chronic inflammation.

3. Nanoparticles have limited targeting capabilities, making it unable to terminate the therapy.

4. Nanotechnology is costly, with potential for significantly higher development costs.

5. Atomic bombs are now more accessible, powerful, and destructive to use.

Strategies for the Synthesis of Nanoparticles (NPs)

The synthesis of nanoparticles is generally classified into **two main approaches**: the **bottom-up method** and the **top-down method**.

1. Bottom-Up Method

The **bottom-up** or **constructive approach** involves assembling materials from atoms or molecules into clusters and ultimately into nanoparticles. This method allows precise control over particle size, shape, and composition. The structural components of method is illustrated in fig.2 Some of the most widely used bottom-up techniques for nanoparticle synthesis include:

a. Sol–gel method

b. Chemical vapor deposition (CVD)

c. Pyrolysis

d. Electrospinning

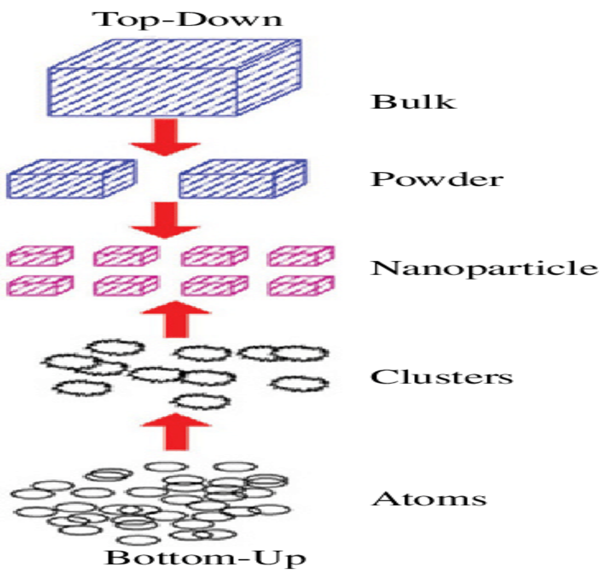

Figure 2 Bottom Method[26]

A. Sol–Gel Method

The sol–gel process is a **wet chemical technique** in which a chemical solution acts as a precursor for forming a network of discrete particles. In this method, a **sol**—a colloidal suspension of solid particles in a liquid—transforms into a **gel**, consisting of solid macromolecules dispersed in a solvent. Commonly, metal oxides and metal chlorides are used as precursors. Upon mixing the precursor with the liquid medium through shaking, stirring, or sonication, a **liquid–solid phase transition** occurs, leading to the formation of nanoparticles[1]. The structural components of method is illustrated in fig.3[28]

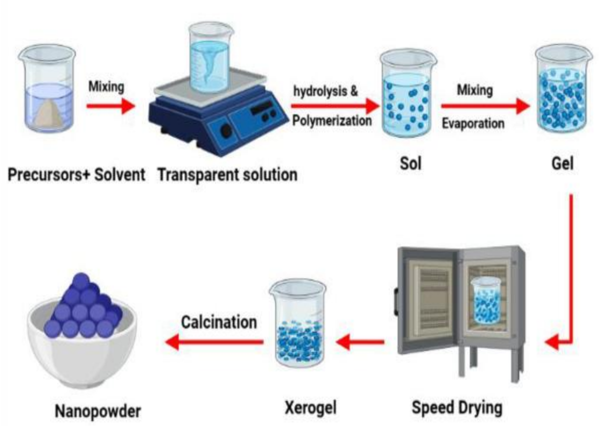

Figure 3 Sole Gel Method

B. Chemical Vapor Deposition (CVD)

Chemical vapor deposition (CVD) is a widely used technique in which a solid material is **deposited onto a heated substrate** through chemical reactions occurring in the gaseous or vapor phase. In **thermal CVD**, the reaction is activated at elevated temperatures, typically above 900 °C. This method has been employed to produce **nanocomposite powders**; for example, a SiC/Si_3N_4 composite powder was successfully synthesized at 1400 °C using SiH_4, CH_4, WF_6, and H_2 as precursor gases[16]. The structural components of method is illustrated in fig.4[31]

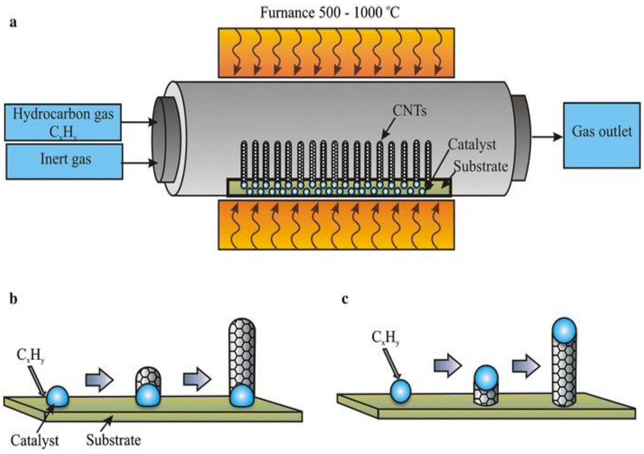

Figure 4 Chemical Vapor Deposition

C. Pyrolysis

In **spray pyrolysis**, a precursor solution is first prepared, typically by dissolving a metal salt in a suitable solvent. This solution is then atomized into fine droplets and introduced into a heated furnace. Inside the furnace, various processes such as **solvent evaporation, solute diffusion, drying, precipitation, reactions between the precursor and surrounding gases, pyrolysis, or sintering** occur, ultimately leading to the formation of fine nanoparticles[17]. The structural components of method is illustrated in fig.5[38]

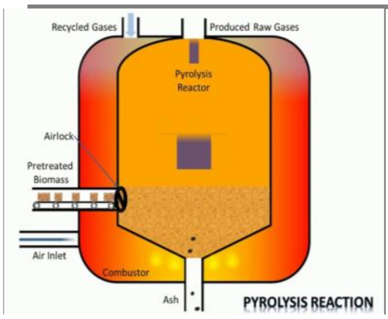

Figure 5 Pyrolysis

D. Spin Coating / Spinning Disc Reactor (SDR) Method

The **spin coating process** involves the uniform deposition of a solution onto a substrate through centrifugal force, producing a constant conversion in the vapor above the substrate. The **evaporation rate** during spin coating is generally uniform, making it a critical step in semiconductor fabrication for creating thin, homogeneous photoresist films.

For nanoparticle synthesis, a **spinning disc reactor (SDR)** incorporates a rotating disc that helps regulate physical parameters such as temperature. To prevent undesired chemical reactions, the reactor is typically filled with inert gases like nitrogen. The precursor solution and water are fed into the SDR, which rotates at controlled speeds, facilitating **fusion, precipitation, collection, and drying** of the nanoparticles. Key factors influencing the synthesis process include **liquid flow rate, disc rotation speed, precursor-to-solvent ratio, feed location, and the characteristics of the disc surface**, all of which allow precise control over nanoparticle formation and properties[18]. The structural components of method is illustrated in fig.6[41]

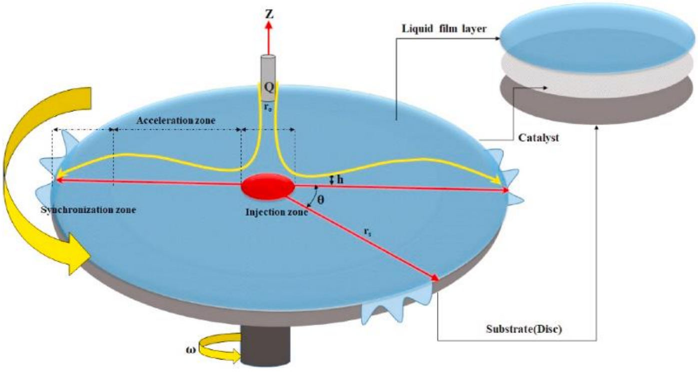

Figure 6 Spin Coating

2. Top-Down Method

The **top-down approach**, also known as destructive synthesis, involves breaking down bulk materials into smaller fragments, which are subsequently converted into nanoparticles. This method is primarily physical and is widely used for large-scale nanoparticle production. The structural components of method is illustrated in figure no.7[44] Common techniques under the top-down approach include:

a. Thermal decomposition method

b. Lithography

c. Laser ablation

d. Sputtering

e. Mechanical milling

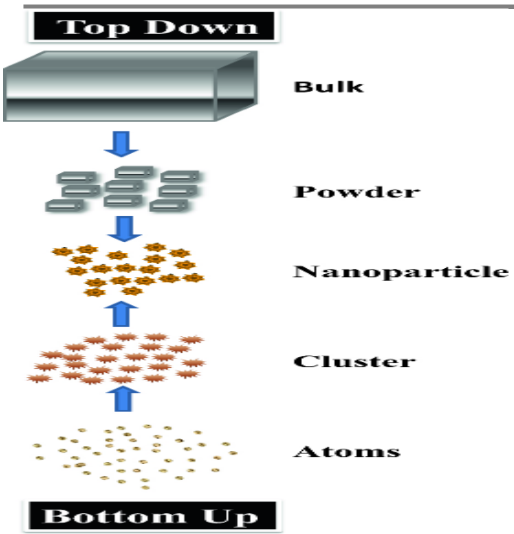

Figure 7 Top-Down Method

A. Thermal Decomposition Method

The **thermal decomposition method** is an endothermic process in which heat induces the chemical breakdown of a compound by disrupting its chemical bonds. The specific temperature at which a substance begins to chemically decompose is referred to as its **decomposition temperature**. This method is commonly employed in nanoparticle synthesis to produce fine, uniform particles through controlled thermal treatment[19].

B. Lithography

Top-down lithographic techniques, either alone or in combination with other fabrication methods such as reactive ion etching (RIE), are widely employed to produce nanoparticles with controlled size and shape. **Photolithography**, a conventional top-down approach, has been extensively developed for the semiconductor industry and other applications requiring precise micro- and nano-patterns. **Ion beam** and **electron-beam (e-beam) lithography** enable direct writing of ultra-small structures with extremely fine patterns, as well as the creation of masks or molds for use in other lithographic processes. However, these techniques are limited by **low throughput and high cost**. **Nanoimprint lithography (NIL)** addresses these limitations by replicating nanostructures from a master mold in a simple, parallel, and cost-effective manner, providing an efficient solution for top-down nanoparticle fabrication[20].

C. Laser Ablation

Laser ablation involves the use of pulsed lasers to remove material from the surface of a substrate, enabling the creation of micro- and nanostructures. This technique is widely applied in the fabrication of **metals, ceramics, polymers, and glasses**. By focusing a laser beam onto the material, energy is absorbed, leading to **melting, evaporation, or ejection of the surface material**. The combined process of vaporization and melt ejection, which occurs consistently during laser machining, defines the mechanism of laser ablation and is integral to nanoparticle production[19].

D. Sputtering

Sputtering is a physical vapor deposition technique in which a target material is bombarded with high-energy inert gas ions, typically argon, causing atoms and clusters to be ejected from the target surface. In this process, a controlled flow of inert gas is introduced into a vacuum chamber, and the cathode is electrically energized to generate a self-sustaining plasma. The ejected material forms a **vapor stream**, which travels through the chamber and deposits onto a substrate, creating a **thin film or surface coating**. This method is widely used for producing nanoparticles and uniform coatings with precise control over thickness and composition[12]. The structural components of **Sputtering** is illustrated in figure no.8

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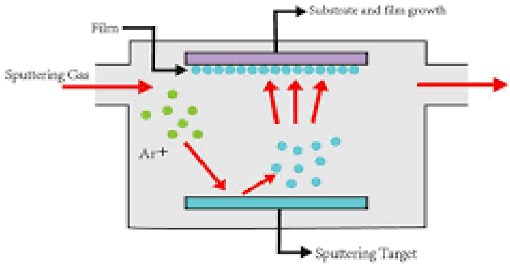

Figure 8 Sputtering

E. Mechanical Milling Method

Mechanical milling involves placing a suitable powder charge with an appropriate milling medium into a high-energy mill. The main aims of this process are particle size reduction and the formation of new phases. During milling, the balls may either fall freely, impacting the powder and other balls, or roll along the chamber surface in layered motion. The extent of energy transferred to the powder depends on the kinetics of the milling or alloying process. This technique is widely utilized in powder metallurgy, mineral processing, and ceramic industries. High-energy ball mills such as tumbler mills, vibratory mills, and planetary ball mills are commonly used for these purposes15. The structural components of Mechanical Milling Method is illustrated in figure no.9[29]

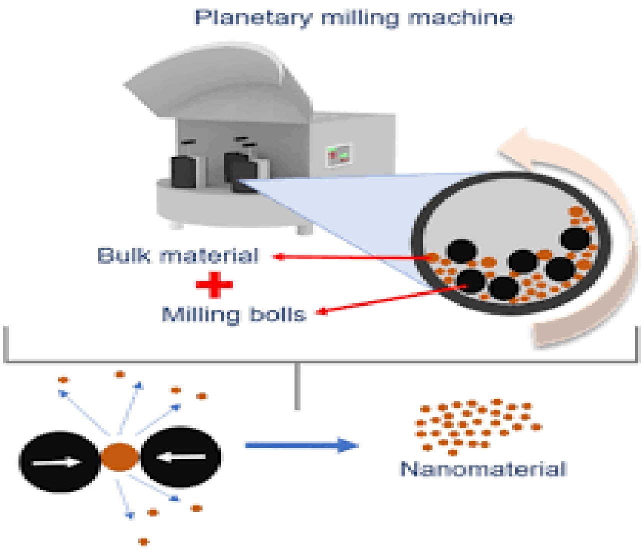

Figure 9 Mechanical Milling Method

Characterization parameters of NPs

Using advanced microscopic techniques such as SEM and TEM, AFM identifies nanoparticles based on their size, shape, and surface charge. The average particle diameter, size distribution, and charge all impact the physical stability and distribution of nanoparticles in living systems. Various technologies, such as nuclear magnetic resonance, optical microscopy, electron microscopy, dynamic light scattering, and atomic force microscopy, are used to determine particle sizes.[26]

1. Nuclear magnetic resonance (NMR)

Nuclear magnetic resonance (NMR) can determine both the size and qualitative features of nanoparticles. Chemical shift provides specific information about the physicochemical status of nanoparticle components, in addition to sensitivity to molecular mobility.[26]

2. Differential scanning calorimetry (DSC)

DSC analysis was performed to assess the physical condition of the medication in nanoparticles. The natural

medication, polymer, and NPs all weighed approximately 2 mg. The sealed standard aluminium pans were heated at 10°C/min under nitrogen environment and scanned between 25°C and 300°C. As a reference, use an empty aluminum pan.[13]

3. Particle size

The particle sizes of NPs were determined using a scanning electron microscope and ranged from 350 nm to 600 nm, depending on the polymer content (35). Particle size and shape are the two most important characteristics for NPs. Nanoformulation is mostly used for drug release and targeted distribution. Data suggests that particles have an impact on the released pharmaceuticals. The loaded medication will be exposed to the particle's surface, resulting in faster drug release. Smaller particles often form foam clumps during storage. Connect stability to reduced particle size. The degradation rate of PLGA increased as particle size increased.[50]

4. Zeta potential

The zeta potential is commonly used to explain the surface charge of nanoparticles. The electrical potential of particles is reflected in the medium in which they are disseminated, influenced by their composition. NPs having a zeta potential exceeding + 30 mV can be suspended due to their surface charge, which precludes aggregation.[51]

5. UV- visible absorption spectroscopy

Absorbance spectroscopy measures a solution's optical properties. The sample solution is lit and the light absorption is measured. Absorbance can be measured at different wavelengths. Beer-Lambert's law can be used to calculate the concentration of a solution based on its absorbance. The UV-visible spectrophotometer measures absorbance at several wavelengths, including 410 nm.[22]

6. Scanning electron microscopy (SEM)

This technique for characterizing NPs provides insights into their morphology, shape, size, chemical content, and orientation. During SEM characterisation, the surface of the sample is measured by secondary and backscattered electrons emitted when the NP solution is turned into dry powder and put on a sample holder. Nanoparticle morphology can be assessed by evaluating surface depression and elevation, as electron release from nanomaterials changes based on surface.[23]

7. Dynamic light scattering (DLS)

The particle size and size distribution of produced particles were analyzed using a particle size analyzer, dynamic light scattering at a fixed angle of 173 at 25°C, and photon correlation spectroscopy. The average volume diameters and polydispersity index were calculated. Samples were analyzed three times.[52]

Method of evaluation for release of drug

The following techniques can be employed to assess the in vitro release of drugs from nanoparticles (NPs):

1. Adjacent diffusion cells utilizing synthetic or natural membranes.

2. Dialysis bag diffusion method.

3. Reverse dialysis bag technique.

4. Agitation followed by centrifugation or ultracentrifugation.

5. Centrifugal ultrafiltration or other ultrafiltration approaches.

Typically, controlled agitation combined with centrifugation is used for release studies. The dialysis method is often favoured because separating nanoparticles from the release medium can be time-consuming and technically challenging. There are five possible mechanisms for drug release: (a) the drug may be adsorbed on the surface, (b) diffusion through the nanoparticle matrix, (c) diffusion through the polymer shell of nano capsules, (d) erosion of the nanoparticle matrix, or (e) a combination of diffusion and erosion. The kinetics of drug release from nanoparticles can be described using a biexponential function: $C = A e^{(-Bt)}$, where C represents the drug concentration remaining in the nanoparticles at time t, and A and B are system-specific constants (A corresponds to diffusion-controlled release, while B relates to erosion-controlled release).

Application of Nanoparticles[25]

Application of nanotechnology in the different field is summarised in table 1

Table 1: Application of nanotechnology in the different field.

Applied Field	Applications / Examples
Chemicals and Cosmetics	Nano medicines, medical devices, tissue engineering; nanoscale chemicals, paints, coatings
Materials	Nanoparticles, carbon nanotubes, biopolymers, paints and coatings
Food Sciences	Processing, nutraceutical food, nanocapsules
Environment & Energy	Water and air purification filters, fuel cells, photovoltaic
Military & Energy	Biosensors, weaponry, sensory improvement
Electronics	Semiconductor chips, memory storage, photonics, optoelectronics
Scientific Tools	Atomic force microscopy, microscopic techniques, scanning tunneling microscopy
Agriculture	Atomic force microscopy, microscopic techniques, scanning tunneling microscopy

Nanoparticles In Drug Delivery System

Nanoparticle drug delivery focuses on maximizing drug efficacy and minimizing cytotoxicity. Fine-tuning nanoparticle properties for effective drug delivery involves addressing the following factors. The surface-area-to-volume ratio of nanoparticles can be altered to allow for more ligand binding to the surface.

Nanocarrier-Based Transdermal Delivery System

Routes of Penetration

Three potential pathways are often used to transport drug molecules across the SC appendageal (transfollicular), transcellular (intracellular), and paracellular (intercellular).

Transcellular Route

In the transcellular pathway, molecules penetrate the matrix (cytoplasm) of dead keratinocytes and the lipids surrounding them, which contain highly hydrated keratin, and drug molecules diffuse alternately in the aqueous and lipid phases. While this is the shortest pathway, molecules need to repeatedly pass through lipophilic cell membranes and aqueous cell contents, which remains challenging for most molecules

Paracellular Route

The intercellular pathway is that in which drug molecules bypass keratinocytes and penetrate the skin through the interstitial of cells tightly packed between keratinocytes. The tiny channels or gaps that form between keratinocytes are mainly composed of lipids and are more permeable compared to lipid-soluble molecules. Since the molecules do not pass directly through the cells, cell damage can be reduced. However, water-soluble molecules do not readily pass through the intercellular matrix composed of lipids, and the natural barrier functions of the skin (e.g., the tight arrangement of the SC and the presence 3 of 35 of a lipid layer) may impede the penetration of certain molecules

Transfollicular Route[53]

The transfollicular route is a strategy for delivering drugs or other substances through hair follicles into the skin, bypassing the stratum corneum. Hair follicles offer a deeper and more efficient pathway into the dermis than the transdermal route, making them ideal for targeting skin conditions like alopecia and acne, or for needle-free vaccination. Nanotechnology can enhance this delivery, and carriers like liposomes and nanoparticles are used to improve drug penetration and release.

Nanocarriers for Transdermal Delivery

Nanocarriers are widely used in topical applications, including vesicular nanocarriers Kneading or slurry method, solution or co-precipitation method, solvent evaporation, dry mixture, damp mixing, extrusion (liposomes, transferosomes), lipid-based nanocarriers (solid lipid nanoparticles, nanostructured lipid carriers), emulsion-based nanocarriers, polymeric nanocarriers, inorganic Cyclodextrins, drugs Significant enhancement of drug solubility and stability Kidney toxicity nanoparticles, and inclusion complexes. Recently, these have been utilized to deliver various drugs via the transdermal route[54].

Transdermal delivery systems also have potential applications in the systemic treatment of psoriasis. To enable effective drug penetration through the hyperkeratotic skin of psoriasis patient and enhance therapeutic efficacy, shen et al.developed HA-modified liposome loaded with MTX and incorporated them into microneedles (HA-MTX-Lipo MNs)[58].The result showed that HA-MTX-Lipo MNS inhibits the progression of psoriasis and reduce erythema scaling, and thickening of the skin by down regulating the expression of mRNA levels of pro-inflammatory cytokines IL-23 and TNF-α shah P et al. used niosomes to deliver desoximeta-sone, which can be used to treat a variety of skin condition such as allergic reactions, eczema, and psoriasis. Desoximeta-sone loaded into niosomes increased the skin permeability of Desoximeta-sone compared to the raw drug[59] He E et al. developed a microemulsion-based drug delivery system for transdermal delivery in order to improve the efficacy and permeability of indirubin. The In Vitro Skin Permeation and Deposition Study showed that the accumulated drug exudation in the final formulation was 2.1-fold and 13.1-fold higher than that of the oil solution and the aqueous solution, respectively; both the permeation and retention of the skin increased. This preparation can improve psoriasis symptoms by down-regulating the expression of IL-17A, Ki67, and CD4+T, providing great scalability for researchers to increase the concentration of targeted drugs[60]. Chamcheu J et al. developed chitosan based nanoformulated (-)-epigallocatechin-3-gallate (EGCG). In the imiquimod-induced psoriasis-like dermatitis model in mice, nanoEGCG showed a 20-fold dose advantage over free EGCG, representing a promising drug delivery strategy[61].

The nano transdermal delivery system has excellent efficacy in the anti-inflammation of wounds. To keep the area moist and decrease the risk of infection while hastening the healing process, a study by Zhang et al. introduced a stimuli-responsive glycopeptide hydrogel (OBPG&MP)constructed from hyacinthine polysaccharides, gallic acid-grafted ε-polylysine, and micelles loaded with paeoniflorin[62]. With each release of therapeutic chemicals, the hydrogel responded to the inflammatory microenvironment of chronic wounds by eliminat ing bacterial infection, neutralizing ROS, modifying macrophage polarization, suppressing inflammation, and promoting vascular regeneration and extracellular matrix remodeling. Studies conducted in vivo and in vitro have shown how effective OBPG&MP is at modifying the wound microenvironment and promoting skin tissue regeneration and remodeling in chronic wounds. Yang et al. prepared propolis nanoparticles (PNPs) using the pH difference method and characterized them. In the full-thickness skin defect model of mice, compared with the wounds of other groups, the wound healing of PNP treatment was 3–4 days faster. Histological observation showed that the wounds treated with PNPs had tissue epithelium, hair follicles, and dense collagen fibers, indicating that PNPs have the potential to become an ideal choice for wound-healing applications[63].

Kazemi M et al. prepared a piroxicam plasmid and combined it with iontophoresis therapy, which significantly enhanced the permeability of the piroxicam plasmid and had a significant inhibitory effect on the inflammatory response of wounds[64].The dihydromyricetin loaded inclusion complex significantly reduced the M1 phenotypic transition in RAW264.7 cells, effectively restoring M2 polarization, there by shortening the inflammatory period. The final formulation exhibited superior free radical scavenging activities, respectively making them excellent candidates for promoting wound healing[65]. **Schematic demonstration of various nanocarriers** is illustrated in figure 10[56]

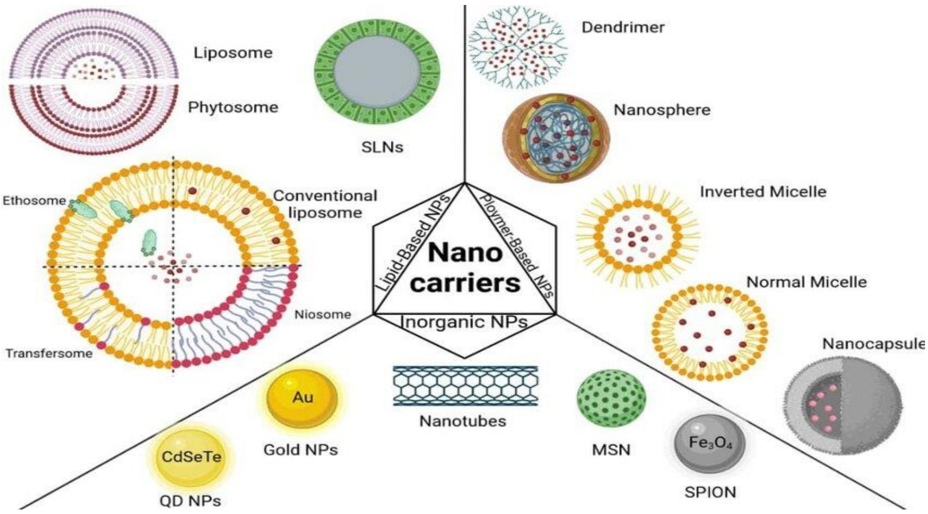

Figure 10 Schematic demonstration of various nanocarriers

Nanocarrier-Based Transdermal Delivery Technology for Dermatological Therapy

Transdermal delivery technology, as a non-invasive drug delivery system, has received widespread attention in recent years for dermatological therapy. Transdermal delivery technology can deliver drugs to the skin through topical administration[55]. In the treatment of common dermatoses (such as psoriasis, vitiligo, skin cancers, etc.), it has a more ideal effect compared to oral and injectable administration In addition, transdermal drug delivery can also deliver medications into the bloodstream to treat various diseases[56].Compared to traditional methods such as oral, intravenous, and subcutaneous injection, it can avoid first-pass metabolism and gastrointestinal side effects, offering the advantages of simplicity, convenience, and high patient compliance[57].

Transdermal drug delivery technologies used for dermatoses in the past five years

Table.no.1

Disease	Drug Delivery System	Loaded Drug	Characterization Parameter	Drug Properties	Advantages of Penetration/Accumulation	Efficacy
	Liposome	ICG	600 µm height, 300 µm diameter	Improves drug stability; drug content in skin 92.2%	Tumor growth inhibited 93.5%; good melanoma candidate	Promising for melanoma therapy
	Polymeric nanoparticle	Polydopamine	100 ± 10 nm	Improves bioavailability	Enhances penetration & retention; Cu-PDA NPs	Synergistic potential for

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue IX September 2025

Skin Cancer[66,67]	(PDA)	(PDA)		& skin permeability	give photothermal effect (~50.4%); effective with NIR	skin cancer
	Drug Delivery System	Loaded Drug	Characterization Parameter	Drug Properties	Advantages of Penetration/Accumulation	Efficacy
[68,59-] **Psoriasis**	Niosome	Desoximetasone	374.80 ± 9.48 nm, PDI 0.289 ± 0.01, zeta potential −63.83 ± 4.26 mV	Improves therapeutic efficacy and targeting; reduces adverse effects; increases patient compliance	Increased skin permeability of Desoximetasone compared to raw drug	Used for allergic reactions, eczema, and psoriasis
	Microemulsion	Indirubin	84.37 nm, PDI <0.2, zeta potential 0 ~ −20 mV	Increases solubility and bioavailability	Transdermal flux 47.34 ± 3.59 μg/cm²; retention 8.77 ± 1.26 μg/cm² at 24 h	Improves psoriasis symptoms by down-regulating IL-17A, Ki67, CD4+T
	Solid lipid nanoparticle	Cyclosporine A	216 ± 5 nm	Increases solubility	Skin permeation (pig ear model): 1.0 mg delivered with transdermal permeation	Topical administration avoids systemic side effects
	Metal nanoparticle	Epigallocatechin gallate (EGCG)	211.3 nm, PDI 0.132	Improves solubility and bioavailability	Controlled release: ~50% in 6 h, ~100% in 24 h	Induced differentiation; decreased proliferation and inflammation with 4-fold dose advantage

Drugs Given By Nanoparticles[69-74]

Table no.2

Disease / Indication	Nanoparticle Type	Drug / Active Agent	Characterization / Size, Zeta, etc.	Advantages / Observations	Reference
Cancer	Liposomal (Lipoplatin)	Cisplatin	~110 nm	Better tumor accumulation, reduced systemic toxicity	Lipoplatin (liposomal cisplatin), [Wikipedia](https://en.wikipedia.org/wiki/Lipoplatin)
Breast cancer	SPION (iron oxide NP)	Doxorubicin (DOX)	Magnetic NP conjugation; uptake in MCF-7, MDA-MB-231	Enhanced cytotoxicity, targeted delivery + hyperthermia synergy	Catalano et al. Superparamagnetic iron oxide nanoparticles conjugated with doxorubicin ([arXiv](https://arxiv.org/abs/1

					911.05378))
Alzheimer's / CNS	Polymeric NP	Tacrine	—	Increased brain concentration, lower dose required	Nanoparticles in Drug Delivery: From History to Therapeutic (MDPI) ([PMC](https://pmc.ncbi.nlm.nih.gov/articles/PMC9781272/))
CNS (brain)	Polymeric NP	Rivastigmine	—	Improved learning/memory	Nanoparticles in Drug Delivery (MDPI) ([PMC](https://pmc.ncbi.nlm.nih.gov/articles/PMC9781272/))
Cancer (various)	Polymeric / Lipid / Metal NPs	Doxorubicin, Paclitaxel, Cisplatin, etc.	Size, PDI, surface charge control	Improved solubility, targeting, controlled release, less side effects	Nanoparticles as Drug Delivery Systems: A Review ([PMC](https://pmc.ncbi.nlm.nih.gov/articles/PMC10096782/))
Cancer (general)	Metallic NPs	Gold, Silver, Platinum-based drugs	Tunable size, surface, stability	Targeting, circulation, combined therapy (photothermal)	Review on metal nanoparticles as nanocarriers ([PMC](https://pmc.ncbi.nlm.nih.gov/articles/PMC8724657/))

CONCLUSION[38,37,36]

Nanoparticles are a promising medication carrier for several drug delivery systems. Nanotechnology is a breakthrough technology that pervades all industries; novel applications of this field are being investigated worldwide. Nanoparticles can improve drug solubility and bioavailability, making them applicable to any poorly soluble medicine. Drug nanoparticles can enhance a drug's solubility, dissolving rate, and surface adhesiveness. Nanoparticulate medication delivery is gaining popularity as an effective alternative for biological pharmaceuticals. Nanoparticles offer effective treatment through targeted and controlled release, making them an attractive option for the biopharmaceutical industry.

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