Available online on 15.02.2026 at http://jddtonline.info

Journal of Drug Delivery and Therapeutics

Open Access to Pharmaceutical and Medical Research

Open Access Full Text Article

Review Article

From Molecules to Medicine: Nanotechnology Transforming Modern Therapeutics

Shiv Kumar Srivastava, Mahesh Prasad, Shashi Shankar, Anant Prakash Pandey, Antesh Kumar Jha *

Kamla Nehru Institute of Management and Technology, NH-96 Ayodhya–Prayagraj ByPass Road, Faridipur, Sultanpur (U.P.), India, PIN – 228119

Article Info:

Article History:

Received 18 Nov 2025
Reviewed 02 Jan 2026
Accepted 27 Jan 2026
Published 15 Feb 2026

Cite this article as:

Srivastava SK, Prasad M, Shankar S, Pandey AP, Jha AK, From Molecules to Medicine: Nanotechnology Transforming Modern Therapeutics, Journal of Drug Delivery and Therapeutics. 2026; 16(2):29-40 *DOI: http://dx.doi.org/10.22270/jddt.v16i2.7557*

For Correspondence:

Dr. Antesh Kumar Jha, Professor, Kamla Nehru Institute of Management & Technology, NH-96 Ayodhya–Prayagraj By Pass Road, Faridipur, Sultanpur (U.P.), India, PIN - 228119

Abstract

Nanotechnology, the manipulation of matter at the molecular and nanometer scale, has emerged as a transformative force across multiple disciplines, particularly in medicine. Its unique physicochemical properties allow the design of nanoscale materials that improve diagnostics, therapeutics, and drug delivery systems. Nanomedicine, a pivotal branch of nanotechnology, focuses on precise targeting of drugs, controlled release, enhanced bioavailability, and improved imaging, ultimately enhancing disease management and patient outcomes. Over the past few decades, the rapid growth of research has facilitated the commercialization of various nanoparticle-based products, with drug delivery platforms comprising the largest market share. Nanoparticles, including liposomes, polymeric micelles, dendrimers, quantum dots, carbon nanotubes, nanoshells, nanobubbles, and solid lipid nanoparticles, offer distinct advantages such as biocompatibility, enhanced cellular uptake, targeted tissue accumulation, and the ability to cross biological barriers like the blood–brain barrier. Various fabrication methods-such as solvent evaporation, emulsification, ionic gelation, nano-spray drying, and supercritical fluid technology-allow precise control over particle size, surface characteristics, and drug encapsulation, enabling customization for specific therapeutic needs. Nanoparticle-based systems have demonstrated significant potential in treating cancer, neurodegenerative disorders, infectious diseases, chronic kidney disease, and in vaccine delivery, including COVID-19.

Keywords: Nanomedicine, Nanoparticles, Targeted drug delivery, Controlled release, Biocompatibility, Therapeutics

1. Background

Nanotechnology refers to the design and creation of functional systems at the scale of molecules and nanometers. At this extremely small scale, materials exhibit unique electrical, optical and physical, properties, making nanotechnology valuable across diverse fields such as materials engineering, medicine, electronics, and biological sciences [1]. Nanomedicine represents a major branch of nanotechnology focused on applying nanoscale materials and strategies to healthcare. It aims to achieve highly precise diagnosis, prevention, and treatment of diseases by enabling improved imaging, targeted drug delivery and controlled therapeutic responses at the cellular and molecular levels [2]. In recent decades, research in nanomedicine has grown rapidly and has increasingly translated into commercial applications worldwide, resulting in the launch of various nanotechnology-based healthcare products. Among these, nanotechnology-enabled drug delivery platforms represent the largest segment of the market, accounting for more than 75% of total global nanomedicine revenues [2].Research on nanomedicine has increased dramatically in the last few decades, which is now being transformed into commercial ventures globally, leading to the launch of various products. Nanomedicine is currently led by drug delivery systems, which represent more than 75% of overall revenue [3].The diameter of nanoparticles ranges from 10 to 1000 nm. The active pharmaceutical ingredient (API) is enclosed, embedded, dissolved, or connected to the nanoparticle matrix. [4] It is possible to create nanoparticles by altering the manufacturing process. Drug delivery using nanoparticles has been demonstrated to be successful. There are numerous applications for nanoparticulate drug delivery systems, such as cancer treatment, gene therapy, radiation therapy, and AIDS treatment. It can additionally be utilized for the transport of antibiotics, proteins, and vaccines, and function as vesicles to traverse the blood–brain barrier [5].

2. Benefits of using nanoparticles in medicine delivery systems

The advantages of using nanoparticles as drug carriers arise mainly from their very small size and the fact that many of them are formulated from biodegradable and biocompatible polymers. In drug delivery, particle size plays a critical role, as reducing particles to the nanoscale can significantly enhance solubility and

improve bioavailability. This improvement is largely due to their large surface area-to-volume ratio, which promotes faster dissolution and better interaction with biological systems. [6, 7] Furthermore, nanoparticles can penetrate biological barriers, including the blood–brain barrier, pulmonary epithelium, tumor vasculature, and even the tight junctions of skin and endothelial cells. Their nanoscale size enables efficient cellular uptake and promotes preferential accumulation of drugs at targeted tissues, enhancing therapeutic efficacy [8]. Nanoparticles are generally more suitable for intravenous administration compared to larger microparticles. Since the diameter of the smallest capillaries in the human body is approximately 5–6 µm, particles intended for systemic circulation must be significantly smaller than this size to prevent vascular blockage or embolism. Therefore, nanoparticles—because of their submicron dimensions—can travel through the microvasculature without obstructing blood flow. [9] The use of biodegradable polymers—both natural and synthetic—in nanoparticle formulation provides several therapeutic advantages. These polymeric nanoparticles enable targeted delivery, enhance the bioavailability of drugs, and support sustained and controlled release, allowing a single dose to maintain therapeutic levels over an extended period. Moreover, by modifying the polymer system, it is possible to protect the drug from degradation by physiological enzymes, improving stability within the biological environment [10]. Moreover, many currently available oral and injectable drug formulations are not always optimal for therapeutic performance. Particularly, biologically sensitive molecules such as proteins and nucleic acids are prone to degradation and instability in physiological environments. Therefore, advanced carrier systems like nanoparticles are required to enhance their stability, protect them from degradation, and improve their therapeutic effectiveness. [11]

3. Types of Pharmaceutical Nanosystems

3.1 Carbon nanotubes

Carbon nanotubes were first discovered and characterized in 1991 by Sumio Iijima. [12] Carbon nanotubes are cylindrical, hollow formations made of rolled sheets of graphene (graphite). Their ends might be sealed with fullerene-like caps. They are categorized as SWCNTs (single-walled carbon nanotubes) or MWCNTs (multi-walled carbon nanotubes) based on the number of graphene layers. Generally, SWCNTs possess diameters around 1–2 nm, roughly double that of a DNA double helix, while MWCNTs can range from a few nanometers to several tens of nanometers, based on the number of concentric layers. The empty interior and adjustable surface chemistry of CNTs render them useful options for drug loading and targeted delivery purposes [13] Carbon nanotubes and Fullerenes are typically produced through methods like arc discharge, chemical vapor deposition (CVD), and combustion processes. These nanostructures are prized for their exceptional mechanical strength and structural stability, qualities that render them dependable carriers for drug delivery. Carbon nanotubes can penetrate cells via endocytosis or by directly traversing the cell membrane. Additionally, nanostructures based on fullerenes have shown targeted tissue selectivity, including localization within mitochondria. Besides their delivery abilities, fullerenes additionally feature significant antioxidant and antimicrobial characteristics. [14]

3.2. Quantum dots

Semiconductor nanocrystals known as quantum dots (QDs) usually have a diameter of 2 to 10 nm. In order to improve their optical stability and fluorescence characteristics, they typically consist of an inorganic semiconductor core, such as cadmium selenide (CdSe), encased in an organic coating and frequently further coated with a zinc sulfide (ZnS) shell. The addition of surface capping agents improves their water solubility and biocompatibility, allowing them to disperse effectively in aqueous environments. [15] The particle radius of quantum dots usually ranges from 2 to 10 nm. Their unique optical properties make them well-suited for in-vitro bio-imaging, long-term intracellular tracking, and real-time monitoring of cellular events. These features include narrow and size-tunable emission spectra, high photostability, broad excitation ranges in the UV region, and intense fluorescence output, which collectively distinguish them from conventional fluorescent dyes [16]. Quantum dots (QDs) are utilized in a variety of diagnostic and therapeutic biomedical applications. They are employed for cell labeling, biomolecule detection, and monitoring cellular and biochemical processes. QDs also play an important role in DNA hybridization assays and immunoassays due to their stable and tunable fluorescence. Additionally, they are being developed as non-viral gene delivery vectors, nanocarriers for anticancer therapies, and as transport systems for both biological and synthetic therapeutic agents [17].

3.3. Nanoshells

Nanoshells are engineered nanostructures typically consisting of a dielectric silica core coated with a thin metallic shell, most commonly gold, and are widely explored for drug targeting and photo-thermal therapeutic applications [18]. Nanoshells have recently attracted significant scientific interest due to their tunable structural and functional properties. By modifying the ratio between the core and the metallic shell, it is possible to precisely control their size, morphology, and optical characteristics. In situations where certain materials cannot naturally form the required shapes, nanoshell technology allows the creation of novel nanostructures by coating pre-formed particles of different shapes with a thin shell layer. This approach also offers economic advantages, as precious metals such as gold can be deposited in very small quantities over inexpensive core materials, reducing overall synthesis costs while retaining desirable functional performance [19]. Nanoshells can be functionalized for active targeting through immunological techniques. For example, gold nanoshells can be conjugated with specific antibodies on their outer metallic surface, enabling them to selectively

recognize and bind to cancer cell antigens. This enhances cellular uptake and improves targeting efficiency toward tumor tissues, making gold nanoshell-based systems highly effective for precision drug delivery and photo-thermal therapy [20]. Nanoshells serve various functional roles in biomedical and material science applications, including chemical stabilization of colloids, enhancement of luminescence properties, and efficient drug loading and delivery. Their tunable core–shell architecture allows controlled optical, chemical, and biological behavior, making them highly versatile in therapeutic and diagnostic systems [21].

3.4. Nanobubbles

Nanobubbles are nanoscale, gas-filled spherical structures that typically form at the interface of hydrophobic (lipophilic) surfaces in aqueous solutions. At physiological temperature, these nanobubbles can coalesce and transform into microbubbles, which remain stable even at room temperature. They generally arise in supersaturated liquid environments, where gas nucleation occurs on hydrophobic surfaces, leading to the trapping of air or other gases within the formed bubble structure. Drugs used in cancer therapy have been effectively incorporated into nanobubble carriers, enabling selective accumulation within tumor tissues. When exposed to ultrasound, these nanobubbles enhance cellular uptake of the encapsulated drug by promoting local bubble oscillation and cavitation, which increases membrane permeability and thereby improves therapeutic efficacy [22, 23, 24].

3.5. Paramagnetic nanoparticles

Magnetic nanoparticles are ultrafine particles, generally smaller than 100 nm, whose movement and localization can be directed using an external magnetic field. These particles are composed of magnetic elements or compounds, and their behavior is categorized based on their magnetic responsiveness. In particular, paramagnetic nanoparticles exhibit significantly greater magnetic susceptibility compared to conventional contrast agents. Due to these properties, magnetic nanoparticles play an important role in both diagnostic imaging and therapeutic applications, where their ability to be magnetically guided enables target-specific delivery and enhanced detection of particular tissues or organ [25, 26].

3.6. Liposomes

Liposomes are synthetic vesicular nanostructures composed of amphiphilic phospholipids, which spontaneously arrange into spherical bilayer membranes enclosing an aqueous interior. Their size can vary widely, typically from about 50 nm up to several micrometers, depending on formulation conditions. They are highly valued in drug delivery due to their excellent biocompatibility and biodegradability. Among nanocarrier systems under clinical development, liposomes are the most extensively studied and clinically advanced, as they are capable of prolonging drug circulation, reducing systemic toxicity, and minimizing off-target effects [27]. Nanoscale-engineered liposomes demonstrate favorable pharmacokinetic behavior and are widely applied for the delivery of DNA, siRNA, therapeutic proteins, and anticancer agents. However, their application is limited by certain disadvantages, including restricted drug loading capacity, premature drug leakage, and limited control over drug release kinetics [28]. Because liposomes generally have limited ability to cross cellular membranes, a significant portion of the encapsulated drug is often released into the extracellular space rather than being delivered directly into the cell interior [29]. After oral or parenteral administration, liposomes may encounter a harsh biological environment that can compromise their structure. However, surface modification (such as polymer or ligand coating) can improve their stability and maintain vesicle integrity, enhancing their performance in systemic delivery [30]. To reduce premature drug leakage from liposomal carriers, an ammonium sulfate gradient can be used to actively load drugs into the aqueous core. This technique enhances stable drug encapsulation, resulting in improved retention and reduced drug loss during systemic circulation [31]. Liposomes can be conjugated with antibodies to enable target-specific drug delivery, allowing the therapeutic agent to be directed precisely to the desired cells or tissues [32].

3.7. Niosomes

Niosomes are vesicular nanostructures formed in aqueous media through the self-assembly of non-ionic surfactants. Their distinctive bilayer architecture enables them to serve as versatile drug delivery systems, capable of encapsulating both hydrophilic and lipophilic therapeutic agents [33].

Niosomes mainly consist of non-ionic surfactants and are known for their low toxicity, excellent stability, and promise as a substitute for liposomes. In vivo, they replicate liposomal behavior by extending the circulation of encapsulated medications and modifying tissue distribution and metabolic stability. The properties of niosomes depend on both the composition of the bilayer and the preparation method. It has been demonstrated that incorporation of cholesterol into the bilayer reduces the internal aqueous volume, which consequently decreases drug entrapment efficiency [34]. Current studies indicate that niosomes are highly effective as drug delivery systems, demonstrating broad applicability for encapsulating potent therapeutics, including anticancer and anti-inflammatory agents. Their stability, biocompatibility, and ability to enhance drug bioavailability make them promising candidates for targeted and controlled drug delivery [35].

3.8. Dendrimers

Dendrimers are a distinct class of highly branched polymers with precisely controllable size and architecture. Their overall dimensions are dictated by the degree of branching, which can be systematically adjusted during synthesis. The spherical internal cavities formed within dendrimers provide spaces that can be utilized for drug encapsulation and delivery, while the terminal functional groups on the periphery can be modified to enable conjugation with targeting

ligands, therapeutic agents, or imaging molecules [36]. Dendrimers are highly advanced nanostructures due to their tunable surface functionalization and inherent stability**,** which make them attractive platforms for targeted drug delivery**.** Their architecture consists of three fundamental components: the central core, the branched interior, and the peripheral surface groups**,** each contributing to their versatility. This structural organization enables dendrimers to carry and deliver a wide range of bioactive molecules, including therapeutic drugs, genes, and vaccines**,** to specific tissues. Beyond drug and gene delivery, dendrimers have been employed in solubilization of poorly soluble compounds, gene therapy, immunoassays, and as contrast agents in magnetic resonance imaging (MRI) [36, 37, 38]

3.9. Polymeric micelles

Polymeric micelles are formed by self-assembly of amphiphilic block copolymers with both lipophilic (hydrophobic) and lipophobic (hydrophilic) segments. They typically consist of a hydrophobic block that aggregates to form the core, while a hydrophilic polymer chain such as polyethylene glycol (PEG) forms the stabilizing corona. In many systems, the hydrophobic (core-forming) block and the hydrophilic (corona-forming) block are of comparable chain length, which assists in achieving stable micellar architecture [39]. Micellar drug delivery systems provide several benefits compared to traditional formulations. The use of micelle-forming surfactants enhances the solubility of poorly water-soluble drugs, thereby improving their dissolution profile. These systems also facilitate greater permeability of drugs across biological membranes, resulting in enhanced bioavailability and altered biodistribution patterns. Additionally, polymeric micelles can decrease the systemic toxicity of potent therapeutic agents. Their small size and hydrophilic outer shell enable prolonged circulation time in the bloodstream after intravenous administration, while simultaneously minimizing uptake by the reticuloendothelial system. Furthermore, micelles can be engineered for site-specific delivery by conjugating targeting molecules to their surface. The micellar core also provides a protective environment that helps prevent drug degradation within the physiological milieu [40, 41].

3.10. Polymeric nanoparticles

Polymeric nanoparticles (PNPs) are generally composed of biocompatible and biodegradable polymers, which make them particularly attractive for use in drug delivery applications. Their ability to safely break down within the body and their minimal toxicity profile has encouraged widespread research and development in this area [42, 43]. Polymeric nanoparticles are generally classified into two structural forms: vesicular systems, known as nanocapsules, and matrix-type systems, known as nanospheres. Recent research has focused on modifying natural polymers to improve performance, alongside the development of synthetic polyesters. Chitosan is among the most widely utilized natural polymers in this context. The use of natural polymer-based nanoparticles helps in minimizing the toxicity concerns commonly associated with purely synthetic polymer systems [44]. Natural polymeric nanoparticles show superior performance compared to conventional drug delivery systems because of their enhanced efficiency and therapeutic effectiveness. However, they are not without limitations; issues such as inconsistent reproducibility, susceptibility to degradation, and the risk of inducing antigenic responses have been reported. The release profile of the drug encapsulated within these nanoparticles largely depends on the preparation method used. Despite these challenges, polymeric nanoparticles exhibit strong potential for intracellular delivery and targeted site-specific drug transport [45].

Nanocapsules and nanospheres differ primarily in their structural organization. Nanocapsules possess a reservoir-type structure in which the drug is confined within an inner core surrounded by a polymeric shell. In contrast, nanospheres represent a matrix system where the therapeutic agent is uniformly dispersed throughout the polymer network [46]. Polymeric nanoparticles can be visualized as a matrix system in which the drug is uniformly incorporated. The active compound may be dissolved, entrapped, or encapsulated either within or throughout the polymer matrix. Because these nanoparticles allow precise control over how a drug is released and delivered, they are considered a highly effective approach for cancer treatment as well as a range of other therapeutic applications [45].

3.11. Solid lipid nanoparticles

SLNs (Solid lipid nanoparticles) were developed as an alternative to conventional colloidal carriers such as liposomes, emulsions, and polymeric nanoparticles. They serve as a controlled drug-delivery system, offering improved stability and regulated release of the encapsulated drug [47]. Solid lipid nanoparticles are formulated using lipids that remain solid at both room and body temperature and are stabilized with one or more surfactants. Compared to other carrier systems, SLNs provide several advantages such as better biocompatibility, safe biodegradation, improved drug bioavailability—especially for ocular administration—and the ability to achieve targeted delivery to the brain [48]. In recent years, the development of solid lipid nanoparticles has grown rapidly, particularly with the advancement of high-pressure homogenization methods. SLNs have been formulated and investigated for numerous therapeutic applications. Their nanoscale size enables intravenous administration and supports targeted delivery of drugs to specific sites within the body [49].

3.12. Nanoemulsions

Self-emulsifying drug delivery systems (SEDDS) and nanoemulsions and have recently gained significant interest as methods to enhance the bioavailability of poorly water-soluble drugs. Nanoemulsions are composed of two immiscible liquids, with one phase dispersed into the other as tiny droplets." [50] When added to an aqueous environment with mild stirring, SNEDDS (self-nanoemulsifying drug delivery systems)

comprise a uniform blend of surfactant, co-surfactant, oil, and drug that effortlessly produce an oil-in-water (o/w) nanoemulsion. [51] These lipid-based formulations improve the oral bioavailability of poorly water-soluble medications through various mechanisms. In particular, their extremely tiny droplet size considerably lowers the interfacial tension between the aqueous gastrointestinal fluids and the oil phase, allowing for a more uniform and thorough medication distribution along the gut lining. [52]

The optimal preparation strategy is determined by the physicochemical characteristics of the selected drug and the polymer. Polymeric nanoparticles are typically produced through techniques like dispersing pre-formulated polymers, coacervating hydrophilic polymers, and polymerizing monomers. Other methods mentioned in the literature encompass supercritical fluid technology and particle replication within non-wetting templates. [53,54]

4. Manufacturing of Nano-systems

4.1. Solvent evaporation method

A commonly used technique for producing polymeric nanoparticles is the solvent-evaporation process. Initially, a solution containing a polymer and drug is emulsified into an aqueous phase, resulting in an oil-in-water (o/w) emulsion. Next, the polymer-solvent is evaporated—by stirring or lowering pressure—which results in the precipitation of the polymer and the creation of nanospheres. The selection of this technique is heavily influenced by the solubility of the polymer and the hydrophobic nature of the organic solvent utilized. In the emulsification process, the drug-polymer blend is distributed in a water-based solution with a surfactant or emulsifier to stabilize the oil-in-water emulsion. After a stable emulsion has been created, the organic solvent is eliminated, resulting in nanoparticles. The ultimate dimensions of the nanoparticles are affected by various formulation and process factors, including the type and concentration of the polymer and stabilizer, along with the speed of the homogeniser. [55] Techniques like high-speed homogenization or ultrasonication can be used to produce small-sized nanoparticles. After the nanoparticles are created, they undergo ultracentrifugation for collection, are rinsed with distilled water to eliminate any leftover stabiliser or unencapsulated drug, and subsequently lyophilized for storage. Two versions of this procedure are typically implemented: the traditional solvent-evaporation technique and a modified method that utilizes high-pressure emulsification. [56] The latter technique involves forming an emulsion that is then subjected to high-pressure homogenisation, followed by evaporation of the organic solvent under stirring. This approach has sufficiently improved the activity of various drugs when reformulated as nano-systems; for example, encapsulating Ibuprofen via the emulsification-solvent-evaporation method enhanced its skin penetration [57] and Betulinic acid nanoparticles as an alternative therapy for Visceral Leishmaniasis. [58]

4.2. Spontaneous emulsification method

This technique can be applied for the formulation of both lipophilic and hydrophilic drugs. For hydrophilic (lipophobic) compounds, a multiple water-in-oil-in-water (w/o/w) emulsion system is typically employed, where the drug is entrapped within the innermost aqueous compartment." [59] This study [60] highlights the significance of spontaneous emulsification in forming both direct (oil-in-water) and reverse (water-in-oil) nano-emulsions. Optimization of formulation parameters—including surfactant type and concentration, oil phase nature, mixing order, and rate—was found to greatly influence droplet size and emulsion stability. The process enables encapsulation of both hydrophilic and lipophilic compounds, preserves sensitive actives, and offers potential for industrial scale-up. Overall, spontaneous nano-emulsification provides an energy-efficient, reproducible, and promising method for advanced pharmaceutical nano-formulations.

4.3. Double emulsion and evaporation method

Evaporation-based nanoparticle fabrication methods often exhibit limited efficiency in entrapping hydrophilic drugs. The double emulsion (water-in-oil-in-water, or w/o/w) approach is frequently employed to encapsulate lipophobic substances in order to get around this restriction. This method creates a primary w/o emulsion by emulsifying an aqueous drug solution into an organic phase that contains polymers while being continuously stirred. To create a stable w/o/w emulsion, this emulsion is subsequently disseminated into a secondary aqueous phase while being stirred. Afterward, solvent evaporation is performed, and nanoparticles are isolated through high-speed centrifugation, followed by washing to remove residual stabilizers or unentrapped drugs before lyophilization. The efficiency and characteristics of the resultant nanoparticles depend on several parameters, including the amount of hydrophilic drug incorporated, polymer and stabilizer concentrations, and the aqueous phase volume. [61]

Double emulsions, often referred to as "emulsions within emulsions," are complex multiphase systems in which the dispersed droplets themselves contain smaller internal droplets. These systems are capable of encapsulating both hydrophilic and hydrophobic compounds, making them useful in pharmaceuticals, cosmetics, food, and other high-value formulations. They are particularly advantageous for entrapping hydrophilic molecules that typically exhibit low encapsulation efficiency in single emulsions due to rapid drug diffusion into the outer aqueous phase. However, achieving uniform droplet size and stability requires precise control of formulation and processing parameters. Recent research has focused on optimizing double emulsion methods for the encapsulation of anticancer, anti-inflammatory, and antibiotic drugs, as well as biomolecules such as proteins and amino acids, demonstrating their promising role in theranostic applications. Furthermore, studies highlight the importance of optimizing solvent systems, stabilizers,

polymers, and phase ratios to improve encapsulation efficiency and stability of the final formulations. [62]

4.4. Emulsions–diffusion method

The solvent diffusion approach is another effective way to produce nanoparticles. In order to achieve thermodynamic equilibrium between the two liquid phases, the encapsulating polymer is dissolved in a somewhat water-miscible solvent, such as benzyl alcohol or propylene carbonate, which is first saturated with water. Depending on the oil-to-polymer ratio, the polymer–solvent mixture is then emulsified into a water phase using a stabilizer, which promotes solvent diffusion into the surrounding environment and produces nanospheres or nanocapsules. In the end, the solvent is removed by either filtration or evaporation, depending on how volatile it is. This method provides numerous benefits, such as superior encapsulation efficiency, lack of high-shear homogenization, great reproducibility, straightforward scaling, operational ease, and consistent particle size distribution. [63] The emulsification–diffusion (E-D) technique was created [64] as a substitute for the conventional emulsification–evaporation method to address the problems linked to harmful organic solvents. This method has garnered attention for its ease, reproducibility, and versatility across different formulations. It represents one of the initial methods for nanoparticle fabrication studied from a mechanistic viewpoint and has effectively been utilized for encapsulating various therapeutic agents, such as peptides and proteins. This study aims to investigate the pharmaceutical significance and progress of the emulsification–diffusion technique since it was first developed. [64]

4.5. Solvent displacement method

This approach represents a modification of the conventional emulsification–diffusion method, distinguished by the absence of a dilution step. During processing, the partially water-miscible solvent is extracted from the emulsion droplets under reduced pressure, promoting its diffusion into the external aqueous phase and leading to lipid aggregation into nanoparticles. The resulting particle size is influenced by key process variables such as stirring speed, phase ratios, stabilizer concentration, and lipid content, all of which were systematically analyzed and optimized for improved formulation performance. [65] The study demonstrated that the Venturi tube (VT) system is an efficient, reproducible, and scalable technique for nanoparticle production via solvent displacement. Turbulence generated within the VT significantly influenced particle size and yield, with the Reynolds number identified as a key factor. Optimal conditions yielded nanoparticles of uniform size and high process efficiency. This method offers great potential for large-scale nanoprecipitation and can be adapted for other polymers with comparable physicochemical characteristics. [66]

4.6. Coacervation or ionic gelation method

Ionotropic gelation is one of the most widely explored techniques for developing nanocarrier systems due to its simplicity and mild preparation conditions. The process relies on the ability of natural polyelectrolytes—such as chitosan, alginate, hyaluronic acid, and carrageenan—to undergo cross-linking in the presence of oppositely charged ions. During ionic cross-linking, a three-dimensional network is formed through electrostatic interactions between polymer chains and multivalent counterions, which act as cross-linking agents with defined molecular characteristics. This technique is commonly employed for the fabrication of nanoparticles, hydrogels, and biofilms. [67] As an example, polysaccharide-based self-assembled nanogels represent a promising platform for drug delivery owing to their excellent biocompatibility, functional versatility, and retention of natural physicochemical properties. Utilizing natural polymers such as chitosan, alginate, and hyaluronan, these nanogels form through ionic cross-linking and metal coordination without requiring chemical modification. Their multiple reactive groups facilitate efficient drug encapsulation and controlled release, making them highly suitable for biomedical applications and offering strong potential for future clinical translation in therapeutic delivery systems. [68]

4.7. Polymerization method

This technique involves the formation of nanoparticles through the polymerization of monomers in an aqueous medium. The drug can be incorporated into the system using two approaches: either by allowing it to diffuse into the polymerization medium during particle formation or by adsorbing it onto the surface of the nanoparticles once polymerization is complete. Both methods enable effective drug loading depending on the physicochemical properties of the drug and the polymer matrix. [69] Ultracentrifugation is employed to isolate nanoparticle suspensions from residual stabilizers and surfactants used during polymerization, after which the nanoparticles are re-dispersed in a surfactant-free isotonic medium. By adjusting the concentrations of stabilizers and surfactants, the desired nanoparticle size can be achieved. Numerous studies have utilized polymerization techniques for applications such as creating superhydrophobic cotton fabrics and developing nonporous polyimide-silsesquioxane nanostructures for soft dielectric materials. [70, 71, 72] Acyclovir, a poorly water-soluble antiviral drug with low oral bioavailability, can be effectively formulated into nanoparticles to enhance solubility and absorption. Using chitosan as a biocompatible polymer, acyclovir nanoparticles prepared by the nanoprecipitation method showed improved drug entrapment, stability, and particle size distribution. This nanotechnological approach offers a promising strategy for enhancing acyclovir's therapeutic efficacy. [73]

4.8. Nano spray drying

Spray drying is a simple, fast, repeatable, and scalable method ideal for drying heat-sensitive biopharmaceuticals at low temperatures. In contrast to alternative drying techniques, it functions continuously to transform liquids into solid particles, enabling regulation of particle size, distribution, porosity, shape, density, and composition. Commercial spray-drying

machinery is readily accessible, and production expenses are reduced in comparison to freeze-drying or related methods. [74] Spray drying generally consists of four stages: (1) heating of the drying gas, (2) atomization to produce fine droplets, (3) solvent evaporation or droplet drying, and (4) collection of the resulting dry particles. The nano-spray drying technique allows the production of much smaller particles than conventional spray dryers, enhancing the bioavailability and controlled release of bioactive compounds and drugs. Nanoparticle-based drug formulations offer several advantages such as increased surface area, improved cellular uptake, enhanced stability, and targeted delivery capabilities. [75] Nanoparticle-based therapies have been increasingly utilized in pulmonary drug delivery to improve the administration of poorly water-soluble drugs, protect them from degradation, and enable controlled release and targeted delivery. This review highlights spray drying as an effective solidification technique to create nanoparticle-loaded microparticles (nanoparticle agglomerates) suitable for inhalation. It discusses the fundamentals of pulmonary drug delivery, spray drying mechanisms, and the formulation of various nanoparticle agglomerates such as nanoporous, nanocrystalline, lipid-based, and polymeric systems. Additionally, advanced methods like nano spray drying and supercritical CO_2-assisted spray drying are examined for producing optimized inhalable formulations. [76]

4.9. Supercritical fluid technology

Traditional nanoparticle fabrication techniques often rely on organic solvents that pose environmental and physiological risks. To overcome these limitations, supercritical fluid technology has emerged as an eco-friendly and efficient alternative for producing biodegradable micro- and nanoparticles. This method eliminates the need for toxic solvents while ensuring controlled particle size and high purity, making it highly suitable for pharmaceutical applications. [77] The green synthesis of chitosan nanoparticles provides an eco-friendly, efficient, and sustainable approach for developing antimicrobial agents. Optimized nanoparticles demonstrated excellent physicochemical properties and potent antibacterial efficacy against multidrug-resistant, biofilm-forming Acinetobacter baumannii. These findings highlight their promising potential as biocompatible nanotherapeutics for combating resistant bacterial infections. [78]

5. Applications of nanoparticles

5.1. Nanoparticles in the treatment of kidney disorders

Nanotechnology offers a promising frontier in kidney disease therapy by enabling targeted, controlled drug delivery and improved treatment efficacy. Despite challenges in synthesis and renal targeting, advancements in nanoparticle design and understanding of kidney pathology provide a strong foundation for future clinical translation, revolutionizing kidney disease management and patient outcomes. [79] Nanotechnology offers promising advancements in the diagnosis and treatment of chronic kidney disease (CKD). Due to their unique physicochemical properties, nanoparticles can cross biological barriers, enabling early detection, targeted drug delivery, and therapeutic interventions for renal fibrosis and vascular calcification. Their use also enhances safety and efficiency in dialysis treatments. Despite challenges such as toxicity and biocompatibility concerns, continued research on nanoparticles holds great potential for improving CKD management and patient outcomes. [80]

5.2. Nanoparticles for treatment of tuberculosis by chemotherapy

Nanoparticle-based drug delivery offers a promising strategy to overcome drug-resistant tuberculosis by enhancing the efficacy, bioavailability, and patient compliance of existing therapies. By reducing treatment duration, pill burden, and dosing frequency, this approach addresses the root causes of resistance and provides a pathway toward more effective TB management. [81] Nanomedicine represents a transformative advancement in tuberculosis treatment, addressing limitations of conventional therapies such as drug resistance, poor bioavailability, and patient noncompliance. By enabling targeted delivery, sustained release, and reduced dosing frequency, nanoparticle-based systems and emerging therapeutics hold great promise for improving treatment outcomes, patient adherence, and global TB control in the future. [82]

5.3. Nanoparticles topical drug delivery for skin diseases

Skin diseases significantly impact patients' physical, emotional, and social well-being. Conventional therapies often face limitations such as prolonged treatment duration, poor efficacy, and systemic side effects. Nanocarrier-based dermal drug delivery systems overcome these challenges by enabling targeted, site-specific delivery, enhanced skin penetration, and controlled drug release. These platforms offer improved therapeutic outcomes, reduced adverse effects, and theranostic benefits, making them a promising approach for managing conditions like psoriasis, atopic dermatitis, and skin cancer effectively and safely. [83] Nanoparticles present promising opportunities for treating skin cancers by enhancing topical drug delivery and overcoming the skin's barrier, especially when compromised by injury or inflammation. Despite extensive research, clinical translation remains limited. This review highlights current skin cancer types, management practices, and nanoparticle-based therapeutic strategies, emphasizing mechanisms of skin penetration and the challenges hindering clinical advancement from laboratory research to effective patient treatments. [84]

5.4. Drug targeting to infectious diseases by nanoparticles

Nanotechnology has emerged as a promising approach in novel drug delivery systems, offering effective solutions for targeted therapy. In infectious diseases, where drug resistance and multidrug resistance pose

major challenges, nanotechnology-based delivery can enhance treatment efficacy and reduce resistance. By enabling site-specific targeting, these systems improve drug action and minimize side effects. This chapter discusses various targeting strategies, nanocarriers, and targeting moieties used against infectious diseases such as tuberculosis, malaria, dengue, HIV, and COVID-19. [85]

5.5. Applications of nanoparticles in treating Alzheimer's disease

The buildup of beta-amyloid plaques in the brain is the cause of Alzheimer's disease (AD), a progressive neurodegenerative condition. Although no permanent cure exists, current medications can only slow its progression. Nanotechnology has shown great promise in medical applications, offering new possibilities for AD diagnosis and therapy. This review highlights advancements and advantages of nanomedicines in AD management and suggests that future nanotechnology-based diagnostic and therapeutic tools for AD and other CNS disorders may soon reach clinical application. [86]

5.6. Nanoparticles containing different anticancer agents

In recent years, innovative approaches for cancer treatment have emerged, with chemotherapy remaining a primary method despite its harmful effects on healthy cells. To address this, advanced nanocarriers have been designed for targeted drug delivery to cancer cells, enhancing safety and efficacy. This review summarizes key nanocarriers such as polymeric micelles, liposomes, magnetic and mesoporous nanoparticles dendrimers, , gold nanoparticles, carbon nanotubes, and quantum dots highlighting their synthesis, applications, benefits, limitations, and potential for clinical translation. [87] Over the past decade, nanotechnology has advanced rapidly, finding applications in medicine, pharmaceuticals, electronics, and more. Nanoparticles offer advantages like targeted and controlled drug release and enhanced bioavailability but face toxicity concerns. Silver nanoparticles, due to their unique properties, are gaining attention as drug carriers for targeted cancer therapy. This review highlights recent progress in using silver nanoparticles for anticancer drug delivery and their role in improving therapeutic efficacy while minimizing side effects. [88]

5.7. Nanoparticles in vaccination against COVID-19

Nanoparticles are employed in several COVID-19 vaccines to protect antigen cargo, whether proteins or nucleic acids, and to boost immunogenicity and vaccine effectiveness. Their complex nature makes characterization challenging, necessitating multidisciplinary methods. Effective evaluation involves a combination of physicochemical, immunological, and toxicological analyses, which help overcome preclinical hurdles, support the rapid development of safe and potent vaccines, and streamline regulatory approval for current and future public health emergencies. [89] Coronaviruses, including MERS-CoV, SARS-CoV-2, and COVID-19, are positive-sense RNA viruses causing high morbidity and mortality, with socioeconomic impacts. Emerging variants demand effective treatments, though vaccines remain essential yet insufficient for full control. Nanotechnology-based vaccines—such as mRNA, DNA, inactivated virus, S-protein, and virus-vectored types—are under clinical evaluation. Nanotechnology aids in precise diagnosis, vaccine delivery, antiviral administration, and sanitizer development, offering innovative strategies for COVID-19 prevention and therapy while presenting both challenges and opportunities. [90]

6. FDA Approved Nanomedicines

Nanomedicine has witnessed remarkable progress over the past decades, demonstrated by the approval of around 90 products, including co-delivery nanomedicines like Vyxeos for acute myeloid leukemia (AML) and siRNA-loaded lipid nanoparticles (LNPs), Onpattro, for hereditary transthyretin-mediated polyneuropathy (hATTR). Since 2005, the FDA has streamlined nanomedicine approval processes, facilitating the commercialization of liposomes, nanocrystals (NCs), and LNPs, including COVID-19 mRNA vaccines such as Comirnaty and mRNA-1273. NCs and Liposomes are particularly successful, accounting for over 60% of marketed nanomedicines due to their stability, high drug-loading capacity, and safety. Despite these advancements, the translation of nanomedicine from research to market remains low compared to the extensive number of publications, with challenges including limited enhanced permeability and retention (EPR) effects in human tumors, uncertain in vivo fate, toxicity, and protein corona effects on biodistribution and targeting. Novel strategies, including radioactive tracing, fluorescence bioimaging, and environment-responsive probes, are emerging to better understand nanoparticle behavior in vivo. Quality control of nanoformulations, including morphology, size, surface charge, drug loading, and release, is critical, and microfluidic techniques combined with quality-by-design approaches support reproducible manufacturing under GMP conditions. Nanomedicine significantly improves drug delivery, enhances the stability and intracellular delivery of biopharmaceuticals, and reduces side effects. Lipid nanoparticles have enabled clinical use of nucleic acid therapies, exemplified by Onpattro and mRNA vaccines, opening a new era in biopharmaceutical applications. With ongoing innovations, nanotechnology is expected to increasingly transform drug development and expand the commercialization of biologics-related nanomedicines. [91]

7. Summary

The article "From Molecules to Medicine: Nanotechnology Transforming Modern Therapeutics" provides a comprehensive overview of the role of nanotechnology in modern medicine, with a strong focus on nanomedicine and nanoparticle-based drug delivery systems. It explains how manipulating materials at the nanoscale leads to unique physicochemical properties that enhance diagnosis, treatment, and disease management. The review highlights the advantages of nanoparticles such as improved solubility, enhanced bioavailability, targeted

drug delivery, controlled and sustained release, reduced toxicity, and the ability to cross biological barriers including the blood–brain barrier. These properties make nanoparticles highly suitable for delivering drugs, proteins, genes, and vaccines.

A detailed classification of pharmaceutical nanosystems is presented, including carbon nanotubes, quantum dots, nanoshells, nanobubbles, magnetic nanoparticles, liposomes, niosomes, dendrimers, polymeric micelles, polymeric nanoparticles, solid lipid nanoparticles, and nanoemulsions. Each system is discussed in terms of structure, properties, advantages, and biomedical applications. The article also reviews manufacturing techniques for nanosystems, such as solvent evaporation, spontaneous emulsification, double emulsion, emulsification–diffusion, solvent displacement, ionic gelation, polymerization, nano-spray drying, and supercritical fluid technology, emphasizing their suitability for different drugs and polymers. Furthermore, it outlines major therapeutic applications of nanoparticles in cancer, kidney disorders, tuberculosis, skin diseases, infectious diseases, Alzheimer's disease, and COVID-19 vaccination. The review concludes with a discussion on FDA-approved nanomedicines, highlighting successful clinical translations and remaining challenges like toxicity, biodistribution, and regulatory issues. Overall, the article underscores nanotechnology's transformative potential in advancing precision medicine and improving patient outcomes.

Conclusion

Nanotechnology has profoundly reshaped modern medicine by enabling precise, controlled, and targeted therapeutic interventions. Systems based on nanoparticles offer substantial advantages over traditional formulations by improving medication stability, bioavailability, and potency while reducing systemic toxicity. With advancements in fabrication methods, diverse nanosystems—including liposomes, dendrimers, polymeric micelles, and lipid nanoparticles-have found applications in cancer therapy, neurodegenerative diseases, infectious disorders, kidney disease, and vaccine development. FDA-approved nanomedicines demonstrate the feasibility of translating laboratory innovations into clinical success. Despite remaining challenges such as toxicity, biodistribution uncertainties, and regulatory hurdles, ongoing technological innovations and research are expected to further expand the scope and effectiveness of nanotherapeutics, paving the way for a new era in precision medicine.

Disclaimers, if any: Not Any

Funding sources: This paper did not receive any grants from public, commercial, or not-for-profit funding agencies.

Ethical Approval: Not applicable

Author's Contribution

Shiv Kumar Srivastava	Critical Analysis & Interpretation
Mahesh Prasad	Conceptualization
Shashi Shankar	Literature Search & Data Collection
Anant Prakash Pandey	Literature Search & Data Collection
Antesh Kumar Jha	Writing – Original Draft

References

1. Ranjbar L, Maleki A, Moradpoor H, Aghayan H. Nanotechnology: an overview and its applications. In: IIP Proceedings. Vol 2, Book 12, Part 1, Chapter 7. IIP Series; 2022. p. 98.

2. Bhushan B. Springer handbook of nanotechnology. 4th ed. Cham: Springer International Publishing; 2017. p. 1545-1550. https://doi.org/10.1007/978-3-662-54357-3

3. Malik S, Muhammad K, Waheed Y. Emerging applications of nanotechnology in healthcare and medicine. Molecules. 2023;28(18):6624. https://doi.org/10.3390/molecules28186624 PMid:37764400 PMCid:PMC10536529

4. Vyas SP, Khar RK. Targeted and controlled drug delivery: novel carrier systems. New Delhi: CBS Publishers & Distributors; 2018. p. 418.

5. Dang Y, Guan J. Nanoparticle-based drug delivery systems for cancer therapy. Smart Mater Med. 2020;1:10-19. https://doi.org/10.1016/j.smaim.2020.04.001 PMid:34553138 PMCid:PMC8455119

6. Geszke-Moritz M, Moritz M. Biodegradable polymeric nanoparticle-based drug delivery systems: comprehensive overview, perspectives and challenges. Polymers. 2024;16:2536. https://doi.org/10.3390/polym16172536 PMid:39274168 PMCid:PMC11397980

7. Rabinow BE. Nanosuspensions in drug delivery. Nat Rev Drug Discov. 2004;3(9):785-796. https://doi.org/10.1038/nrd1494 PMid:15340388

8. Saraiva C, Praça C, Ferreira R, Santos T, Ferreira L, Bernardino L. Nanoparticle-mediated brain drug delivery: overcoming blood-brain barrier to treat neurodegenerative diseases. J Control Release. 2016;235:34-47. https://doi.org/10.1016/j.jconrel.2016.05.044 PMid:27208862

9. Buzea C, Pacheco II, Robbie K. Nanomaterials and nanoparticles: sources and toxicity. Biointerphases. 2007;2(4):MR17-MR71. https://doi.org/10.1116/1.2815690 PMid:20419892

10. Patra JK, Das G, Fraceto LF, et al. Nano based drug delivery systems: recent developments and future prospects. J Nanobiotechnol. 2018;16:71. https://doi.org/10.1186/s12951-018-0392-8 PMid:30231877 PMCid:PMC6145203

11. Duan L, Li X, Ji R, et al. Nanoparticle-based drug delivery systems: an inspiring therapeutic strategy for neurodegenerative diseases. Polymers. 2023;15:2196. https://doi.org/10.3390/polym15092196 PMid:37177342 PMCid:PMC10181407

12. Iijima S. Helical microtubules of graphitic carbon. Nature. 1991;354(6348):56-58. https://doi.org/10.1038/354056a0

13. Murjani BO, Kadu PS, Bansod M, Vaidya SS, Yadav MD. Carbon nanotubes in biomedical applications: current status, promises, and challenges. Carbon Lett. 2022;32(5):1207-1226. https://doi.org/10.1007/s42823-022-00364-4 PMid:40477687 PMCid:PMC9252568

14. Gaur M, Misra C, Yadav AB, et al. Biomedical applications of carbon nanomaterials. Materials (Basel). 2021;14(20):5978. https://doi.org/10.3390/ma14205978 PMid:34683568 PMCid:PMC8538389

15. Iga AM, Robertson JH, Winslet MC, Seifalian AM. Clinical potential of quantum dots. Biomed Res Int. 2007;2007:76087.

https://doi.org/10.1155/2007/76087 PMid:18317518 PMCid:PMC2254660

16. Lee JS, Youn YH, Kwon IK, et al. Recent advances in quantum dots for biomedical applications. J Pharm Investig. 2018;48:209-214. https://doi.org/10.1007/s40005-018-0387-3

17. Wagner AM, Knipe JM, Orive G, Peppas NA. Quantum dots in biomedical applications. Acta Biomater. 2019;94:44-63. https://doi.org/10.1016/j.actbio.2019.05.022 PMid:31082570 PMCid:PMC6642839

18. West JL, Halas NJ. Applications of nanotechnology to biotechnology. Curr Opin Biotechnol. 2000;11(2):215-217. https://doi.org/10.1016/S0958-1669(00)00082-3 PMid:10753774

19. Kalele SW, Gosavi S, Urban J, Kulkarni S. Nanoshell particles: synthesis, properties and applications. Curr Sci. 2006;91(8):1038-1052.

20. De Matteis V, Cascione M, Toma CC, Rinaldi R. Engineered gold nanoshells killing tumour cells. Curr Pharm Des. 2019;25(13). https://doi.org/10.2174/1381612825666190618155127 PMid:31258061

21. Topete A, Varela A, Navarro-Real M, et al. Revisiting gold nanoshells as multifunctional biomedical nanotools. Coord Chem Rev. 2025;523:216250. https://doi.org/10.1016/j.ccr.2024.216250

22. Eklund F, Alheshibri M, Swenson J. Differentiating bulk nanobubbles from nanodroplets and nanoparticles. Curr Opin Colloid Interface Sci. 2021;53:101427. https://doi.org/10.1016/j.cocis.2021.101427

23. Zhou J, Wang S, Zhang L, Hu J. Generation and stability of bulk nanobubbles. Curr Opin Colloid Interface Sci. 2021;53:101439. https://doi.org/10.1016/j.cocis.2021.101439

24. Xie X, Lin W, Liu H, et al. Ultrasound-responsive nanobubbles for targeted drug delivery. Drug Deliv. 2016;23(8):2756-2764. https://doi.org/10.3109/10717544.2015.1077289 PMid:26289216

25. Konnova S, Rozhina E. Magnetic nanoparticles for biomedical and imaging applications. Int J Mol Sci. 2024;25(11):5847. https://doi.org/10.3390/ijms25115847 PMid:38892034 PMCid:PMC11172554

26. Materón EM, Miyazaki CM, Carr O, et al. Magnetic nanoparticles in biomedical applications. Appl Surf Sci Adv. 2021;6:100163. https://doi.org/10.1016/j.apsadv.2021.100163

27. Nsairat H, Khater D, Sayed U, et al. Liposomes: structure, composition, types, and clinical applications. Heliyon. 2022;8(5):e09394. https://doi.org/10.1016/j.heliyon.2022.e09394 PMid:35600452 PMCid:PMC9118483

28. Sobol Ż, Chiczewski R, Wątróbska-Świetlikowska D. Advances in liposomal drug delivery. Pharmaceutics. 2025;17(7):885. https://doi.org/10.3390/pharmaceutics17070885 PMid:40733094 PMCid:PMC12298344

29. Bozzuto G, Molinari A. Liposomes as nanomedical devices. Int J Nanomedicine. 2015;10:975-999. https://doi.org/10.2147/IJN.S68861 PMid:25678787 PMCid:PMC4324542

30. Chelliah R, Rubab M, Vijayalakshmi S, et al. Liposomes for drug delivery. Next Nanotechnol. 2025;8:100209. https://doi.org/10.1016/j.nxnano.2025.100209

31. Gabizon AA, Shmeeda H, Zalipsky S. Pros and cons of the liposome platform. J Liposome Res. 2006;16(3):175-183. https://doi.org/10.1080/08982100600848769 PMid:16952872

32. Wang S, Chen Y, Guo J, Huang Q. Liposomes for tumor targeted therapy. Int J Mol Sci. 2023;24(3):2643. https://doi.org/10.3390/ijms24032643 PMid:36768966 PMCid:PMC9916501

33. Moammeri A, Chegeni MM, Sahrayi H, et al. Current advances in niosomes applications for drug delivery and cancer treatment. Mater Today Bio. 2023;23:100837. https://doi.org/10.1016/j.mtbio.2023.100837 PMid:37953758 PMCid:PMC10632535

34. Gharbavi M, Amani J, Kheiri-Manjili H, Danafar H, Sharafi A. Niosome: a promising nanocarrier for natural drug delivery through blood-brain barrier. Adv Pharmacol Sci. 2018;2018:6847971. https://doi.org/10.1155/2018/6847971 PMid:30651728 PMCid:PMC6311792

35. Antonara L, Triantafyllopoulou E, Chountoulesi M, et al. Recent advances in niosome-based transdermal drug delivery systems. Curr Opin Biomed Eng. 2025;35:100603. https://doi.org/10.1016/j.cobme.2025.100603

36. Wang J, Li B, Qiu L, et al. Dendrimer-based drug delivery systems: history, challenges, and latest developments. J Biol Eng. 2022;16:18. https://doi.org/10.1186/s13036-022-00298-5 PMid:35879774 PMCid:PMC9317453

37. Chis AA, Dobrea C, Morgovan C, et al. Applications and limitations of dendrimers in biomedicine. Molecules. 2020;25(17):3982. https://doi.org/10.3390/molecules25173982 PMid:32882920 PMCid:PMC7504821

38. Alamos-Musre S, Beltrán-Chacana D, Moyano J, et al. From structure to function: the promise of PAMAM dendrimers in biomedical applications. Pharmaceutics. 2025;17:927. https://doi.org/10.3390/pharmaceutics17070927 PMid:40733135 PMCid:PMC12299782

39. Akiba I, Sakurai K. Characterizing block-copolymer micelles used in nanomedicines. Polym J. 2021;53:951-973. https://doi.org/10.1038/s41428-021-00489-9

40. Haladjova E, Rangelov S. Application of polymeric micelles for drug and gene delivery. Pharmaceutics. 2024;16(5):646. https://doi.org/10.3390/pharmaceutics16050646 PMid:38794308 PMCid:PMC11125079

41. Ghezzi M, Pescina S, Padula C, et al. Polymeric micelles in drug delivery. J Control Release. 2021;332:312-336. https://doi.org/10.1016/j.jconrel.2021.02.031 PMid:33652113

42. Begines B, Ortiz T, Pérez-Aranda M, et al. Polymeric nanoparticles for drug delivery. Nanomaterials. 2020;10(7):1403. https://doi.org/10.3390/nano10071403 PMid:32707641 PMCid:PMC7408012

43. Rodriguez-Cruz JJ, Chapa-Villarreal FA, Duggal I, Peppas NA. Advanced rational design of polymeric nanoparticles. J Control Release. 2025;384:113940. https://doi.org/10.1016/j.jconrel.2025.113940 PMid:40484283

44. Niu Y, Wu J, Kang Y, et al. Recent advances of magnetic chitosan hydrogel. Int J Biol Macromol. 2023;247:125722. https://doi.org/10.1016/j.ijbiomac.2023.125722 PMid:37419264

45. Eltaib L. Polymeric nanoparticles in targeted drug delivery. Polymers. 2025;17(7):833. https://doi.org/10.3390/polym17070833 PMid:40219222 PMCid:PMC11991310

46. Sultana F, Zare M, Thomas V, et al. Nano-based drug delivery systems. Med Drug Discov. 2022;15:100134. https://doi.org/10.1016/j.medidd.2022.100134

47. Arabestani MR, Bigham A, Kamarehei F, et al. Solid lipid nanoparticles in bacterial infections. Biomed Pharmacother. 2024;174:116433. https://doi.org/10.1016/j.biopha.2024.116433 PMid:38508079

48. Han H, Li S, Xu M, et al. Polymer- and lipid-based nanocarriers for ocular drug delivery. Adv Drug Deliv Rev. 2023;196:114770. https://doi.org/10.1016/j.addr.2023.114770 PMid:36894134

49. Reddy SH, Umashankar MS, Damodharan N. Solid lipid nanoparticles: a review. Res J Pharm Technol. 2018;11(12):5691-5700. https://doi.org/10.5958/0974-360X.2018.01031.4

50. Fahim M, Verma A, Faizan M. Nanoemulsions in novel drug delivery systems. J Pharmacogn Phytochem. 2024;13(5):562-567. https://doi.org/10.22271/phyto.2024.v13.i5h.15127

51. Kumar M, Chawla PA, Faruk A, et al. Solid self-nanoemulsifying drug delivery systems of nimodipine. Futur J Pharm Sci. 2024;10:87. https://doi.org/10.1186/s43094-024-00653-x

52. Miao Y, Zhao S, Zuo J, et al. Enhanced oral bioavailability using SNEDDS. Drug Des Devel Ther. 2022;16:1531-1546. https://doi.org/10.2147/DDDT.S356967 PMid:35637746 PMCid:PMC9143795

53. Zielińska A, Carreiró F, Oliveira AM, et al. Polymeric nanoparticles: production and toxicology. Molecules. 2020;25(16):3731. https://doi.org/10.3390/molecules25163731 PMid:32824172 PMCid:PMC7464532

54. Gillella S, M D, R S, et al. Polymeric nanoparticles - a review. J Innov Appl Pharm Sci. 2024;9(1):25-31. https://doi.org/10.37022/jiaps.v9i1.575

55. Hernández-Giottonini KY, Rodríguez-Córdova RJ, et al. PLGA nanoparticles by emulsification. RSC Adv. 2020;10:4218-4231. https://doi.org/10.1039/C9RA10857B PMid:35495261 PMCid:PMC9049000

56. Kothapalli VG, Vasanthan M. Solid lipid nanoparticles for oral absorption. Cureus. 2024;16(8):e68339. https://doi.org/10.1007/s12668-025-02277-8

57. Deng Y, Yang F, Zhao X, et al. Ibuprofen nanoparticles for skin penetration. Eur J Pharm Sci. 2018;114:293-302. https://doi.org/10.1016/j.ejps.2017.12.024 PMid:29288707

58. Halder A, Shukla D, Das S, et al. Lactoferrin-modified betulinic acid nanoparticles. Cytokine. 2018;110:412-415. https://doi.org/10.1016/j.cyto.2018.05.010 PMid:29784509

59. Silva BFB, Rodríguez-Abreu C, Vilanova N. Advances in multiple emulsions. Curr Opin Colloid Interface Sci. 2016;25:98-108. https://doi.org/10.1016/j.cocis.2016.07.006

60. Akram S, Anton N, Omran Z, Vandamme T. Water-in-oil nano-emulsions. Pharmaceutics. 2021;13:1030. https://doi.org/10.3390/pharmaceutics13071030 PMid:34371723 PMCid:PMC8309089

61. Piñón-Segundo E, Nava-Arzaluz MG, Lechuga-Ballesteros D. Double emulsion technique. Recent Pat Drug Deliv Formul. 2012;6(3):224-235. https://doi.org/10.2174/187221112802652606 PMid:22734870

62. Iqbal M, Zafar N, Fessi H, Elaissari A. Double emulsion solvent evaporation. Int J Pharm. 2015;496:173-190. https://doi.org/10.1016/j.ijpharm.2015.10.057 PMid:26522982

63. Geszke-Moritz M, Moritz M. Biodegradable polymeric nanoparticles. Polymers. 2024;16:2536. https://doi.org/10.3390/polym16172536 PMid:39274168 PMCid:PMC11397980

64. Piñón-Segundo E, Llera-Rojas VG, Leyva-Gómez G, et al. Emulsification-diffusion method. In: Grumezescu AM, editor. Pharmaceutical nanotechnology. 2018. p. 51-83. https://doi.org/10.1016/B978-0-12-813629-4.00002-4

65. Noriega-Peláez EK, Mendoza-Muñoz N, Ganem A, Quintanar D. Solvent displacement method. Drug Dev Ind Pharm. 2010;37(2):160-166. https://doi.org/10.3109/03639045.2010.501800 PMid:21073323

66. García-Salazar G, Zambrano-Zaragoza ML, Quintanar-Guerrero D. Nanodispersions using Venturi tube. Int J Pharm. 2018;545:254-260. https://doi.org/10.1016/j.ijpharm.2018.05.005 PMid:29729406

67. Fernández-Quiroz D, Tohidi MM, Paymard B, et al. Immobilization of essential oils. Stud Nat Prod Chem. 2023;78:365-401.

68. Wang H, Deng H, Gao M, Zhang W. Self-assembled nanogels. Front Bioeng Biotechnol. 2021;9:703559. https://doi.org/10.3389/fbioe.2021.703559 PMid:34336811 PMCid:PMC8322728

69. Mazayen ZM, Ghoneim AM, Elbatanony RS, et al. Pharmaceutical nanotechnology. Futur J Pharm Sci. 2022;8:12. https://doi.org/10.1186/s43094-022-00400-0 PMid:35071609 PMCid:PMC8760885

70. Chen D, Han S, Zhu Y, et al. Kidney-targeted nanoparticles. Int J Nanomedicine. 2018;13:3507-3527. https://doi.org/10.2147/IJN.S166445 PMid:29950832 PMCid:PMC6016261

71. Jiang B, Chen Z, Sun Y, et al. Superhydrophobic cotton fabrics. Appl Surf Sci. 2018;441:554-563. https://doi.org/10.1016/j.apsusc.2018.01.285

72. Hawkins M, Saha S, Ravindran E, Rathnayake H. Sol-gel polymerization method. J Polym Sci A. 2019;57(4):562-571. https://doi.org/10.1002/pola.29295

73. Umbarkar MG, Rindhe PS, Chandrawanshi SS, et al. Polymeric nanoparticles by nanoprecipitation. J Drug Deliv Ther. 2020;10(5-s):136-142. https://doi.org/10.22270/jddt.v10i5-s.4496

74. Kumoro AC, Wardhani DH, Kusworo TD, et al. Spray drying technology. J Hum Earth Future. 2024;5(2):279-305. https://doi.org/10.28991/HEF-2024-05-02-09

75. Arpagaus C, Collenberg A, Rütti D, et al. Nano spray drying for encapsulation. Int J Pharm. 2018;546:194-214. https://doi.org/10.1016/j.ijpharm.2018.05.037 PMid:29778825

76. Malamatari M, Charisi A, Malamataris S, et al. Spray drying for inhalation. Processes. 2020;8:788. https://doi.org/10.3390/pr8070788

77. Afonso IS, Cardoso B, Nobrega G, et al. Green synthesis of nanoparticles. J Environ Chem Eng. 2024;12(5):114022. https://doi.org/10.1016/j.jece.2024.114022

78. El-Naggar NEA, Shiha AM, Mahrous H, et al. Green synthesis of chitosan nanoparticles. Sci Rep. 2022;12:19869. https://doi.org/10.1038/s41598-022-24303-5 PMid:36400832 PMCid:PMC9674591

79. Roointan A, Xu R, Corrie S, et al. Nanotherapeutics in kidney disease. J Am Soc Nephrol. 2025;36(3):500-518. https://doi.org/10.1681/ASN.0000000608 PMid:39705082

80. Yang K, Shang Y, Yang N, et al. Nanoparticles in chronic kidney disease. Front Med (Lausanne). 2023;10:1132355. https://doi.org/10.3389/fmed.2023.1132355 PMid:37138743 PMCid:PMC10149997

81. Smith JP. Nanoparticle delivery of anti-tuberculosis chemotherapy. Yale J Biol Med. 2011;84(4):361-369.

82. Nair A, Greeny A, Nandan A, et al. Advanced strategies for tuberculosis treatment. J Nanobiotechnol. 2023;21:414. https://doi.org/10.1186/s12951-023-02156-y PMid:37946240 PMCid:PMC10634178

83. Sharma P, Prabhu A. Nanocarrier-mediated dermal drug delivery. IP Indian J Clin Exp Dermatol. 2025;11(1):10-21. https://doi.org/10.18231/j.ijced.2025.002

84. Krishnan V, Mitragotri S. Nanoparticles for topical drug delivery. Adv Drug Deliv Rev. 2020;153:87-108. https://doi.org/10.1016/j.addr.2020.05.011 PMid:32497707

85. Bhoyar V, Trivedi S, Gaikwad S, et al. Nanotechnology-based drug targeting. In: Rai M, Khan S, Belgamwar A, editors. Nanotechnology principles in drug targeting. Elsevier; 2023. p. 269-300. https://doi.org/10.1016/B978-0-323-91763-6.00007-2

86. Cao Y, Zhang R. Nanotechnology in Alzheimer's disease treatment. Front Bioeng Biotechnol. 2022;10:1042986. https://doi.org/10.3389/fbioe.2022.1042986 PMid:36466349 PMCid:PMC9713307

87. Ajith S, Almomani F, Elhissi A, Husseini GA. Nanoparticle-based anticancer delivery. Heliyon. 2023;9(11):e21227. https://doi.org/10.1016/j.heliyon.2023.e21227 PMid:37954330 PMCid:PMC10637937

88. Gomes HIO, Martins CSM, Prior JAV. Silver nanoparticles as anticancer carriers. Nanomaterials. 2021;11:964. https://doi.org/10.3390/nano11040964 PMid:33918740 PMCid:PMC8069134

89. Guerrini G, Magrì D, Gioria S, et al. Nanoparticle-based COVID-19 vaccines. Nat Nanotechnol. 2022;17:570-576. https://doi.org/10.1038/s41565-022-01129-w PMid:35710950

90. Prabhakar PK, Khurana N, Vyas M, et al. Nanotechnology for COVID-19 vaccine development. Pharmaceutics. 2023;15(2):451. https://doi.org/10.3390/pharmaceutics15020451 PMid:36839773 PMCid:PMC9960567

91. Jia Y, Jiang Y, He Y, et al. Approved nanomedicine against diseases. Pharmaceutics. 2023;15(3):774. https://doi.org/10.3390/pharmaceutics15030774 PMid:36986635 PMCid:PMC10059816