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NANOTECHNOLOGY THE FUTURE OF TARGETED DRUG DELIVERY AND CONTROLLED DRUG DELIVERY IN PHARMACEUTICS

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Abstract:
Nanotechnology is a rapidly advancing interdisciplinary domain that encompasses the design, synthesis, characterization, and application of materials and devices at the nanoscale, typically within the range of 1–100 nm. This field has significantly transformed numerous scientific and industrial sectors, including medicine, electronics, energy, and environmental sciences. In the pharmaceutical sciences, nanotechnology has become a cornerstone for developing innovative drug delivery systems such as nanosuspensions, liposomes, polymeric nanoparticles, metallic nanoparticles, and nanogels. These nano-based platforms enhance drug solubility, improve bioavailability, and enable precise and targeted delivery.

The present review provides an in-depth understanding of the fundamental concepts of nanotechnology, various classes of nanoparticles, and their broad applications in pharmaceutics. It further outlines recent progress in nanotechnology-enabled drug delivery systems, with an emphasis on targeting mechanisms and their therapeutic applications in cancer, neurological disorders, and infectious diseases. Additionally, the review discusses existing challenges, regulatory considerations, and future directions that may influence the successful translation of nanomedicine from experimental research to clinical practice. Overall, nanotechnology continues to hold immense promise in redefining the future of pharmaceutical science by supporting the development of more effective, precise, and personalized therapeutic strategies.

Keywords: *Nanotechnology, Micelle, Liposomes, Dendrimers, Carbon nanotubes, Quantum dots, Top down, bottom up, Characterization, Nanomedicine, Anticancer, Diabetes, Textiles, Energy, Environment, Controlled drug delivery, Targeted drug delivery.*

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INTRODUCTION:

The term nano originates from the Latin word meaning "dwarf," reflecting the extremely small scale at which nanotechnology operates. Nanotechnology represents a highly interdisciplinary field that integrates principles from chemistry, physics, biology, and material science to design, synthesize, and characterize materials and systems at the nanometer scale, typically between 1 and 100 nm. At this dimension, materials exhibit unique physicochemical properties due to their increased surface area and altered atomic interactions, enabling functionalities not observed at the bulk level.

Rather than being a single distinct discipline, nanotechnology serves as a convergence platform for multiple scientific areas, allowing researchers to develop innovative tools and technologies. Scientists worldwide are exploring its potential to address challenges in energy, environment, defense, and human health. These efforts envision a future where nanoscale materials contribute to sustainable energy production, environmental protection, and advanced medical interventions capable of early disease detection and effective treatment of conditions such as cancer, cardiovascular disorders, and diabetes. Although several scientific hurdles still remain, nanotechnology has facilitated significant breakthroughs and opened new avenues for molecular-level investigation and technological advancement.

The rapid growth of nanotechnology applications across numerous sectors has spurred increased interest in optimizing system performance in engineering, electronics, computing, and biomedical sciences. In the pharmaceutical field, nanotechnology has emerged as a transformative approach for enhancing drug delivery and therapeutic outcomes. A wide range of nanocarrier systems—such as liposomes, dendrimers, polymeric nanoparticles, solid lipid nanoparticles, and metallic nanostructures—have shown the ability to overcome limitations associated with conventional drug formulations. These nanoscale systems enable site-specific drug delivery, improved solubility, controlled and sustained release, and enhanced bioavailability. They can also traverse biological barriers, reduce off-target toxicity, and increase patient compliance by allowing reduced dosing frequency.

This review summarizes recent developments in nanotechnology-based drug delivery platforms, with particular attention to their targeting strategies and therapeutic roles in cancer, neurological disorders, and infectious diseases. Additionally, it addresses ongoing challenges, safety considerations, and regulatory frameworks that influence the successful clinical translation of nanomedicines.

PRINCIPLE OF NANOTECHNOLOGY:

Nanotechnology works on the principle that as the particle size reduction, their properties and change in behavior. It is a technology which is a small unit measurement which cannot be seen with our naked eye. It works on the materials whose dimensions ranges from 1 to 100 nanometers. The principles of nanotechnology are based on the unique behaviors exhibited by materials when their dimensions fall within the nanoscale range of 1–100 nm. At this scale, materials display distinct physicochemical characteristics primarily due to an increased surface area-to-volume ratio, which enhances reactivity, dissolution, and interaction with biological systems, making Nano sized materials particularly advantageous for drug delivery and catalytic applications. Quantum confinement effects also become significant, altering the optical, electrical, and magnetic properties of nanoparticles and enabling phenomena such as tunable fluorescence in quantum dots and superparamagnetic in metallic nanostructures. Another foundational principle is molecular self-assembly, where atoms and molecules spontaneously organize into ordered nanostructures through non-covalent interactions, forming systems such as liposomes, micelles, and dendrimers. Surface functionalization further contributes to the versatility of nanomaterials by allowing modification with polymers, ligands, or targeting moieties to improve stability, enhance biocompatibility, and facilitate targeted delivery. Additionally, the interaction of nanoparticles with biological systems is governed by the formation of a protein corona, which influences bio distribution, cellular uptake, and overall biological identity. Together, these principles explain the distinct behavior of nanomaterials compared to their bulk counterparts and support their extensive applications in pharmaceutics, electronics, environmental science, and biotechnology.

TYPES OF NANOPARTICLES

Various nanoparticles have been clinically used and approved till date. Some of the common are:

MICELLE:

The micelles consist of both lipids and amphiphilic molecules and they are also called as amphiphilic surfactants molecules. Its diameter ranges from 10-100nm. They enhancement of the solubility of hydrophobic drugs is a unique property of micelles. Thus, improving bioavailability. Under aqueous condition it consist of hydrophilic outer monolayer and a hydrophobic core which is used to incorporate hydrophobic therapeutic agents. They are applicable in drug delivery system, imaging agents and therapeutic agents.

LIPOSOMES

Liposomes are spherical particle sizes ranging from 30nm to several microns. It helps in incorporation of hydrophilic therapeutic agents in the aqueous space and hydrophobic therapeutic agents in the liposomal membrane. The modification of their surface characteristics can be done by using polymers, antibodies, proteins, nucleic acid.

DENDRIMERS:

Dendrimers are branched repeating units consist of central core and exterior functional groups. These functional groups are either anionic, cationic or neutral which is used to modify chemical and physical properties by modifying the entire structure. They have various applications in drug delivery and biomedical.

CARBON NANOTUBES

They are composed of several concentrically interlinked nanotubes and can be single walled or multi-walled. They have high loading capacities as drug carriers due to their high external surface area.

QUANTUM DOTS

These are semiconductor nanoparticles which exhibits their quantum effect in optical and electronic properties. Thet are applicable based on their emission, conversion and detection. It is also called as artificial atoms whose properties are determined by their nano scale size.

NANOTECHNOLOGY IN TARGETED DRUG DELIVERY

Targeted drug delivery system is defined as system in which drug is transported to the site of action. This system also prevents the unnecessary interactions with other health tissues. It helps in reducing the drug dosage and improving the uniformity of drug effect. It takes place in cytosol and cell membrane. Using large sized materials for drug delivery presents multiple difficulties such as low stability within the body, limited solubility and absorption, poor bioavailability and lack of precision in targeting specific sites.

Moreover, these materials can cause unwanted side effects. Hence, the development of advanced drug delivery system capable of directing drugs to particular regions of the body offers a promising solution to overcome these challenges.

Nanotechnology focuses on designing nanoscale materials made from polymers, lipids, or metals that can serve as efficient carriers for therapeutic agents. These nanoparticles (NPs) are capable of enhancing drug delivery by improving the biological stability, bioavailability, and controlled accumulation of drugs in the desired tissues. Colloidal-based nanocarriers can deliver drugs directly to targeted sites, thereby increasing treatment efficiency, minimizing toxicity, and reducing side effects. They also protect drugs from premature degradation and ensure spatial and temporal control over drug release at the specific site of a disease.

Initially, nanocarriers were primarily designed based on passive targeting mechanisms, where drugs accumulate in diseased tissues through the Enhanced Permeability and Retention (EPR) effect. However, active targeting approaches have now been developed, where nanoparticles are functionalized with specific ligands that recognize and bind to target cell receptors. This strategy enhances site-specific delivery and overall therapeutic performance. Nanotechnology therefore offers immense potential for innovation in both drug formulations and delivery systems.

Achieving a therapeutic outcome that effectively treats tumors, inflammatory, or immune-related diseases requires a system that delivers drugs precisely to the desired site. Consequently, ongoing research in nanotechnology seeks to explore novel materials, delivery agents, and modeling techniques to predict and optimize nanoparticle behavior within the body. Studies have also examined magnetic nanoparticles, lipid-based carriers, and biodegradable polymeric systems for targeted delivery of various drugs, particularly anticancer and antiviral agents.

Overall, nanotechnology-based delivery platforms, such as liposomes, polymeric nanoparticles, and hybrid nano systems represent a major advancement in overcoming the limitations of traditional therapies. By enhancing bioavailability, reducing systemic toxicity, and ensuring controlled release, they have significantly improved the efficiency and safety of drug delivery systems.

NANOTECHNOLOGY IN CONTROLLED DRUG DELIVERY SYSTEM:

Nanoscience and nanotechnology have greatly influenced the advancement of controlled drug delivery (CDD) systems by providing innovative scientific tools for precise manipulation and observation at the molecular level. These technologies have enhanced our understanding of diseases and drug actions, paving the way for the development of safer and more efficient therapeutic methods. With the ability to design nanomedicines that specifically target diseased cells or organelles, drug release can now be localized and optimized according to the body's therapeutic needs in real time.

The emergence of nanotechnology in pharmaceuticals has led to improved characterization techniques and more efficient drug formulation processes. Modern methods such as combinatorial chemistry and high-throughput screening have accelerated the discovery of new biomaterials and bioactive agents. Furthermore, nanomedicines are designed to enhance the safety, efficacy, and bioavailability of therapeutic compounds, addressing long-standing challenges in conventional drug delivery.

Successful integration of nanomedicine into clinical applications requires interdisciplinary collaboration, focusing on both technological innovation and regulatory compliance. The use of nanocarriers-like liposomes, polymeric nanoparticles, and micelles, has shown promising results for targeted therapy, sustained release, and reduction of side effects. However, ongoing challenges such as large-scale production, long-term safety, and ethical concerns remain to be resolved.

In addition, genomic and molecular biology tools have improved the identification of specific cellular targets and clarified the mechanisms of drug action. Understanding cellular transport systems, such as ATP-binding cassette (ABC) transporters, has further contributed to overcoming drug resistance and improving therapeutic outcomes. Recent progress in bioengineering and nanocarrier systems continues to drive innovation in targeted and controlled drug delivery, moving toward more precise and personalized treatments.

ADVANTAGES:

- The small size of nanocarrier in nanotechnology improve solubility and permeability of poorly water-soluble drugs. The small size of particles allows for site specific targeted, reducing systemic side effects and improving therapeutic activity.
- Nanotechnology ensures prolonged therapeutic activity by designing of drug delivery systems capable of providing controlled or sustained drug release.
- Nanotechnology has enhanced diagnostic and imaging capabilities.
- Nanotechnology allows the development of diverse formulations and is versatile in formulation design.
- It improves pharmacokinetic and pharmacodynamic profiles resulting in improved bio efficacy.
- It improves stability of formulations by enhancing the physical and chemical stability of drugs.
- It requires lower doses and fewer administrations which reduces long term treatment cost.

DISADVANTAGES:

- Many nanoparticles—particularly metallic and inorganic ones such as silver, zinc oxide, and carbon nanotubes—can cause cellular and genetic toxicity, as well as oxidative damage in biological systems. Due to their nanoscale size, they can easily cross biological membranes, accumulate within various organs, and potentially induce long-term adverse effects that are not yet fully understood.
- The production of nanomaterials typically demands sophisticated equipment and intricate manufacturing methods, which increases costs and limits large-scale application, especially in developing countries. Additionally, unsafe disposal or unintentional release of these materials can pollute soil and water, resulting in their accumulation in living organisms and causing disturbances to ecological balance.
- The synthesis of nanomaterials generally involves the use of specialized equipment and intricate techniques, which makes mass production costly and less feasible in developing countries.
- Improper disposal or accidental leakage of nanomaterials can pollute soil and water, resulting in their buildup within plants, animals, and humans, which may ultimately disturb ecological balance.
- The long-term effects of continuous exposure to nanomaterials on human health and the environment are still uncertain, highlighting the need for comprehensive toxicological and epidemiological studies.
- Regulatory agencies closely evaluate nano formulated drugs because of issues related to their pharmacokinetics, stability, and possible toxicity, which often results in extended approval processes.

PREPARATION METHODS USED IN NANOTECHNOLOGY:

Nanotechnology mainly uses mainly two methods to create nanomaterials or nanosuspensions. One is conventional method of precipitation called as Bottom-up Technology and the other are disintegration methods called as Top-Down Technology. Disintegration methods are preferred over precipitation methods.

Bottom-Up Technology:

Bottom-up techniques begin at the molecular level, allowing atoms or molecules to assemble into larger structures. Methods such as precipitation, solvent–antisolvent crystallization, and supercritical fluid processing rely on controlled nucleation and growth to create nanoparticles. These techniques are particularly useful for producing uniform particles of poorly soluble drugs and offer excellent control over crystal morphology and composition. However, stabilizers are often required to prevent aggregation and ensure long-term dispersion stability.

1.Precipitation method: Over the last ten years, the precipitation method has been widely employed to produce submicron particles, especially for drugs with poor solubility. In this process, the drug is first dissolved in a suitable solvent and then mixed with a miscible antisolvent, usually water, in the presence of surfactants. Rapid addition of the drug solution to the antisolvent causes supersaturation, leading to the creation of fine crystalline or amorphous drug particles. The process occurs in two main steps: nucleation and crystal growth. Achieving a high nucleation rate and a low crystal growth rate is crucial for obtaining a stable dispersion with minimal particle size. Temperature plays a significant role in these steps—the best temperature for nucleation is often lower than that for crystal growth, enabling control through temperature adjustment. This technique is straightforward, inexpensive, and easily scalable for industrial use. However, the use of surfactants is required to manage crystal growth, and the drug must be soluble in at least one of the solvents used.

2.Super Critical Fluid Process: Supercritical fluid (SCF) techniques, when integrated with solubilization and nanosizing methods, help achieve further particle size reduction. SCFs are dense, non-condensable fluids that exist at temperatures and pressures above their critical temperature (Tc) and critical pressure (Tp). This approach enables the micronization of drug particles down to the submicron range. Recent developments in SCF technology have made it possible to produce nanoparticle suspensions with sizes between 5 and 2000 nm. However, the limited solubility of surfactants and poorly water-soluble drugs in supercritical CO_2, along with the need for high operating pressures, restricts the broader use of this technique in the pharmaceutical industry.
Additionally, newer bottom-up approaches—such as liquid antisolvent precipitation, acid-base-assisted precipitation, and emulsion polymerization—provide improved control over particle size and distribution.

3.Liquid emulsion technique: The Liquid emulsion technique is a widely used method for preparing nanoparticles, microspheres, and nanocarriers in pharmaceutical formulations. It is based on forming an emulsion a mixture of two immiscible liquids usually oil and water followed by solidification of the dispersed phase. The method involves emulsifying a drug containing polymer solution in an aqueous phase with the help of surfactants or stabilizers. When the solvent of the dispersed phase evaporates or diffuses, nanoparticles are formed.

4.Solvent Antisolvent: The solvent–antisolvent method is a widely adopted approach for producing nanoparticles, especially for drugs with low aqueous solubility. The technique is based on the principle that when a solution containing the drug in a suitable solvent is introduced into another liquid (the antisolvent) in which the drug is poorly soluble, a sudden decrease in solubility occurs. This causes rapid supersaturation, leading to nucleation and subsequent formation of fine drug particles.

In this process, the drug (and sometimes a stabilizer or polymer) is first dissolved in a water-miscible organic solvent such as acetone, ethanol, or acetonitrile. The prepared drug solution is then slowly added or injected into an antisolvent like water under continuous stirring or sonication. Surfactants such as polyvinylpyrrolidone (PVP), Tween 80, or poloxamers are commonly used to prevent aggregation and maintain particle stability. The resulting nanoparticles are collected by centrifugation or filtration, washed to remove residual solvents, and dried—often by lyophilization—to obtain the final product.

The key factors that affect nanoparticle formation include the solvent-to-antisolvent ratio, mixing speed, temperature, and stabilizer concentration. Faster mixing and higher supersaturation levels typically produce smaller and more uniform particles.

This method is simple, rapid, and easily scalable, making it ideal for preparing nanoparticles of poorly water-soluble drugs. However, it has certain drawbacks such as possible particle agglomeration without stabilizers and residual solvent traces in the final formulation.

Top-Down Technology:
Top-down techniques start with bulk materials that are mechanically reduced to the nanoscale. Media milling, high-pressure homogenization, micro fluidization, and co-grinding are among the most established methods in pharmaceutical nanotechnology. These techniques are valued for their scalability, reproducibility, and ability to process a wide range of drug types. However, they may generate heat, require substantial energy input, and pose risks such as contamination from milling media.

1.Media Milling: Nanosuspensions are commonly prepared using high-shear media or pearl milling techniques. The milling system typically includes a milling chamber, shaft, and recirculation unit. In this process, an aqueous drug suspension is introduced into the mill containing small grinding balls or pearls. As these media rotate at high shear rates under controlled temperature conditions, they collide with the drug particles and the chamber walls, generating intense friction and impact forces that effectively reduce particle size. The grinding media are generally composed of materials such as ceramic-sintered aluminum oxide, zirconium oxide, or highly cross-linked polystyrene resin, all known for their strong abrasion resistance. Planetary ball mills (e.g., PM100 and PM200, Retsch GmbH & Co., KG, Haan, Germany) are examples of equipment capable of achieving particle sizes below 0.1 µm. For instance, a Zn–Insulin nanosuspension with an average particle size of 150 nm has been successfully produced using the wet milling approach. However, this technique has some limitations, including potential contamination from the erosion of milling media, thermal degradation of heat-sensitive drugs due to process-generated heat, and the formation of relatively large particles (≥5 µm) within the final product.

2. High-Pressure Homogenization: High-pressure homogenization is a widely adopted top-down method for generating nanosuspensions from coarse drug particles. During this process, a drug dispersion is forced at extremely high pressure through a narrow homogenization valve. Inside the valve, the sudden drop in pressure creates intense turbulence and cavitation bubbles. When these bubbles collapse, powerful shear and impact forces fracture the drug particles into the nanometer range. Multiple homogenization cycles are typically required to achieve uniform particle size distribution, with parameters such as pressure intensity, formulation viscosity, and drug hardness influencing efficiency. The technique is suitable for both dilute and concentrated systems, scalable to industrial production, and compatible with sterile manufacturing environments.

3.Co-Grinding: Co-grinding, also referred to as dry co-grinding or mechanochemical milling, is a top-down approach employed to achieve nanoscale particle reduction. In this technique, the active pharmaceutical ingredient (API) is simultaneously ground with one or more excipients—such as polymers, stabilizers, or surfactants—to decrease particle size, modify surface properties, and enhance dissolution performance. The mixture of drug and excipient is introduced into a milling chamber containing grinding media, where it is exposed to mechanical forces including shear, impact, and attrition. These forces not only reduce the particle size of the drug but also promote uniform mixing with the excipients. The incorporated excipients serve several critical functions: they prevent aggregation of nanoparticles, aid in disrupting the drug's crystalline matrix (leading in some cases to partial amorphization), and modify surface characteristics—such as increasing hydrophilicity—which collectively improve wettability and dissolution behavior.

4.Microfluidization: Micro fluidization is an advanced top-down nanonization technique used to produce nanosuspensions and nano emulsions with narrow particle size distribution and enhanced physical stability. It operates on the principle of high-pressure fluid dynamics, where a coarse drug suspension or emulsion is forced through microchannels within a microfluidizer under extremely high pressures—typically ranging from 500 to 2000 bar. Inside the interaction chamber, the fluid streams collide at high velocity within precisely engineered microchannels, creating intense shear, cavitation, and impact forces that break down coarse drug particles into the nanometer range (generally 50–500 nm). The process utilizes a unique system of fixed-geometry microchannels to ensure uniform energy input and reproducibility. Compared to conventional high-pressure homogenization, micro fluidization offers more consistent particle size reduction, improved scalability, and better control over product uniformity. The technique also facilitates the formation of stable nanosuspensions, liposomes, and lipid nanoparticles without significant thermal degradation, making it especially useful for thermolabile and poorly water-soluble drugs**.** micro fluidization can be performed in a continuous process, which makes it highly suitable for industrial applications. The number of processing cycles, operating pressure, and formulation components (such as surfactants or stabilizers) determine the final particle size and stability.

CHARACTERIZATION TECHNIQUES:

In- Vitro Evaluations:

In-vitro evaluation plays a critical role in understanding the behavior of nanoscale drug delivery systems. Key parameters include particle size distribution, surface charge, morphology, and dissolution properties. Techniques such as dynamic light scattering (DLS), laser diffraction, and Coulter counting provide insights into size uniformity and potential aggregation. Crystallinity and structural changes induced during processing can be studied using X-ray diffraction, differential scanning calorimetry, or thermal analysis. Zeta potential measurements help predict colloidal stability by assessing electrostatic repulsion among dispersed particles. Assessing saturation solubility and dissolution rate in physiologically relevant media provides information on the formulation's ability to enhance bioavailability. Additional parameters such as viscosity, pH, and organoleptic characteristics support the development of robust, stable, and patient-acceptable products.

1. **Organoleptic Properties:** In the development of oral formulations, physicochemical properties such as particle size, crystal habit, and disintegration behavior play a crucial role in determining the product's overall sensory and stability profile. Variations in these parameters can significantly influence the organoleptic characteristics, particularly taste, which is a critical factor affecting patient compliance, especially in pediatric and geriatric populations. For instance, smaller particle sizes may enhance dissolution and alter the perceived intensity of taste, while changes in crystal form can affect both solubility and mouthfeel.
Moreover, sensory changes such as alterations in taste, odor, or color often serve as early indicators of chemical instability or degradation processes occurring within the formulation. These changes may result from oxidation, hydrolysis, or interactions between the active pharmaceutical ingredient (API) and excipients. Therefore, continuous monitoring of these physical and sensory attributes is essential during formulation development and stability testing to ensure product quality, efficacy, and patient acceptability.

2. **Particle Size Distribution:** Particle size plays a vital role in determining key physicochemical properties such as dissolution rate, saturation solubility, and physical stability of a formulation. Various analytical techniques are employed to assess particle size distribution, including the Coulter Counter Multisizer, laser diffraction (LD), and photon correlation spectroscopy (PCS). PCS is capable of measuring particles within the range of 3 nm to 3 µm, whereas LD covers a broader range of approximately 0.05–80 µm. Unlike LD, which provides a relative size distribution, the Coulter Counter Multisizer offers an absolute particle count. For intravenous (IV) formulations, it is essential to maintain particle sizes below 5 µm to prevent potential complications such as capillary blockage or embolism, since the smallest capillaries measure around 5–6 µm in diameter.

3. **Dissolution rate and saturation solubility:** Nanosuspensions offer a distinct advantage over conventional formulations by enhancing both saturation solubility and dissolution rate. Evaluating these properties in various physiological media is essential to fully understand the formulation's in vitro performance. As reported by Böhm et al., reducing particle size to the nanoscale can significantly increase dissolution pressure and rate, demonstrating that smaller particles dissolve more rapidly.

4. **Crystal morphology:** Crystal morphology can be evaluated using techniques such as X-ray diffraction (XRD) in combination with differential thermal analysis (DTA) or differential scanning calorimetry (DSC) to investigate the effects of high-pressure homogenization on a drug's crystalline structure. In nanosuspensions, this process may induce changes in crystallinity, leading to the formation of amorphous regions or alternative polymorphic forms.

5. **Zeta potential:** Zeta potential is commonly used to assess the stability of colloidal suspensions. For suspensions stabilized purely by electrostatic repulsion, a zeta potential of at least 30 mV is generally required to ensure stability. However, when both electrostatic and steric stabilization mechanisms are present, a lower zeta potential of around 20 mV is considered sufficient to maintain stability.

6. **pH Value:** The pH of an aqueous formulation should be measured at a controlled temperature to prevent "pH drift" and avoid electrode surface fouling caused by suspended particles, ensuring that equilibrium has been reached. To maintain pH stability, it is recommended to exclude electrolytes from the external phase of the formulation.

7. **Droplet Size:** The droplet size distribution in microemulsion vesicles can be characterized using electron microscopy. Alternatively, dynamic light scattering (DLS) with a neon laser at 632 nm can be employed for precise size measurements.

8. **Viscosity Measurement:** The viscosity of lipid-based formulations with varying compositions can be evaluated using a rotational Brookfield viscometer across different shear rates and temperatures. Samples should be placed in the instrument's thermally controlled chamber, maintained at 37°C, to ensure accurate measurements.

In Vivo Evaluations:
Evaluating nanotechnology-based formulations in vivo is essential to understand their pharmacokinetic and pharmacodynamic profiles, biodistribution, toxicity, and therapeutic efficacy. Key parameters

include absorption, distribution, metabolism, and excretion (ADME), which determine the formulation's bioavailability and targeting efficiency. Imaging techniques such as fluorescence, MRI, or PET can track nanoparticles in real time, providing insights into tissue distribution and accumulation. Additionally, hematological and biochemical analyses are conducted to assess systemic toxicity, while histopathological studies evaluate potential organ-specific effects. Overall, in vivo characterization ensures that nanotechnology-based systems are both safe and effective for clinical applications.

1.Safety and Toxicity: Despite their advantages, nanoparticles may pose unique toxicological challenges. In vivo toxicity assessments include hematological and biochemical analysis, as well as histopathological examinations of major organs. These studies evaluate potential systemic toxicity, immune responses, and organ-specific damage. The safety profile often depends on the nanoparticle's material, size, surface chemistry, and dose.

2.Therapeutic Efficacy: In vivo performance studies also include the evaluation of pharmacodynamic responses in relevant disease models. Nanoparticles have demonstrated improved efficacy in tumor regression, infection control, and sustained drug release compared to conventional formulations. Controlled release, targeted delivery, and reduced systemic exposure contribute to enhanced therapeutic outcomes.

3. Imaging Techniques: Non-invasive imaging allows dynamic tracking of nanoparticles in living organisms:

- Fluorescence Imaging: Real-time tracking using fluorescent probes; limited by tissue penetration.
- Bioluminescence Imaging: High sensitivity detection of nanoparticles via luminescent reporters.
- Magnetic Resonance Imaging (MRI): High-resolution, non-ionizing imaging of nanoparticle localization.
- PET/CT: Combines functional and anatomical imaging using radiolabeled nanoparticles for quantitative biodistribution.

4.Histological Analysis: Histology provides tissue-level insights into nanoparticle effects:

- Hematoxylin & Eosin (H&E) Staining: Evaluates tissue morphology and pathological changes.
- Immunohistochemistry (IHC): Detects biomarkers for apoptosis, inflammation, or cellular uptake.

5.Blood and Serum Analysis: Assesses systemic toxicity and organ function:

- Liver and Kidney Function Tests: ALT, AST, creatinine, and BUN as indicators of organ health.
- Complete Blood Count (CBC): Monitors hematological changes or immune activation

6.Molecular Techniques: Quantitative analysis of biological responses:

- ELISA: Measures cytokine levels to assess immune or inflammatory responses.
- PCR: Quantifies gene expression changes induced by nanoparticle treatment.

7.Biodistribution Tracking: Determines organ-specific accumulation and clearance:

- Radioisotope Labeling: Highly sensitive quantitative tracking.
- Fluorescent Dye Labeling: Visual confirmation of localization in organs and tissues.

8.Evaluation of Surface-Modified Particles (Surface Hydrophilicity): For intravenously administered nanosuspensions, several additional parameters must be assessed as they influence the in vivo behavior of drug nanoparticles. Among these, surface hydrophilicity or hydrophobicity is a critical determinant of organ distribution following intravenous injection. The degree of surface hydrophobicity influences nanoparticle interactions with cells prior to phagocytosis and plays a key role in plasma protein adsorption, which in turn governs organ targeting and biodistribution. To obtain accurate measurements, surface hydrophobicity should be evaluated in the nanoparticles' native aqueous dispersion environment to avoid artifacts. Hydrophobic interaction chromatography (HIC), originally used for assessing bacterial surface hydrophobicity, has been successfully adapted for characterizing the surface properties of nanoparticulate drug carriers.

9.Interaction with Body Proteins: Nanoparticle interactions with proteins, such as mucin, can be assessed in vitro by incubating nanoparticles with mucin (1:4 w/w) under physiological conditions (37°C) in acidic or neutral media. After centrifugation, the unbound mucin in the supernatant is quantified using a Micro BCA Protein Assay, and adsorption is calculated from the difference between initial and remaining mucin concentrations, based on a standard curve. This method provides insight into protein–nanoparticle interactions relevant to in vivo behavior

APPLICATIONS: -

1. **Nanomedicine:** -Nanotechnology has revolutionized healthcare by enabling targeted

drug delivery, advanced diagnostics, and regenerative therapies. Nanoscale carriers, including liposomes, polymeric nanoparticles, dendrimers, and metallic nanoparticles, enhance drug bioavailability and specificity while minimizing systemic toxicity. For instance, studies have demonstrated that liposomal doxorubicin preferentially accumulates in tumor tissues, reducing cardiotoxic effects. Furthermore, nanoparticles serve as contrast agents in imaging techniques such as MRI, PET, and CT, thereby improving early disease detection.

2. **Diagnostics and Imaging: -** The integration of nanomaterials into diagnostic platforms has significantly improved the sensitivity and precision of biomarker detection. Materials such as quantum dots, gold nanoparticles, and magnetic nanoparticles are widely used in biosensing and molecular imaging applications, facilitating the detection of low-abundance biological targets. Gold nanoparticles, for example, can be functionalized with antibodies to enable rapid, colorimetric detection of cancer biomarkers.

3. **Electronics and Information Technology: -** In electronics, nanotechnology supports device miniaturization and enhanced performance. Carbon-based nanomaterials, including graphene and carbon nanotubes, exhibit exceptional electrical conductivity and mechanical strength, enabling the development of faster, smaller, and more energy-efficient components such as transistors, memory devices, and sensors.

4. **Food and Agriculture: -**Nanotechnology offers innovative solutions in agriculture and food safety. Nano formulated fertilizers and pesticides enable controlled release, reducing environmental impact while improving efficacy. Research indicates that nano-encapsulated pesticides can minimize leaching and optimize targeted delivery to crops, enhancing productivity and sustainability.

5. **Cosmetics and Consumer Products: -** In consumer products, nanomaterials enhance functionality and performance. Titanium dioxide and zinc oxide nanoparticles provide superior UV protection in sunscreens without leaving a visible residue. Moreover, nanotechnology facilitates antimicrobial coatings, improved stability, and enhanced texture in cosmetic and textile formulations.

6. **Anticancer: -** Biomedical applications, particularly in cancer therapy, have driven significant interest in certain nanomaterials. Precious metals, notably gold (Au) and silver (Ag), as well as magnetic oxides such as magnetite (Fe_3O_4), have been extensively studied, alongside quantum dots and naturally derived nanoparticles (Bououdina et al., 2013). Additionally, the distinctive up conversion properties of up conversion nanoparticles (UCNPs) offer potential for activating photosensitive therapeutic agents, providing promising strategies for cancer treatment.

7. **Application in food: -**The term nanofood refers to foods developed using nanotechnology techniques, tools, or engineered nanomaterials introduced at any stage of cultivation, production, processing, or packaging. The development of nanofood serves multiple purposes, including improving food safety, enhancing nutritional value and flavor, and reducing production and consumer costs. Moreover, nanofood offers additional benefits such as health-promoting additives, extended shelf life, and novel flavor profiles. The application of nanotechnology in the food sector is rapidly expanding, encompassing the entire food chain from agricultural practices to food processing and improved nutrient bioavailability.

8. **Applications of Nanoparticles in Gene Delivery: -** Gene delivery is a critical technique for efficiently introducing a target gene to achieve expression of its encoded protein in a suitable host or host cell. Traditionally, gene delivery systems have relied on viral vectors, including retroviruses and adenoviruses, as well as non-viral approaches such as nucleic acid electroporation and transfection. In recent years, nanoparticles have emerged as promising carriers for gene delivery, offering advantages such as enhanced cellular uptake, protection of nucleic acids from degradation, targeted delivery, and reduced immunogenicity.

9. **Targeted Drug Delivery: -**The size of drug-loaded nanoparticles plays a crucial role in their absorption and overall therapeutic efficacy. Targeted delivery can be achieved by modulating the in vivo behavior of nanoparticles through modifications of their physicochemical properties, particularly the surface characteristics. Approaches such as the development of smart crystals or stealth nanocrystals with particle sizes below 100 nm enable precise targeting. Among these strategies, the formulation of nanosuspensions offers a cost-effective and straightforward method for achieving targeted delivery. Key surface properties—including hydrophobicity,

surface charge, and the type or density of functional groups—significantly influence the biodistribution of nanoparticles. Notably, the potential of Tween 80-coated nanocrystals for brain-targeted delivery has been demonstrated; for instance, atovaquone nanocrystals coated with Tween 80 effectively eliminated parasites in the brain during toxoplasmosis treatment, highlighting the promise of surface-engineered nanoparticles for organ-specific therapy.

10. **Energy Applications: -**Nanotechnology plays a significant role in advancing both conventional and alternative energy technologies to address growing global energy needs. Current research focuses on utilizing nanoscale materials to develop cleaner, more efficient, and environmentally sustainable energy systems. In conventional energy production, nanomaterials are being used to enhance catalytic processes, allowing petroleum-based fuels to be refined more efficiently and with lower energy input. Nanoscale additives and engineered surfaces also contribute to improved performance in engines and power plants by promoting more complete combustion and reducing mechanical friction, ultimately lowering overall fuel consumption. These innovations highlight the potential of nanotechnology to optimize traditional energy systems while supporting the transition toward more sustainable energy solutions.

11. **Environmental Applications: -**Nanotechnology offers several eco-friendly solutions for environmental management. Ion-based air purification systems enhance the removal of airborne pollutants, while advanced wastewater treatment technologies—such as nanobubbles and nanofiltration membranes, enable efficient elimination of heavy metals and other contaminants. Additionally, nano catalysts contribute to cleaner industrial processes by improving reaction efficiency and reducing the generation of harmful by-products.

12. **Cardiovascular diseases: -**cardiovascular diseases remain the leading cause of death worldwide, with coronary artery disease (CAD) contributing significantly to global morbidity and mortality. Despite remarkable progress in cardiovascular research and diagnostic technologies, existing clinical tools for the detection and management of CAD still face considerable limitations. Nanotechnology, as an interdisciplinary innovation, offers promising solutions to overcome these challenges. In the therapeutic domain, various nanocarriers such as liposomes, polymeric nanoparticles (e.g., PLGA), inorganic nanoparticles (AuNPs, MnO_2), natural nanoparticles (HDL, hyaluronic acid), and biomimetic platforms (such as cell-membrane–coated nanostructures) are being engineered for targeted delivery of drugs, peptides, proteins, and nucleic acids directly to pathological lesions. Additionally, some nanomaterials exhibit intrinsic therapeutic activities—including antioxidative, anti-inflammatory, photothermal, and photoelectric properties—making them valuable candidates for modulating the complex microenvironment of atherosclerotic plaques.
Overall, ongoing advancements in nanotechnology and their translation into clinical practice are expected to significantly broaden the scope of nanoscale strategies for the diagnosis and treatment of CAD in the near future. The incorporation of diverse nanomaterials has markedly enhanced the sensitivity and specificity of biosensors used for detecting cardiovascular biomarkers. Moreover, molecular imaging techniques—including magnetic resonance imaging, optical imaging, nuclear scintigraphy, and multimodal imaging—have benefited substantially from nanoparticle-assisted signal amplification and targeted contrast delivery.

13. **Diabetes: -**Nanotechnology has significantly advanced diabetes research by enabling innovative strategies for both glucose monitoring and insulin administration. Recent developments highlight how nanoscale materials have improved the performance of glucose-sensing platforms. Metal nanoparticles, carbon-based nanostructures, and other nanomaterials enhance sensor sensitivity, accelerate response times, and support the creation of continuous in vivo glucose monitoring systems. Beyond diagnostics, nanotechnology is also central to emerging "closed-loop" insulin delivery systems, in which insulin release is automatically modulated according to real-time blood glucose levels. By integrating nanoscale biosensors with smart delivery vehicles, such closed-loop approaches aim to minimize patient intervention and have the potential to substantially enhance metabolic control and overall quality of life for individuals with diabetes.

14. **Textiles: -**Nanotechnology in the textile sector involves manipulating and tailoring materials at the nanoscale to modify their physical, chemical, and biological properties. By engineering matter at the level of atoms, molecules, and nanoscale structures, it becomes possible to design textiles with enhanced

performance and entirely new functionalities. Recent nanotechnological advancements have introduced both promising opportunities and notable challenges for the textile industry, influencing the development of next-generation fibers, yarns, and fabrics. This review highlights contemporary applications of nanomaterials in textiles and provides an overview of how nanoscale innovations are transforming conventional textile materials.

NANOTECHNOLOGY IN ANCIENT TIMES:

Long before the emergence of the modern "nano era," humans encountered and utilized nanoscale phenomena, albeit without a scientific understanding of the underlying principles. Early civilizations often exploited unique properties of materials at the nanoscale intuitively. Although they observed that small particles of certain substances exhibited properties distinct from larger particles, the scientific rationale behind these effects remained unknown. Knowledge of nano production was frequently transmitted through generations, preserving techniques without comprehension of the nanoscale mechanisms involved.

As early as several thousand years BC, humans cultivated and processed natural fabrics such as flax, cotton, wool, and silk. These materials are inherently nanoporous, with pore sizes ranging from 1 to 20 nanometers. The nanoscale porosity of these fabrics contributed to their remarkable functional properties, including efficient sweat absorption, rapid swelling, and quick drying.

Nanotechnology principles were also central to ancient food processing. Fermentation processes involved in making bread, wine, beer, and cheese rely on nanoscale biochemical reactions that were exploited empirically.

Evidence of nanoscale applications in cosmetics is found in Ancient Egypt. Hair dyeing, previously thought to rely solely on plant-based pigments such as henna, has been shown to involve nanoparticles. Studies of hair samples from Egyptian burial sites by Ph. Walter revealed that black dyes were produced by combining lime, lead oxide, and water, resulting in the formation of lead sulfide (galena) nanoparticles. These nanoparticles interacted with keratin-bound sulfur to create uniform, long-lasting coloration.

Nanotechnology also played a role in ancient glassmaking. The British Museum houses the Licurgus Cup, a Roman artifact exhibiting remarkable color-changing optical properties appearing green in reflected light and red when illuminated from within. Analysis conducted by General Electric in 1959 revealed the glass contained about 1% gold and silver and 0.5% manganese. Later investigations using advanced electron microscopy confirmed the presence of 50–100 nm gold and silver nanoparticles, responsible for the cup's unique coloration. This phenomenon is now explained by plasmonic effects, as discussed by H.A. Atwater in a 2007 review in Scientific American. Similarly, medieval European stained-glass windows incorporated metallic nanoparticles, particularly gold, to achieve vibrant, long-lasting colors.

The production of Damascus steel blades during the Crusades provides another example of early nano structuring. European knights noted the extraordinary strength and sharpness of these blades, which could not be replicated by contemporary metallurgical methods. In 2006, P. Paufler's analysis of Damascus steel fragments via electron microscopy revealed a nanofibrous structure, likely resulting from specialized thermomechanical processing of ore with unique properties.

In summary, although ancient civilizations lacked formal scientific knowledge, they inadvertently harnessed nanoscale effects across textiles, food, cosmetics, glassmaking, and metallurgy. These historical examples demonstrate that intuitive nanotechnology has been an integral, if unrecognized, part of human innovation for millennia.

Long before nanotechnology became a scientific discipline, ancient civilizations unknowingly harnessed nanoscale phenomena. Natural fibers such as cotton, wool, and silk exhibit intrinsic nanoporous structures that contributed to their absorbency, breathability, and comfort. Early fermentation processes used in bread, wine, and cheese relied on nanoscale biochemical transformations, despite limited understanding of microbiology. Egyptian artisans produced black hair dyes using mixtures that generated lead sulfide nanoparticles, enabling durable and uniform coloration. The Roman Lycurgus Cup demonstrates early use of metallic nanoparticles, where gold and silver particles in the glass caused the vessel to shift color under different lighting. Similarly, medieval stained-glass makers unknowingly created plasmonic nanoparticles that produced vibrant hues. The exceptional strength of Damascus steel has also been attributed to carbon nanotube-like nanostructures formed during its unique forging process. These examples highlight how ancient practices often exploited nanoscale effects through empirical craftsmanship.

RECENT ADVANCES IN NANOTECHNOLOGY:

Nanotechnology is a rapidly evolving field characterized by continuous innovations and breakthroughs across diverse scientific and industrial domains. While ongoing developments occur at a fast pace, several notable recent trends can be highlighted:

Nanomedicine: Significant progress has been made in the development of targeted drug delivery systems, particularly for cancer therapy, enabling more precise and effective treatments. In addition, nanoscale imaging agents are being engineered for earlier and more accurate disease diagnosis.

Nanoelectronics: Efforts continue to push the limits of Moore's Law, with the design of nanoscale transistors, memory devices, and novel 2D materials such as graphene for electronic components and interconnects.

Quantum Nanotechnology: Advances in quantum computing and communication rely on nanoscale quantum bits (qubits), while quantum sensors and detectors are being developed for applications in metrology, cryptography, and precision measurement.

Energy Applications: Nanomaterials are increasingly applied to energy technologies, including high-efficiency solar cells (notably perovskite-based), high-capacity batteries, supercapacitors, and thermoelectric devices aimed at improving energy conversion and storage.

Environmental Remediation: Nano catalysts and nanomaterial-based filtration systems are being explored for pollution control, wastewater treatment, and water purification, offering enhanced efficiency and sustainability.

Materials Science: Novel nanocomposites with improved strength, conductivity, and other functional properties are being developed. Advances in nanoscale fabrication techniques also support the manufacturing of miniaturized devices and components.

Food and Agriculture: Nanotechnology is being applied in food packaging to extend shelf life and reduce waste. Nanoscale delivery systems for precision agriculture, including targeted nutrient and pesticide delivery, are also gaining attention.

Nanorobotics: Progress is being made in engineering nanoscale robots capable of performing tasks at the molecular level, with potential applications in medicine, manufacturing, and environmental monitoring.

Ethics, **Safety**, **and Responsible Research**: Increased focus is being placed on ethical considerations, safety protocols, and responsible research practices to ensure the sustainable and safe development of nanotechnology.

Advanced Imaging Techniques: Cutting-edge methods such as cryo-electron microscopy are enabling high-resolution visualization of nanoscale structures and dynamic processes.

Space and Clean Energy Applications: Nanotechnology is being explored in spacecraft materials, propulsion systems, sensors for space missions, and in technologies that enhance clean energy production and storage.

FUTURE PROSPECTS OF NANOTECHNOLOGY IN DRUG DELIVERY:

Nanotechnology has revolutionized pharmaceutical sciences by offering innovative solutions to longstanding challenges such as poor solubility, low bioavailability, and limited stability of therapeutic agents. Among various nanotechnology-based approaches, nanosuspensions have emerged as a promising platform for enhancing the delivery of hydrophobic drugs that are poorly soluble in both aqueous and organic media.

Production techniques like media milling and high-pressure homogenization have enabled scalable and reproducible manufacturing of nanosuspensions, facilitating their integration with traditional dosage forms such as tablets, capsules, pellets, and parenteral formulations. This versatility allows for tailored drug delivery while maintaining patient compliance, making nanosuspensions a valuable tool for both oral and non-oral applications.

The future of nanotechnology lies in the development of multifunctional nano systems capable of targeted, controlled, and sustained drug release. By modifying surface characteristics, particle size, and composition, nanosuspensions can improve tissue penetration, enhance cellular uptake, and reduce systemic toxicity. Moreover, stimuli-responsive and biomimetic nanoparticles offer the potential for precision medicine, enabling site-specific drug release in response to physiological triggers.

Beyond oral delivery, nanosuspensions are increasingly explored for ocular, pulmonary, transdermal, and intravenous routes, expanding the therapeutic scope of poorly soluble drugs. Additionally, combination therapies incorporating multiple drugs within a single nano system can improve treatment efficacy and patient adherence. Integration with emerging technologies such as 3D printing, personalized medicine, and advanced imaging further enhances the potential of nanosuspensions, enabling patient-specific dosage forms and real-time monitoring of drug distribution. With the evolution of regulatory frameworks and advances in scalable production methods, nanotechnology-based therapeutics are poised for significant commercial growth. Nanosuspensions, in particular, represent a renaissance in formulation technology, offering practical solutions to challenges that have limited drug delivery for decades.

In conclusion, nanotechnology promises to reshape drug delivery by providing versatile, efficient, and patient-centric therapeutic strategies. Continued innovation in nanosuspension development and its integration with modern pharmaceutical technologies will ensure its pivotal role in future therapeutics, ultimately improving drug efficacy, safety, and patient outcomes.

CHALLENGES IN NANOTECHNOLOGY BASED DRUG DELIVERY

Although nanotechnology has shown tremendous promise in improving drug delivery, several obstacles continue to hinder its full integration into clinical practice. A major limitation is the interaction of nanoparticles with complex biological systems, which often leads to rapid clearance by the mononuclear phagocyte system and inconsistent distribution within the body. As a result, nanoparticles may fail to reach the intended site of action or may accumulate in healthy tissues, compromising therapeutic outcomes. Their restricted ability to traverse physiological barriers—such as the blood–brain barrier and the dense extracellular matrix of tumors—further reduces the effectiveness of targeted delivery approaches. Another significant challenge is maintaining the stability of nanocarriers during storage, transport, and administration; nanoparticles may aggregate, undergo undesired changes in size or surface properties, or allow premature degradation of the encapsulated drug, all of which can negatively impact performance.

Safety and biocompatibility also remain major concerns, as nanoscale materials can trigger oxidative stress, inflammatory reactions, immune responses, or long-term tissue retention. These potential risks highlight the need for comprehensive toxicological assessments and long-term safety studies. From a manufacturing standpoint, producing nanoparticles on an industrial scale is difficult because many fabrication techniques are sensitive to slight variations, leading to inconsistencies between batches. These complexities also contribute to high production costs. Additionally, regulatory frameworks for nanomedicines are still under development, and the lack of uniform standards for characterization, quality control, and toxicity testing creates uncertainty in the approval process. Consequently, only a small number of nanoparticle-based formulations have successfully advanced into clinical use. Public concerns related to ethical considerations, possible environmental consequences, and limited understanding of nanotechnology further influence its acceptance. Overcoming these scientific, technical, and regulatory barriers is essential to fully realize the potential of nanotechnology in advancing modern therapeutics.

CONCLUSION:

Nanotechnology has emerged as a transformative force in modern pharmaceutics, offering solutions to long-standing challenges in drug delivery, bioavailability, and therapeutic precision. Through nanosized carriers such as liposomes, polymeric nanoparticles, dendrimers, solid-lipid nanoparticles, and nanosuspensions, it is now possible to achieve targeted, controlled, and sustained drug release while minimizing systemic toxicity. These nano-enabled systems have shown significant potential in treating complex diseases such as cancer, neurological disorders, cardiovascular diseases, and diabetes by enabling site-specific delivery, improved cellular uptake, and enhanced diagnostic accuracy.

Recent advancements, including stimuli-responsive platforms, biomimetic nanocarriers, multifunctional hybrid systems, and integration with personalized medicine—highlight the rapid evolution of nano-therapeutics. However, several barriers remain, including scalability issues, long-term safety concerns, regulatory complexity, and the need for standardized characterization methods. Addressing these limitations through interdisciplinary research, robust toxicological evaluation, and harmonized regulatory frameworks will be crucial for translating nanotechnology-based innovations into widespread clinical applications.

Overall, nanotechnology represents a pivotal step toward next-generation therapeutics, providing opportunities for more effective, safer, and patient-centered drug delivery systems. Continued innovation in formulation engineering and nanoscale biomaterials will ensure that nanomedicine continues to redefine the future of pharmaceutical sciences.

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