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## **Nanotechnology-Driven Drug Delivery: Recent Advances and Future Perspectives**

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### **ABSTRACT**

In the field of medicine the nanotechnology has been widely used in the creation of targeted drug delivery systems that make use of nanomaterial. This review emphasizes how novel medication delivery methods made possible by nanotechnology breakthroughs greatly improve the efficacy and safety of therapeutic interventions. Researchers have precisely targeted therapeutic chemicals to diseased tissues by using a variety of nanoparticle forms, such as liposomes, polymeric nanoparticles, dendrimers, and inorganic nanoparticles. This has reduced side effects and increased the effectiveness of treatment. Beyond oncology, these cutting edge drug delivery systems are used to treat a variety of medical conditions, including as illnesses of the central nervous system, diabetes, and orthopaedics. Nanotechnology has a lot of promise for medication delivery, but there are still a number of obstacles to overcome, such as toxicity issues, legal restrictions, and the requirement for efficient delivery systems. In order to get past current biological hurdles, future



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perspectives in this sector place a strong emphasis on integrating personalized medical approaches and continuously improving delivery technology. By concentrating on these areas, researchers hope to improve patient outcomes and treatment efficacy, which will ultimately result in more effective therapeutic treatments across a variety of medical specialties

**Keywords:** Therapeutic Intervention, Oncology, Personalize Medicine, Toxicity, Regulatory Challenges.

### INTRODUCTION

Nanotechnology has rapidly evolved from a macro-scale curiosity to a transformative force in diagnostics and therapeutics, particularly through the development of innovative nanomaterial [1, 2]. Recent advancements have introduced ground breaking tools that enhance the safety and efficiency of both diagnostic and therapeutic procedures across various disciplines [3]. This fast-growing field, dealing with structures from a few to several hundred nanometers, offers wide-ranging applications in engineering, medicine, and life sciences [4]. Over the past decade, precise drug delivery systems have gained attention for their superior benefits over conventional therapies. Nanotechnology holds vast potential in healthcare, paving the way for novel and more effective treatments for numerous diseases [5,4,6, 7,8]. According to [9] and [10], it has specifically made it possible to develop drug delivery systems that improve the safe and effective treatment of illnesses like cancer. Delivering therapeutic and diagnostic agents within biological systems for disease prevention, diagnosis, and treatment is the main goal of nanomedicine, which is characterised by the use of nanoscale materials (1–1,000 nm) [5,4, 7,8,9]. Nanotechnology is used in several medical specialities, such as surgery, dentistry, neuroscience, dermatology, and analytical sciences. It offers instruments that can target certain molecules and penetrate biological barriers [11].

Nanotechnology-based drug delivery has become a viable way to overcome the drawbacks of conventional treatment, including low solubility, toxicity, and restricted bioavailability [12]. In order to minimise systemic side effects, targeted drug administration enables therapeutic agents to accumulate primarily in afflicted areas [13] Making sure the delivery system stays in the body long enough to interact with the targeted cells and tissues while avoiding immune system destruction results in high targeting efficiency [14]. The pharmaceutical and biomedical sectors have benefited greatly from the worldwide nanotechnology boom, with their markets expanding significantly [15]. Conventional medications continue to face inefficiencies like high dosages, toxicity, and non-specific targeting, even with the development of new drugs [16]. Because they allow for site-specific and regulated drug release, drug delivery systems (DDS) have thus become more and more important [16,17]. DDS based on nanoparticles provide a way to co-deliver several therapeutic compounds straight to specific tissues, increasing therapy efficacy and safety [13]. All things considered, nanotechnology has transformed contemporary medicine by resolving long-standing issues with medication administration and providing a framework for upcoming innovations [14].

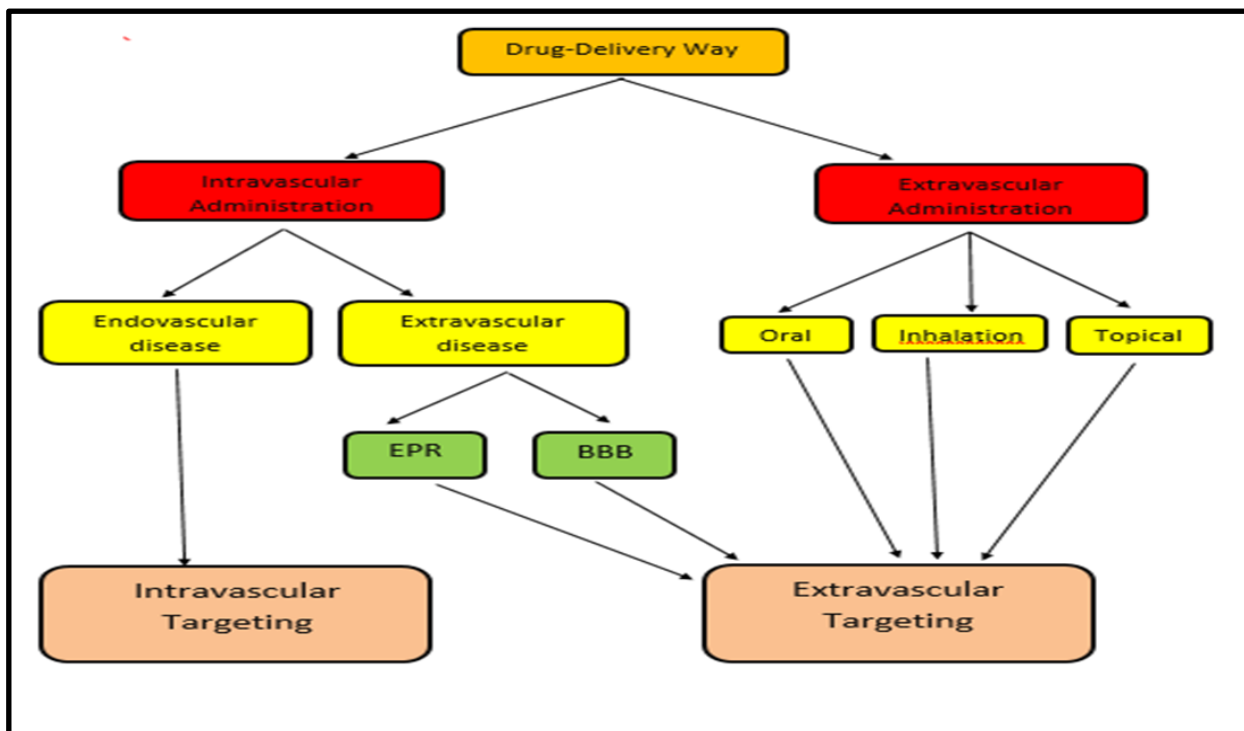


Figure1: The Flow Chart of Various Routes Used in the Administration of Endovascular and Extravascular Targeting [18]

Biodegradable materials like metals, lipids, and natural and manmade polymers make up drug delivery nanoparticles. They are usually less than 100 nm in at least one dimension [19, 20,21,22]. These nanoparticles' small size makes it easier for cells to absorb them, making them efficient delivery methods for medications. By using them, medication bioavailability, disease site targeting, and the uptake of poorly soluble medicines can all be improved [23,24]. According to [25,26], nanomaterials—defined as materials with a size between 1 and 100nm—are essential to the development of nanomedicine in fields such as drug delivery, tissue engineering, biosensors, microfluidics, and microarray technologies. Using therapeutic materials at the nanoscale to create nanomedicines, nanotechnology makes a substantial contribution to biomedical advancements such as nanobiotechnology [27]. Usually made of atomic or molecular materials, these nanoparticles are nanospheres [28] Longer circulation durations, better transmembrane transport, and increased stability and solubility of encapsulated medications are some advantages [29] Extravascular drug delivery refers to administration by means such as oral, inhaled, or subcutaneous methods, which allow particles to traverse endothelial barriers or reach target tissues, whereas intravascular drug delivery entails nanoparticles entering the bloodstream and acting directly at sites within blood vessels (Figure 1). Nanomaterials provide more technological adaptability by having different physicochemical properties from larger particles of the same composition [3] Moreover, nanoparticles can come from industrial, natural, or synthetic sources and can be tailored for a variety of uses [17]

## 2) Different Kinds of Nanoparticles in Drug Administration:



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Different therapeutic applications call for different kinds of nanoparticles. The many types of nanoparticles used in medicine delivery and disease targeting were reviewed in this article. Targeting ligands, surface coatings, or pH-responsive characteristics can be added to these nanoparticles to improve their performance and specificity in intricate disease settings.

### 2.1) Liposomes:

Because of their capacity to encapsulate hydrophilic pharmaceuticals in their aqueous core and hydrophobic medications within the lipid bilayers, liposomes—spherical vesicles made of lipid bilayers—are among the most researched nanocarriers in drug delivery [30]. They are efficient transporters for a variety of pharmacological drugs due to their amphiphilic nature, biocompatibility, and flexibility. By shielding encapsulated molecules from enzymatic breakdown and other destabilizing processes, liposomes improve therapeutic stability and increase the percentage of active medication that reaches target areas [31]. Because of these qualities, they are widely used in medicine, especially in oncology. For instance, Doxil® (liposomal doxorubicin), a PEGylated liposomal formulation, offers clinical advantages over traditional doxorubicin due to its decreased cardiotoxicity and improved tumor targeting via the increased permeability and retention (EPR) effect [32,33]. PEGylated liposomes, which are altered with polyethylene glycol (PEG) to avoid detection by the mononuclear phagocyte system (MPS), are an example of advancements in liposome technology that lead to longer circulation and enhanced therapeutic efficacy [34].

Furthermore, controlled, site-specific drug release in response to environmental triggers such as pH, temperature, or enzymes is made possible by the development of stimuli-responsive ("smart") liposomes [35]. These characteristics help to maximize therapeutic results while minimizing systemic negative effects. Because liposomes can carry a variety of molecules, they are also being used for purposes other than cancer therapy, such as the delivery of vaccines, antifungals, antibiotics, and gene therapies [36].

Liposomes have demonstrated significant potential in herbal therapy as delivery systems for hydrophilic and hydrophobic herbal chemicals. They allow for targeted and controlled release while enhancing the solubility, stability, and bioavailability of herbal medications. Targeting ligands, antibodies, or peptides can be added to the surface of liposomes to enable selective delivery to particular cells, tissues, or receptors while minimizing exposure to non-target regions and minimizing adverse effects [37,38]. The specificity and therapeutic results of herbal medication delivery are greatly improved by these targeted liposomal formulations. Liposomes continue to be a vital component of contemporary drug delivery systems as nanotechnology advances, and their adaptability and biocompatibility spur innovation in a wide range of therapeutic fields.

### 2.2) Polymeric NPs:

Because of their high drug-loading capacity, controlled and sustained release, and capacity to shield therapeutic agents from degradation, polymeric nanoparticles—which are made of biodegradable and biocompatible polymers like poly(lactic-co-glycolic acid) (PLGA), polyethylene glycol (PEG), polylactic acid (PLA), polyglycolic acid (PGA), or chitosan—offer substantial advantages in drug delivery systems [39]. The stability, bioavailability, and therapeutic efficacy of a variety of medications, including herbal substances, can be improved by these nanoparticles' ability to encapsulate or adsorb them within or on their surfaces. Through modifications such as ligand, antibody, or PEG attachment, their



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variable surface features allow for targeted distribution, increasing biological stability, lowering immune detection, and improving targeting efficiency [40]. Polymeric nanoparticles have demonstrated efficacy in oncology by delivering chemotherapeutic drugs directly to tumors, reducing systemic toxicity and improving results. Additionally, they are being investigated for better antimicrobial delivery in infectious diseases and for prolonged insulin release in diabetes [41]. They also play a part in regenerative medicine, gene therapy, and vaccine delivery, where they safeguard and distribute delicate biomolecules like proteins, RNA, or DNA to particular cells. Their capacity to encapsulate and preserve plant-based compounds while guaranteeing regulated release has made them a promising platform for augmenting the therapeutic potential of natural remedies, especially in the field of herbal medicine. All things considered, polymeric nanoparticles are a revolutionary development in nanomedicine, providing adaptable, secure, and effective remedies for a variety of medicinal uses [42].

### 2.3) Dendrimers:

A central core, multiple branching units, and a distinct outer shell define dendrimers, which are highly branched, three-dimensional macromolecules that form a homogeneous and symmetrical nanoscale structure [43]. Functional groups that can be chemically modified to attach a broad range of molecules, including as medicinal medicines, targeting ligands, and diagnostic instruments, are densely packed on their surfaces [44]. Because of their special structure, dendrimers can combine pharmaceuticals on their surfaces or encapsulate them in their internal cavities, enabling effective and precise delivery. Dendrimers can precisely target medications to diseased cells, such as cancer cells, by attaching targeting ligands like peptides or antibodies. This increases therapeutic efficacy and reduces off-target effects. Their homogeneity and tiny size facilitate effective tissue penetration and circulation, improving medication distribution throughout the body. Dendrimers are perfect for targeted and prolonged drug release, especially in cancer therapy, since they provide precise control over drug release kinetics that may be adjusted in response to stimuli like pH, temperature, or enzyme activity [45]. Dendrimers have been investigated in gene therapy in addition to medication delivery because of their positively charged surfaces, which allow them to interact with negatively charged nucleic acids (such as DNA and RNA) to prevent degradation and improve cellular uptake. Furthermore, by rupturing bacterial membranes or delivering medications straight to infection sites, dendrimers exhibit potential in antimicrobial applications. Their application in medical imaging is also expanding; dendrimers are useful imaging probes for MRI and CT scans that enhance disease monitoring and diagnostic precision when coupled with contrast agents or fluorescent dyes [46]. In herbal medicine, dendrimers can improve solubility, stability, bioavailability, and therapeutic efficacy by encasing hydrophilic herbal chemicals on their surfaces or functional groups and hydrophobic ones within their internal cavities. By functionalizing them with certain targeting ligands, herbal substances can be delivered to targeted cells or tissues with greater efficiency and fewer negative effects [47,48]. All things considered, dendrimers are innovative nanomaterials that have a wide range of uses in drug delivery, gene therapy, antibacterial treatments, diagnostics, and herbal medicine. Their high loading capacity, precise control, and targeted distribution will transform contemporary healthcare.

### 2.4) Inorganic Nanoparticles:

Because of their superior biocompatibility and functionalization capacities, inorganic



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nanomaterials—which are mainly made of metals and metal oxides—offer encouraging promise for the treatment of obesity. The ability to easily modify the surface of gold nanoparticles (AuNPs) with aptamers, peptides, or antibodies makes them stand out among the others. This allows for effective, targeted drug delivery to adipose tissue, increasing therapeutic efficacy while reducing adverse effects [49]. AuNPs can also break down fat cell membranes and release lipids for metabolic clearance because of their localized surface plasmon resonance, which enables them to absorb particular light wavelengths and transform that energy into heat [50]. By lowering cytokine release and reducing inflammatory responses, silver nanoparticles (AgNPs) also exhibit anti-obesity potential [51]. Furthermore, superparamagnetic iron oxide nanoparticles can be targeted to adipose tissue using external magnetic fields, resulting in a photothermal action akin to that of AuNPs [52][53]. Zinc oxide nanoparticles (ZnO NPs) also have potent antioxidant qualities [54]. Due to their special nanoscale characteristics, which include a high surface area-to-volume ratio, quantum effects, and improved chemical reactivity, inorganic nanoparticles—which are mostly made of metals, metal oxides, and semiconductors—are extremely beneficial in a wide range of scientific and industrial fields. The optical and electrical properties of gold nanoparticles, especially their surface plasmon resonance, make them noteworthy and allow for uses in biosensing, targeted drug administration, and medical imaging. Due to their superparamagnetic properties, iron oxide nanoparticles are frequently utilized in magnetic resonance imaging (MRI) and magnetically based cancer treatments. Because their surfaces can be readily altered for specific applications, silica nanoparticles are notable for their stability, biocompatibility, and adaptability in transporting medications or imaging agents. Each way of creating these nanoparticles—physical, chemical, or biological—offers control over their size, shape, and functioning. Additionally, their surfaces can be designed to interact better with biological systems, increasing their effectiveness in environmental, electronics, and catalysis applications. These materials' versatility facilitates theranostics, which combines therapy and diagnostics on a single platform and enables real-time treatment monitoring and modification, improving patient outcomes, efficacy, and precision.

### 2.5) Organic Nanoparticles:

Because of their phospholipid bilayer structure, which is similar to biological membranes, liposomes have exceptional fluidity and biocompatibility. This allows them to fuse with adipocyte membranes efficiently and release encapsulated chemicals that limit fat formation and increase lipolysis, which helps treat obesity.

To increase drug-carrying capacity, its structural design facilitates the distinct encapsulation of hydrophilic pharmaceuticals in the lipid bilayer and hydrophobic medications in the aqueous core [55]. In addition to exhibiting good biocompatibility, polymeric nanoparticles (PNPs) like PLA and PLGA enable surface modification with drugs and targeting ligands to enhance stability, bioavailability, and targeted delivery to adipose tissues, reducing off-target effects and improving weight loss results [56, 57]. With their highly branched three-dimensional architectures, dendrimers provide exquisite control over molecular characteristics and a high drug-loading capacity, which makes them appropriate for tailored therapeutic applications [58].

In addition to acting as active therapeutic agents and drug carriers, cationic nanomaterials, such as polyamidoamine dendrimers, can neutralize negatively charged pathogens and treat cancer and inflammatory conditions. Third-generation polyglutamine (P-G3), for instance, increases energy expenditure and reduces metabolic dysfunctions associated with obesity by targeting visceral fat [59,60]. Through catechol or galloyl groups, polyphenols—natural



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plant chemicals with antioxidation, UV absorption, and metal ion coordination—support dynamic and reversible binding to substrates. This makes it possible to create multipurpose polyphenol-functionalized nanostructures for immunological modulation and medication administration [61,62,63].

Multifunctional treatment approaches are made possible by further engineering these structures by adjusting metal ion types, concentrations, or the addition of polymers. Tannic acid and ferric ion-based coatings have demonstrated potential for enhancing gut health during antibiotic therapy [64], and tea polyphenols and D- $\alpha$ -tocopherol-containing pH-responsive polyphenol microspheres efficiently absorb and eliminate fat derivatives in the gastrointestinal tract, thereby lowering fat absorption [65]. These cutting-edge nanomaterials offer creative, multifaceted uses in the battle against obesity.

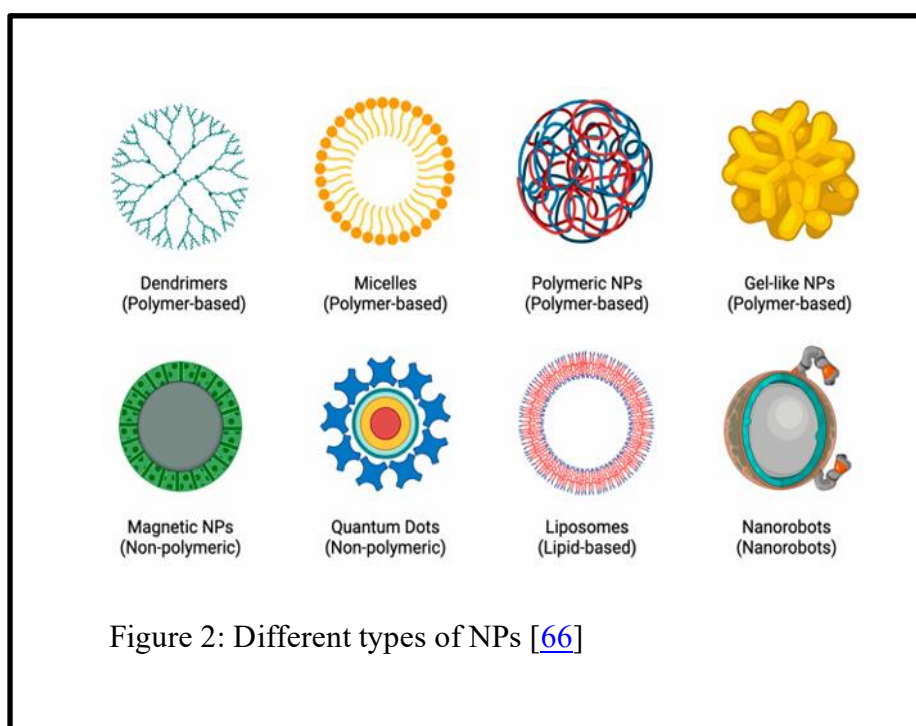


Figure 2: Different types of NPs [66]

Table 1: Applications of Drug-loaded Nanoparticles

Drug Name	Type of NPs	Active Drug	Uses / Application	Reference
Doxil	Liposome	Doxorubicin	Breast cancer, Ovarian cancer	[67]
Ambisome	Liposome	Amphotericin B	Fungal infections	[68]



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Abraxane	Polymer (Albumin NPs)	Paclitaxel	Breast, pancreatic, non-small cell lung cancer	[69]
Genexol-PM	Polymer (PEG-PLA micelles)	Paclitaxel	Breast cancer	[70]
VivaGel	Dendrimer (PAMAM)	SPL7013	Anti-viral (HIV prevention)	[71]
Auroshell	Inorganic (Gold nanoshells)	—	Photothermal therapy for solid tumors	[72]
AguIX	Inorganic (Gadolinium NPs)	Gadolinium	MRI contrast agent, radiosensitizer for cancer	[73]
BIND-014	Polymeric NP (targeted)	Docetaxel	Prostate and lung cancer	[74]
Theracurmin	Organic NP (Colloidal)	Curcumin	Arthritis, cancer, Alzheimer's	[75]

### 3) Advanced Application of Nanotechnology:

Here is the advance Application of Nanotechnology Are Listed below in Table:

**Table 2**

Application Area	Technology / Approach	Key Benefits / Novelty	Challenges / Future Steps	References
Targeted Brain-Drug Delivery	IRAK4 inhibitor-loaded dual-peptide nanocarriers for glioblastoma-associated cachexia	Enhanced delivery across the BBB, 94% bodyweight retention in vivo	Clinical translation, human BBB modeling, polymer toxicity	[76]



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Nano-needle Patch for Cancer Diagnostics	Silicon nanoneedles paired with AI-based MS analysis for real-time tumor detection	Enables rapid, non-invasive diagnosis ( $\approx 20$ min), intraoperative use	Large-cohort validation, clinical approval	[77]
Swarm-Controlled Nanobots	Electromagnetic control via intermittent randomization of magnetic field vectors	Individual nanobot control in swarm without need for embedded electronics	Scale-up for biological delivery, integration with imaging	[78]
Quantum-AI Nanopore DNA Sequencing	AI-augmented nanopore tunneling-based DNA readout with high sensitivity	Accurate mutation detection, label-free, beyond current NGS limits	Device fabrication, AI model generalizability	[79]
Nutraceutical Delivery	Polymeric nanocarriers, liposomes, nanogels for targeted delivery of natural compounds	Enhanced solubility, bioavailability, disease prevention	Stability, safety, regulatory issues	[80]
Skymion-Based Devices	Topological magnetic skyrmions for memory and environmental sensing at nanoscale	Ultra-dense storage, robust data retention, low energy usage	Room-temperature stabilization, fabrication methods	[81]
Water Purification	Graphene oxide membranes, TiO <sub>2</sub> nanocatalysts, and AgNP filters	Heavy metal removal, dye degradation, antibacterial properties	Scalability, membrane fouling, long-term stability	[82]
Energy Conversion and Storage	Carbon nanotubes, nanowires, and perovskite nanostructures for solar and battery tech	Higher energy density, faster charging, longer lifespans	Material cost, integration, environmental impact	[83]

#### 4) Nanotechnology's Role in Combating Diseases:

Modern medicine has seen a transformation because to nanotechnology, which provides precise and creative methods to treat a variety of diseases. Scientists can create medication



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delivery devices that target diseased cells without endangering healthy tissue by modifying materials at the nanoscale. This method reduces negative effects while greatly enhancing therapeutic results. By using sophisticated imaging and diagnostic methods, nanoparticles can also identify illnesses in their early stages. Nanotechnology gives up new possibilities in personalized and regenerative medicine, addressing anything from genetic abnormalities to cancer and infections. Research keeps changing our understanding, diagnosis, and treatment of diseases.

### 4.1) Atherosclerosis:

Approximately 20 million occurrences of acute coronary syndrome each year and a high one-year mortality rate, atherosclerosis—the principal cause of coronary artery disease (CAD)—remains the leading cause of death worldwide, especially in middle- and high-income nations [84–85]. The process starts with the buildup of oxidized phospholipids and lipoproteins containing apoB, which stimulate endothelial cells. This causes monocyte adhesion, macrophage infiltration, foam cell formation, plaque development, and vascular inflammation [86–91]. Plaques become unstable as the necrotic core grows and matrix-degrading enzymes erode the fibrous cap, raising the risk of rupture, ischemia, thrombosis, and abrupt cardiac events like myocardial infarction and stroke [92–94]. The resolution or molecular data limitations of current diagnostic imaging technologies, including MRI, CT, IVUS, and OCT, limit their ability to detect high-risk plaques and call for novel methods [95]. By enhancing targeted delivery and reducing toxicity, nanoparticle-based drug delivery systems present promising alternatives to conventional and surgical therapies, which are limited in advanced stages of the disease. This opens the door to safer and more efficient treatment of atherosclerosis [96–99].

Nanoparticle (NP) systems are used in targeted drug delivery for atherosclerosis in order to obtain precision therapy by taking advantage of particular plaque properties like inflammation, endothelial dysfunction, and enzymatic activity. While endothelial markers such as ICAM-1 and  $\alpha\beta 3$  integrin direct antibody-liposomes and RGD-peptide NPs to activated endothelium and neovessels [100–103], macrophage targeting via the mannose receptor (CD206) using Cy7-labeled glycol chitosan NPs allows localization to inflamed plaques [104–109]. Passive targeting through leaky vasculature allows accumulation of NPs like USPIO and PEG-gold nanorods [110–116], while enzyme-responsive systems like MMP-2-targeted gold nanorods allow imaging of unstable plaques [117–120]. Lesion-specific release is further enhanced by stimuli-responsive NPs that are activated by pH, ROS, or shear stress [121–125], and biomimetic carriers (leukosomes, PLNs, RBC-coated NPs) promote immune evasion and plaque adhesion [126–133]. All of these approaches, in addition to localized delivery techniques such as microneedles and drug-eluting stents [134–139], provide a comprehensive platform for effective, site-specific atherosclerosis treatment [140–145].

When it comes to treating atherosclerosis, nanorobotics—which is influenced by molecular biology, supramolecular chemistry, and nanoscale physics—offers substantial improvements over conventional techniques. Nanorobots can deliver contrast agents or medications to inflammatory areas by physically or chemically targeting stenotic arteries. Plaque stabilization and arterial repair have been demonstrated in vivo by polymeric collagen type IV nanoparticles loaded with biomimetic peptides and anti-inflammatory agents. For targeted drug delivery, a variety of polymeric nanocarriers are also being developed, including metal or lipid-based NPs, PEG, PEO, poly(lactic acid), poly(caprolactone), and poly(lactic acid). Advanced techniques also include magnetic field-guided nanocarriers for improved plaque targeting, exosome-based delivery systems



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for anti-miRNA therapies, and CRISPR-Cas9-loaded NPs for gene editing of pro-atherogenic pathways.

### 4.2) Cancer:

With a projected 9.7 million fatalities and approximately 20 million new cases in 2022, cancer is still a major global health concern. By 2050, it is predicted that there will be over 35 million cases [146]. New research shows that mechanical changes, such as decreased cancer cell stiffness [147,148] and increased tumor microenvironment rigidity [149,150], play a crucial role in cancer progression and invasiveness, even though these changes have historically been understood through genetic pathways [151,152]. These mechanical changes have an impact on nuclear and cytoskeletal integrity [153], indicating that early cancer development may be triggered by destabilization of nuclear stiffness [154,155]. By connecting mechanical forces to genetic and physiological cascades, this developing understanding of cancer mechanics expands upon early morphological observations and now influences diagnosis and treatment [156,157]. Therefore, comprehending the biophysical characteristics of cancer cells offers a further avenue for deciphering its intricate pathophysiology and creating more potent treatments.

By enabling precise targeting and lower toxicity using gold nanoparticles [158], which can transport medicines like TNF- $\alpha$  directly to tumors, recent advances in nanobiotechnology have transformed the delivery of cancer drugs. Gold-silica "nanobullets" enhance deep tissue therapy using near-infrared light [159], whereas dendrimers with pH-sensitive acetal groups and DNA-linkers offer controlled release and multifunctional delivery, including photodynamic and neutron capture therapies [160,161]. Albumin-based nanoparticles boost the transport of antisense oligonucleotides through improved degradation pathways, while folic acid-modified PAMAM dendrimers improve the administration of methotrexate to tumors that overexpress the folate receptor [162]. Targeting gastric cancer with transferrin-doxorubicin conjugates is a promising use of theranostic nanomedicines, particularly GNPs [163-170].

The absence of effective treatments for metastatic and recurrent malignancies, despite advancements in traditional cancer therapy, has led to a turn toward advanced gene editing and nanotechnology-based approaches. Although off-target effects and delivery issues still exist, CRISPR/Cas9's accuracy and effectiveness allow for targeted genomic alterations and transcriptional regulation. [171-173] To improve CRISPR delivery and therapeutic potential, rational nanocarrier designs are being investigated. [174-176] In the meantime, drug solubility, targeting, and controlled release are enhanced by nanocarriers such as liposomes, PNPs, and dendrimers through ligand modifications and the EPR effect, which dramatically lowers toxicity and overcomes drug resistance. Through the integration of gene therapy, precise delivery, and diagnostics into a single platform, these multifunctional nanosystems—including clinically effective formulations like Doxil—are transforming the treatment of cancer.

### 4.3) Orthopedics:

Nanotechnology, originally proposed by Richard P. Feynman in 1959 [177], has emerged as a multidisciplinary field revolutionizing medicine through nanomedicine, which enables targeted, efficient disease prevention, diagnosis, and treatment [178-180]. Orthopedic disorders—being the second leading cause of global disability—pose major health and economic challenges, especially among aging populations. [181,182] Conventional treatments often fail due to the structural complexity of bone and poor drug specificity. [183] Nanotechnology addresses these issues by improving drug solubility,



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targeting, and therapeutic outcomes using advanced carriers like liposomes, dendrimers, and polymeric nanoparticles.[184-186] Yet, clinical success depends on overcoming barriers such as biocompatibility, immune responses, and toxicity through robust, standardized models.[187,188].

Using carriers such as polymeric, lipid, dendrimer, and metallic nanoparticles, nanotechnology-based drug delivery systems (DDS) have transformed the treatment of orthopedic conditions like osteoarthritis, osteosarcoma, and bone infections by providing targeted, controlled, and sustained therapeutic release with low systemic toxicity [189]. While multifunctional nanocarriers, such as hyaluronic acid nanogels and pH-responsive frameworks, improve tumor targeting in osteosarcoma and metastatic bone cancers [190], platforms such as kartogenin-loaded polymers and thermoresponsive nanospheres improve treatment efficacy in osteoarthritis [191,192]. Systems like bone-targeting nano-iron oxide (BTNPs) and TGF-loaded micellar nanoparticles also aid in bone remodeling and cartilage regeneration [193,194]. Additionally, 3D-printed ciprofloxacin implants [195], PMMA-based carriers [196], and NSAID-releasing coatings [197-198] offer localized solutions, and 4D printing with shape-memory materials enables intelligent, long-acting DDS for orthopedic and chronic disease applications [199]. These methods increase treatment results and patient comfort in addition to increasing therapeutic precision [200].

Despite the body's inherent ability to regenerate, large-scale abnormalities frequently necessitate intervention beyond the body's self-healing capacity, which has historically relied on bone transplants that are constrained by donor site morbidity and supply. With the ability to create dynamic, patient-specific scaffolds that adapt to the physiological conditions and bone defect geometries, 4D printing has become a game-changing option that improves osteogenesis and integration [201]. In order to support minimally invasive and customized bone and cartilage regeneration, methods that employ SMPs, hydrogels, and bioactive fillers (such as hydroxyapatite, alendronate, and Col-Dex coatings) exhibit efficient shape recovery, biocompatibility, and sustained drug release [202-203]. Additionally, 4D printing incorporates bioinks and smart materials, such as conductive graphene-based structures and periosteum engineering, for vascular and neuronal restoration in complex defects [204]. Additionally, the technology includes customized prosthetics that are made using CT data and react to heat, magnetic, and near-infrared radiation, such as acetabular cups, spinal implants, and knee joints. As 4D-6D additive manufacturing develops, its combination with biomedicine opens up new, patient-focused orthopedic treatments that promise better surgical results, comfort, and treatment efficacy [205].

### 4.4) Diabetes:

T1DM is caused by autoimmune destruction of pancreatic  $\beta$ -cells [206,207], while T2DM is associated with insulin resistance and impaired insulin signaling [208]. Diabetes mellitus (DM) is a chronic and increasingly common metabolic disorder that is characterized by persistent hyperglycemia due to insulin deficiency or resistance [209]. Over 400 million people worldwide are impacted by it, and by 2045, that number is expected to rise to 700 million [210,211]. Particularly in T1DM, where lifetime insulin use may result in hypoglycemia, conventional treatments like insulin and oral medications have drawbacks such as low patient adherence and poor bioavailability [212]. Through cutting-edge drug carriers like liposomes and nanoparticles, nanotechnology provides game-changing solutions that enhance delivery, minimize side effects, and enable non-invasive insulin administration (e.g., oral or inhalable methods) [213-214]. Additionally, wearable biosensors for real-time monitoring and glucose-responsive insulin systems are being



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advanced by nanomedicine, which also has the potential to cure diabetes complications such as retinopathy and nephropathy [215,216; 217,218].

By enhancing the solubility, absorption, and targeted release of both conventional and biological therapies, nanotechnology has revolutionized the delivery of diabetes medications [219]. Nanostructured medications such as nanocrystals and nanocarrier systems composed of synthetic or natural polymers that improve the stability and half-life of loaded medicines are included in nanomedicine [220, 221]. Delivery systems that mimic the physiological action of insulin and provide controlled, glucose-responsive, and minimally invasive treatment options include nanoparticles, liposomes, nanogels, and microneedles [222,223]. Through particular processes like biodegradation or phospholipid encapsulation, polymeric nanoparticles, nanocapsules, and lipid-based carriers like liposomes and lipid nanoparticles offer customized delivery of hydrophilic or lipophilic medications [224]. Together, these interconnected nanotechnologies improve accuracy and results in the treatment of type 2 diabetes by overcoming the drawbacks of traditional insulin therapy.

Insulin therapy for type 1 diabetes and several medication classes for type 2 diabetes, including biguanides, sulfonylureas, thiazolidinediones, DPP-4 inhibitors, and GLP-1 analogues [225], are included in the treatment of diabetes; however, these frequently result in side effects and low adherence [226]. Traditional methods, such as altering one's lifestyle, work well but are constrained by difficulties with adherence and the inability to stop the progression of the disease or regenerate  $\beta$ -cells [227,228]. Technologies that target the AMPK or PTP1B pathways and teplizumab immunotherapy have the potential to improve insulin sensitivity and preserve  $\beta$ -cell function [229,230,231]. Nanotechnology-based systems, using PLGA, chitosan, or Fc-functionalized carriers, enhance drug stability, targeted delivery, and bioavailability, mimicking physiological insulin action. A notable advancement is HDV insulin, which demonstrates safety and efficacy by replicating natural hepatic insulin delivery in clinical trials [232].

### 4.5) Obesity:

Nearly 64% of Americans are expected to be overweight or obese by 2025, making obesity, a chronic and multifactorial inflammatory illness, a global health concern that affects over 1 billion people [233,234]. Through dysfunctions in white adipose tissue and systemic metaflammation, it contributes to serious health risks such as cardiovascular disease, type 2 diabetes, MASH, and cancer [235,236]. The WHO defines excessive fat accumulation as having a BMI  $\geq 30$  kg/m<sup>2</sup>. The long-term effectiveness and safety of traditional treatments, such as medication, surgery, and lifestyle modifications, are frequently limited [237,238]. By improving drug delivery, regulating immunological responses, and regulating metabolism, nanotechnology presents intriguing answers. It also has advantages, such as increasing gut microbiota [239–240,241]. Together with new nanomaterial treatments, diagnostic techniques such as BMI, waist circumference, and in-silico prediction models suggest a more focused, individualized, and long-term strategy for managing obesity [242,243].

To enable precise, long-lasting, and tissue-specific therapies, nanotechnology-based drug delivery systems in the management of obesity use a variety of nanomaterials, including inorganic (e.g., AuNPs for hyperthermia), organic (e.g., liposomes for hydrophilic/hydrophobic drug encapsulation), and biomimetic (e.g., exosomes for targeted delivery) nanomaterials [244]. The bioavailability, adipose targeting, and systemic side effects of drugs such as resveratrol, capsaicinoids, T3, and mirabegron are all improved by liposomes and polymeric nanocarriers like PLGA and PEG-PLGA NPs [245]. Bio-



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nanomaterials, such as rHDL platforms and systems coated with macrophage membranes, improve delivery that targets inflammation and work in concert to control angiogenesis and adipose browning [246]. By facilitating the localized, minimally invasive, and long-acting delivery of medications or gene materials to WAT and BAT, transdermal techniques employing microneedles and hydrogels further improve the treatment of obesity [247]. Furthermore, hybrid nanoplateforms, such as lipid-silica nanohybrids, MSN-polymer systems, and tFNA carriers, are examples of multifunctional strategies that alter metabolism, cause WAT browning, and go past leptin resistance for all-encompassing anti-obesity benefits [248–249]. By facilitating the localized, minimally invasive, and long-acting delivery of medications or gene materials to WAT and BAT, transdermal techniques employing microneedles and hydrogels further improve the treatment of obesity [250]. Furthermore, hybrid nanoplateforms, such as lipid-silica nanohybrids, MSN-polymer systems, and tFNA carriers, are examples of multifunctional strategies that alter metabolism, cause WAT browning, and go past leptin resistance for all-encompassing anti-obesity benefits.

To improve fat metabolism, inflammatory control, and targeted drug delivery, obesity treatment incorporates cutting-edge nanotechnologies, including inorganic (e.g., AuNPs, ZnO NPs), organic (e.g., dendrimers, polyphenols), and biomimetic systems (e.g., exosomes, cell membrane-coated NPs) [251,252]. While organic and biomimetic systems provide biocompatibility, immune evasion, and blood-brain barrier penetration for appetite management, inorganic NPs, such as AuNPs, use photothermal effects. The shortcomings of traditional techniques, such as pharmaceutical medications (orlistat, sibutramine, etc.) and surgery, which frequently result in major adverse effects like depression and cardiovascular risks, are addressed by these contemporary strategies [253]. In addition to these, herbal medications are becoming available for the safer treatment of obesity and associated diseases like diabetes and cancer [254]. In order to maintain energy balance and avoid relapse, effective long-term results still depend on customized diet plans that are informed by BMI and other metrics in addition to regular physical activity.

### 4.6) CNS Disorders:

As the population ages, neurodegenerative disorders (NDs) like AD, PD, HD, ALS, FTD, and prion diseases are becoming more prevalent. They account for 8% of the world's health burden and cause significant impairments in cognition, motor skills, and behavior [255,256]. Pathological characteristics such as neuroinflammation, oxidative stress, mitochondrial dysfunction, and protein aggregation are common to many multifactorial disorders and are frequently impacted by environmental, genetic, and epigenetic variables [257,258]. Current therapies are hampered by issues like drug delivery across the blood-brain barrier (BBB) and continue to cause symptoms despite treatments like memantine, cholinesterase inhibitors, and levodopa [259,260]. While novel biomarkers and insights into mechanisms like RNA modifications and the gut-brain axis support early diagnosis and targeted intervention, emerging nanocarrier strategies, such as cyclodextrin-based nanoparticles, offer promising solutions by improving solubility, targeting specificity, and minimizing toxicity [261]. Through customized therapy, nanotechnology-based treatments, and a deeper comprehension of the molecular mechanisms underlying CNS illnesses, ongoing research seeks to enhance outcomes [262,263].

Drug access and efficacy through systemic routes are restricted by restrictive barriers such as the BCSFB and BBB, which pose significant challenges to effective drug delivery to the central nervous system [264,265]. To get over these obstacles and promote drug retention, tissue penetration, and targeted distribution, intrathecal and localized



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administration techniques have been developed, including polymer pellets, liposomal nanoparticles, and convection-enhanced delivery (CED) [266,267]. Despite issues like toxicity and cost, nanomedicine further improves CNS drug delivery by increasing solubility, controlled release, and targeting precision using formulations including liposomes, dendrimers, and micelles [268-269]. Techniques like intranasal administration and CED, especially with nanoparticles under 100 nm, facilitate access to deep brain regions by overcoming ECM resistance and enabling real-time guided infusion [270,271]. When combined, anatomical knowledge and Nano technological advancements offer revolutionary approaches to better treating CNS illnesses [272,273].

pharmacological and non-pharmacological approaches, the therapy of CNS and neurodegenerative disorders (NDs) is becoming more individualized, focusing on underlying pathologies including protein misfolding, neuroinflammation, and mitochondrial dysfunction in addition to symptom relief [274]. However, due to systemic constraints and genetic diversity, correct identification remains a major issue, sometimes leading to misdiagnosis and delayed treatment, especially for rare illnesses like ALS. Through processes like transcytosis and paracellular diffusion, nanotechnology-based systems are assisting in overcoming the problems that traditional therapies for diseases like AD and PD face, such as poor BBB penetration, low bioavailability, and rapid drug degradation [275]. While hydrogels and cyclodextrins increase solubility and regulate drug release, advanced nanocarriers—including liposomes, PNPs, SLNs, NLCs, and MNPs—offer targeted, prolonged delivery, improved bioimaging, and therapeutic efficacy [276-277]. Together, these developments in nanomedicine are changing CNS treatment by enabling precise medication delivery, minimizing adverse effects, and potentially influencing disease progression [278].

### 4.7) Ocular Disease:

Due to aging, diabetes, and lifestyle factors, ocular disorders as diabetic retinopathy (DR), age-related macular degeneration (AMD), glaucoma, and cataract are becoming more common worldwide. These conditions greatly contribute to vision loss and public health burdens [279,280]. Anatomical and physiological ocular barriers (such as blood-retina and blood-aqueous barriers) impede traditional treatments, such as anti-VEGF agents, corticosteroids, and eye drops, resulting in low bioavailability, short retention, and possible complications from invasive methods [281,282]. Over 217 million people are impacted globally, and effective medication administration and early diagnosis continue to be significant obstacles [283]. Nanotechnology offers customized, long-lasting, and less invasive ocular treatments through complex systems such as nanomicelles, nanoparticles, liposomes, and microneedles that improve permeability, bioavailability, and therapeutic results while reducing side effects [284]. Although they are still being studied, magnetic, lipid, and polymer-based nanocarriers have enormous promise to transform ocular therapy and regenerative ophthalmology [285].

Effective medication administration, particularly to the posterior region, is extremely difficult due to the eye's complex anatomy and physiological barriers, including the tear film, cornea, and blood-ocular barriers [286-287]. Traditional methods, such as systemic administration and eye drops, frequently have low bioavailability and require frequent dosing [288]. Advanced carriers such as liposomes, SLNs, NLCs, dendrimers, polymeric, and lipid-based nanoparticles have been made possible by nanotechnology. These carriers improve patient compliance by increasing drug penetration, extending retention, preventing drug degradation, and lowering the frequency of dose [289]. Notwithstanding their potential, worries regarding nanotoxicity—which are linked to the size, charge, and



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deposition of nanoparticles in ocular tissues—emphasize the necessity of thorough safety assessments [290,291]. Nanomedicine is a potential yet developing approach to ocular medication administration since Quality-by-Design (QbD) is now used to address problems such as nanoparticle instability and repeatability [292].

FDA-approved nanoformulations like Restasis®, Cequa®, Durezol®, and Cyclokate® improving drug stability, penetration, and reducing toxicity in dry eye syndrome through nanoemulsions, nanotechnology-based ocular drug delivery has seen tremendous clinical and commercial traction [293,294]. Targeted and long-lasting treatment for keratitis, neovascular disorders, macular edema, and uveitis is provided by cutting-edge platforms like Ikervis®, Visudyne®, and Macugen®, as well as implants like Ozurdex®, Iluvien®, and Retisert® [295]. Products such as SYSTANE®, Lacrisek®, and Artelac Rebalance® use lipid nanoparticles, micelles, PLGA matrices, and mucus-penetrating particles to increase bioavailability and patient compliance [296]. The effectiveness of liposomal and polymeric nanocarriers in treating diseases such as ocular hypertension, glaucoma, and AMD is demonstrated by ongoing clinical trials (e.g., NCT03001466, NCT02466399) and experimental medications like POLAT-001 and AR-13503. [297,298]. Patents like CN105726484B and US20190070302A1 support this advancement by revealing novel nanoparticle-based systems with potent drug-loading capacity and targeted delivery, establishing nanotechnology as a revolutionary and developing solution in ocular therapeutics [299].

### 5) Challenges and Future Perspective of Various Diseases:

Clinical translation is still difficult in many diseases despite significant advancements in nanomedicine because of common issues such as toxicity, inadequate long-term safety evidence, batch variability, and regulatory complexity. Through biomimetic, multi-targeted, and stimulus-responsive systems such as pH- or ROS-sensitive probes, nanoparticle-based approaches in **atherosclerosis** hold promise for improving plaque-targeted delivery and diagnostics [300,301]. Nonetheless, issues with immunological response, unclear excretion pathways, and unfavorable surface characteristics continue to exist [302,303]. Because of their poor safety validation, innovative techniques like nanorobots and micro/nanobubbles are still only used in preclinical investigations [304,305]. Enhancing immune evasion, improving nanoparticle dynamics, and adjusting to plaque-specific shear stress should be the main goals of future research. Concerns regarding toxicity, biodistribution, and off-target effects, especially with Cas9 RNPs, necessitate stringent standardization and quality control even though nanocarriers like MOFs, AuNPs, and vesicles enhance drug targeting and CRISPR/Cas9 gene editing in **cancer** [306,307,308]. While site-specific CRISPR delivery is made possible by responsive nanocarriers [309,310], smart nanoparticles (such as AgNPs) and green synthesis provide safer alternatives [311]. However, wider usage necessitates scalable, affordable systems [312]. Personalized tissue engineering in **orthopedics** is made possible by 4D-printed scaffolds and nanomaterials; yet, problems with inflammation, long-term biocompatibility, and non-standardized production impede their use. Integrating AI and ML can speed up the creation of customized nanoparticles, and working with regulators is essential to balancing innovation and clinical safety. Although polymer-coated medications, liposomes, and glucose-responsive microneedles are examples of nanocarriers that enhance bioavailability and compliance in **diabetes**, they encounter challenges with toxicity, ambiguous mechanisms, and scalability [313,314,315]. Although COVID-19-related immunological changes and complex gene regulation necessitate further research, personalized methods such as stem cell therapy, gene therapy, siRNA,



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and bioprinting show promise [316]. Nanotechnology has made it possible to treat **obesity** by immune regulation, adipose-targeting, and photothermal therapies; nonetheless, biological heterogeneity, tissue accumulation, and oxidative stress remain significant obstacles [317]. Complex adipose architecture is being addressed by dual-targeting, biomimetic, and stimulus-responsive nanocarriers [318], while AI-guided design, nanofoods, and macrophage browning interventions provide promising future options [319,320]. Clinical prediction is hampered by the paucity of humanized models, but [321]. Since nearly 98% of CNS medications are unable to cross the blood-brain barrier, nanoparticle distribution over the BBB continues to be a crucial barrier for **neurodegenerative disorders (NDs)** [322,323]. New hope is provided by cyclodextrin-based nanocarriers, sophisticated nasal and intravenous delivery, and gene therapy-compatible systems [324]. However, more thorough research utilizing customized, primate-based models is required due to nanoparticle toxicity, off-target dangers, and age-related vulnerabilities [325,326]. For accurate neuroinflammation targeting, future research must improve nanoformulations and clarify cell-nanoparticle interactions [327,328]. Low-toxicity, prolonged anterior segment drug release is made possible by PLGA-based polymeric nanoparticles in **ocular illnesses** [329,330], but bioavailability is still low (<5%) because to ocular obstacles [331,332]. Clinical progress is halted by poor in vivo human data, high production costs, and toxicity issues [333,334]. To improve the results of anterior and posterior ocular treatment, future efforts should concentrate on non-invasive systems, surface charge optimization, and integration of gene therapy, exosomes, and diagnostic-therapeutic platforms. Ultimately, to get past translational constraints and realize the full clinical promise of Nano medicine, early regulatory alignment across all domains, biomimetic designs, and artificial intelligence must come together.

### 6) Conclusion:

Nanotechnology has revolutionized drug delivery systems, significantly enhancing the safety and efficacy of treatments, particularly in oncology. By utilizing various types of nanoparticles, including liposomes, polymeric nanoparticles, dendrimers, and inorganic nanoparticles, researchers can achieve targeted delivery of therapeutic agents, minimizing side effects and maximizing treatment effectiveness. These nanoparticles are engineered to possess unique properties that allow them to navigate biological barriers and deliver drugs directly to diseased cells, thereby improving therapeutic outcomes. The applications of these advanced drug delivery systems extend beyond cancer treatment to include areas such as orthopaedics, diabetes management, and central nervous system disorders, showcasing their versatility in addressing a wide range of medical challenges. However, the development and implementation of targeted medication delivery systems face several challenges, including potential toxicity, regulatory hurdles, and the need for effective delivery mechanisms that ensure the drugs reach their intended targets. Addressing these challenges is crucial for the successful translation of nanotechnology from laboratory research to clinical practice. Looking ahead, the future of targeted medication delivery systems lies in the integration of personalized medicine approaches, which tailor treatments to individual patient profiles, and the continued advancement of delivery technologies that can overcome existing biological barriers. By focusing on these areas, researchers aim to enhance the effectiveness of treatments and improve patient outcomes, ultimately leading to more successful therapeutic interventions in various medical fields.

### REFERENCES

[1] C. Kinnear, T. L. Moore, L. Rodriguez-Lorenzo, B. Rothen-Rutishauser, and A. Petri-



## Vol. 4 No. 3 (March) (2026)

- Fink, "Form follows function: Nanoparticle shape and its implications for nanomedicine," *Chem. Rev.*, vol. 117 (17), pp. 11476–11521, 2017. doi: 10.1021/acs.chemrev.7b00194.
- [2] R. D. A. Miguel, A. S. Hirata, P. C. Jimenez, L. B. Lopes, and L. V. Costa-Lotufo, "Beyond formulation: Contributions of nanotechnology for translation of anticancer natural products into new drugs," *Pharmaceutics*, vol. 14 (8), pp. 1722, 2022. doi: 10.3390/pharmaceutics14081722.
- [3] J. Jeevanandam, A. Barhoum, Y. S. Chan, A. Dufresne, and M. K. Danquah, "Review on nanoparticles and nanostructured materials: history, sources, toxicity and regulations," *Beilstein J. Nanotechnol.*, vol. 9, pp. 1050–1074, 2018.
- [4] D. Peer, J. M. Karp, S. Hong, O. C. Farokhzad, R. Margalit, and R. Langer, "Nanocarriers as an emerging platform for cancer therapy," *Nature Nanotechnol.*, vol. 2 (12), pp. 751–760, 2007.
- [5] B. Y. Kim, J. T. Rutka, and W. C. Chan, "Nanomedicine," *N. Engl. J. Med.*, vol. 363 (25), pp. 2434–2443, 2010.
- [6] L. Zhang, F. X. Gu, J. M. Chan, A. Z. Wang, R. S. Langer, and O. C. Farokhzad, "Nanoparticles in medicine: Therapeutic applications and developments," *Clin. Pharmacol. Ther.*, vol. 83, no. 5, pp. 761–769, 2008.
- [7] K. Riehemann, S. W. Schneider, T. A. Luger, B. Godin, M. Ferrari, and H. Fuchs, "Nanomedicine – Challenge and perspectives," *Angew. Chem. Int. Ed.*, vol. 48, no. 5, pp. 872–897, 2009.
- [8] T. L. Doane and C. Burda, "The unique role of nanoparticles in nanomedicine: Imaging, drug delivery and therapy," *Chem. Soc. Rev.*, vol. 41, no. 7, pp. 2885–2911, 2012.
- [9] K. Freimann, P. Arukuusk, K. Kurrikoff, L. Pärnaste, R. Raid, A. Piirsoo, *et al.*, "Formulation of stable and homogeneous cell-penetrating peptide NF55 nanoparticles for efficient gene delivery," *J. Controlled Release*, vol. 285, pp. 75–86, 2018.
- [10] L. Wang, J. Yao, X. Zhang, Y. Zhang, C. Xu, R. J. Lee, *et al.*, "Delivery of paclitaxel using nanoparticles composed of poly (ethylene oxide)-b-poly (butylene oxide) (PEO-PBO)," *Colloids Surf. B Biointerfaces*, vol. 161, pp. 464–470, 2018.
- [11] A. Malakar, S. R. Kanel, C. Ray, D. D. Snow, and M. N. Nadagouda, "Nanomaterials in the environment, human exposure pathway, and health effects: a review," *Sci. Total Environ.*, vol. 759, p. 143470, 2021.
- [12] D. F. Emerich and C. G. Thanos, "Targeted nanoparticle-based drug delivery and diagnosis," *J. Drug Target.*, vol. 15, pp. 163–183, 2007.
- S. T. Jahan, S. M. A. Sadat, M. Walliser, and A. Haddadi, "Targeted therapeutic nanoparticles: An immense promise to fight against cancer," *J. Drug Deliv.*, vol. 2017, Art. no. 9090325, pp. 1–24, 2017.
- [13] R. Jahanban-Esfahlan, K. Seidi, and N. Zarghami, "Tumor vascular infarction: Prospects and challenges," *Int. J. Hematol.*, vol. 105, no. 3, pp. 244–256, 2017, doi: 10.1007/s12185-016-2171-3.
- [14] M. E. Davis, Z. G. Chen, and D. M. Shin, "Nanoparticle therapeutics: An emerging treatment modality for cancer," *Nat. Rev. Drug Discov.*, vol. 7, no. 9, pp. 771–782, 2008, doi: 10.1038/nrd2614.
- [15] A. A. Shukla, B. Hubbard, T. Tressel, S. Guhan, and D. Low, "Downstream processing of monoclonal antibodies—Application of platform approaches," *J. Chromatogr. B*, vol. 848, no. 1, pp. 28–39, 2007.
- [16] S. Parveen, R. Misra, and S. K. Sahoo, "Nanoparticles: A boon to drug delivery, therapeutics, diagnostics and imaging," *Nanomedicine*, vol. 8, no. 2, pp. 147–166,



## Vol. 4 No. 3 (March) (2026)

2012.

- [17] G. Tiwari, R. Tiwari, B. Sriwastawa, L. Bhati, S. Pandey, P. Pandey, and S. K. Bannerjee, "Drug delivery systems: An updated review," *Int. J. Pharm. Investig.*, vol. 2, no. 1, pp. 2–11, 2012.
- [18] X. Cheng, Q. Xie, and Y. Sun, "Advances in nanomaterials-based targeted drug delivery systems," *Frontiers in Bioengineering and Biotechnology*, vol. 11, p. 1177151, 2023, doi: 10.3389/fbioe.2023.1177151.
- [19] L. Brannon-Peppas and J. Q. Blanchette, "Nanoparticle and targeted systems for cancer therapy," *Adv. Drug Deliv. Rev.*, vol. 56, no. 11, pp. 1649–1659, 2004.
- [20] G. K. Stylios, P. V. Giannoudis, and T. Wan, "Applications of nanotechnologies in medical practice," *Injury*, vol. 36, pp. S6–S13, 2005.
- [21] M. Yokoyama, "Drug targeting with nano-sized carrier systems," *J. Artif. Organs*, vol. 8, no. 2, pp. 77–84, 2005.
- [22] A. G. Schatzlein, "Delivering cancer stem cell therapies – A role for nanomedicines?," *Eur. J. Cancer*, vol. 42, no. 9, pp. 1309–1315, 2006.
- [23] L. Ould-Ouali, M. Noppe, X. Langlois, B. Willems, P. Te Riele, P. Timmerman, M. E. Brewster, A. Arien, and V. Preat, "Self-assembling PEG-p(CL-co-TMC) copolymers for oral delivery of poorly water-soluble drugs: A case study with risperidone," *J. Control. Release*, vol. 102, no. 3, pp. 657–668, 2005.
- [24] J. E. Kipp, "The role of solid nanoparticle technology in the parenteral delivery of poorly water-soluble drugs," *Int. J. Pharm.*, vol. 284, no. 1–2, pp. 109–122, 2004.
- [25] M. S. Arayne, N. Sultana, and F. Qureshi, "Nanoparticles in delivery of cardiovascular drugs," *Pak. J. Pharm. Sci.*, vol. 20, pp. 340–348, 2007.
- [26] R. R. Joseph and S. S. Venkatraman, "Drug delivery to the eye: What benefits do nanocarriers offer?," *Nanomedicine*, vol. 12, pp. 683–702, 2017.
- [27] A. Z. Mirza and F. A. Siddiqui, "Nanomedicine and drug delivery: A mini review," *Int. Nano Lett.*, vol. 4, pp. 94, 2014.
- [28] G. R. Rudramurthy, N. Swamy, M. Sinniah, and Y. M. Ghasemzadeh, "Nanoparticles: Alternatives for conventional antibiotics and antibacterial agents," *Int. J. Pharm. Sci. Nanotechnol.*, vol. 9, no. 6, pp. 3683–3692, 2016.
- [29] L. Kou, Y. D. Bhutia, Q. Yao, Z. He, J. Sun, and V. Ganapathy, "Transporter-guided delivery of nanoparticles to improve drug permeation across cellular barriers and drug exposure to selective cell types," *Front. Pharmacol.*, vol. 9, pp. 27, 2018, doi: 10.3389/fphar.2018.00027.
- [30] A. Khosa, S. Reddi, and R. N. Saha, "Nanoformulation approaches for improved therapeutic delivery of resveratrol," *Biomed. Pharmacother.*, vol. 103, pp. 598–610, 2018.
- [31] W. I. Higuchi and J. Misra, "Rate of release of medicaments from ointment bases containing drugs in suspension," *J. Pharm. Sci.*, vol. 51, no. 5, pp. 459–464, 1962.
- [32] M. Y. Koroleva and E. V. Yurtov, "Nanoemulsions: The properties, methods of preparation and promising application areas," *Russ. Chem. Rev.*, vol. 90, no. 3, pp. 293–311, 2021.
- [33] D. J. McClements and S. M. Jafari, "Introduction to nanoemulsions: Definition, classification, and importance," in *Nanoemulsions: Formulation, Applications, and Characterization*, New York, NY, USA: Academic Press, 2018, ch. 1, pp. 3–20.
- [34] M. Y. Koroleva and E. V. Yurtov, "Stability of nanoemulsions," *Russ. Chem. Rev.*, vol. 81, no. 1, pp. 21–37, 2012.
- [35] M. Koroleva, I. Portnaya, E. Mischenko, et al., "Physicochemical properties of



## Vol. 4 No. 3 (March) (2026)

- nanodispersed systems: Interaction between surfactants and polymers,” *J. Colloid Interface Sci.*, vol. 610, pp. 61–72, 2022.
- [36] M. Koroleva, “Self-assembled nanostructures for encapsulation and delivery,” *Phys. Chem. Chem. Phys.*, vol. 25, no. 31, pp. 21836–21846, 2023.
- [37] S. Harada, S. Ehara, K. Ishii, et al., “Radiation therapy combined with chemotherapy in cancer treatment,” *Int. J. Radiat. Oncol. Biol. Phys.*, vol. 75, no. 2, pp. 455–462, 2009.
- [38] S. M. Alshahrani, “Recent developments in targeted drug delivery using nanoformulations,” *J. Drug Deliv. Sci. Technol.*, vol. 68, p. 103085, 2022.
- [39] H. A. Joshi, R. S. Patwardhan, D. Sharma, et al., “Development and characterization of polymeric nanoparticles for drug delivery,” *Int. J. Pharm.*, vol. 595, p. 120181, 2021.
- [40] M. Adhikari and R. Arora, “Toxicological evaluation of engineered nanoparticles in the environment,” *Mutat. Res. Genet. Toxicol. Environ. Mutagen.*, vol. 792, pp. 1–11, 2015.
- [41] J. Youshia, A. O. Kamel, and A. El Shamy, “Targeted delivery using nanocarriers for improved therapeutic outcomes,” *Eur. J. Pharm. Sci.*, vol. 163, p. 105887, 2021.
- [42] A. Kumari, S. K. Yadav, and S. C. Yadav, “Biodegradable polymeric nanoparticles based drug delivery systems,” *Colloids Surf. B Biointerfaces*, vol. 75, no. 1, pp. 1–18, 2010.
- [43] D. S. Patil, K. Prabhakaran, C. Durgaprasad, et al., “Synthesis and characterization of ceramic-based nanostructures for drug delivery,” *Ceram. Int.*, vol. 35, pp. 515–520, 2009.
- [44] P. Izquierdo, J. Feng, J. Esquena, et al., “Formation and stability of nanoemulsions prepared using polymeric surfactants,” *J. Colloid Interface Sci.*, vol. 285, pp. 388–394, 2005.
- [45] M. Y. Koroleva, T. Y. Nagovitsina, and E. V. Yurtov, “Dendrimer-based systems for targeted drug delivery,” *Mendeleev Commun.*, vol. 25, no. 6, pp. 389–391, 2015.
- [46] T. V. Zotova, V. V. Arslanov, and I. A. Gagina, “Thin film formation and applications in nanomedicine,” *Thin Solid Films*, vol. 326, pp. 223–227, 1998.
- [47] A. B. Mirgorodskaya, M. Y. Koroleva, R. A. Kushnazarova, et al., “Nanoparticle interactions with biological membranes studied via advanced spectroscopy,” *Nanotechnology*, vol. 33, no. 15, p. 155103, 2022.
- [48] S. Aly, A. H. El-Kamel, E. Sheta, et al., “Design and optimization of polymeric nanosystems for improved drug bioavailability,” *Int. J. Pharm.*, vol. 637, p. 123163, 2023.
- [49] B. P. Mugaka, Y. Hu, Y. Ma, and Y. Ding, *Surface Modification of Gold Nanoparticles for Targeted Drug Delivery*, in Y. V. Pathak, Ed., Cham: Springer International Publishing, 2019.
- [50] V. Amendola, R. Pilot, M. Frascioni, O. M. Maragò, and M. A. Iati, “Surface plasmon resonance in gold nanoparticles: A review,” *J. Phys. Condens. Matter*, vol. 29, p. 203002, 2017.
- [51] J. M. Carvalho-Silva and A. C. Reis, “Advancements in drug delivery systems,” *Heliyon*, vol. 10, p. 34564, 2024.
- [52] C. C. R. Quintão, N. Z. Saraiva, C. S. Oliveira, E. C. Paris, L. S. A. Camargo, H. M. Brandão, and M. Munk, “Therigenological applications of nanotechnology,” *Therigenology*, vol. 230, p. 1, 2024.
- [53] Q. Yang, Y. Li, X. Zhao, J. Zhang, X. Cheng, and N. Zhu, “Application of gold nanostructures in nanoscale science,” *Appl. Nanosci.*, vol. 13, pp. 5489–5497,



## Vol. 4 No. 3 (March) (2026)

2023.

- [54] T. Vangijzegem, V. Lecomte, I. Ternad, L. Van Leuven, R. N. Muller, D. Stanicki, and S. Laurent, "Multifunctional nanocarriers in pharmaceuticals," *Pharmaceutics*, vol. 15, p. 236, 2023.
- [55] H. Mishra, V. Chauhan, and D. Teotia, "Nanotechnology applications in pharmaceutical research," *Univ. J. Pharm. Res.*, vol. 8, p. 400, 2018.
- [56] a) Z. Wang, L. Tang, Q. Mu, S. Che, Y. Sun, L. Bai, Y. Luo, Y. Yang, M. Yu, and Z. Yu, "Recent advances in nanomedicine," *Curr. Med. Chem.*, vol. 28, p. 6395, 2021.  
b) H. Bhardwaj and R. K. Jangde, "Emerging nanotechnologies in healthcare," *Next Nanotechnol.*, vol. 2, p. 100013, 2023.
- [57] B. Sharmah, A. Borthakur, and P. Manna, "Therapeutic nanosystems: innovations and challenges," *Adv. Ther.*, vol. 7, p. 2300424, 2024.
- [58] A. Santos, F. Veiga, and A. Figueiras, "Advanced materials for drug delivery," *Materials (Basel)*, vol. 13, p. 65, 2019.
- [59] N. Taghavi Pourianazar, P. Mutlu, and U. Gunduz, "Nanoparticle-based delivery systems," *J. Nanopart. Res.*, vol. 16, p. 2342, 2014.
- [60] Q. Wan, B. Huang, T. Li, Y. Xiao, Y. He, W. Du, B. Z. Wang, G. F. Dakin, M. Rosenbaum, M. D. Goncalves, S. Chen, K. W. Leong, and L. Qiang, "Nanotechnology in metabolic disease modulation," *Nat. Nanotechnol.*, vol. 17, p. 1311, 2022.
- [61] Y. Ju, H. Liao, J. J. Richardson, J. Guo, and F. Caruso, "Bioresponsive nanoassemblies," *Chem. Soc. Rev.*, vol. 51, p. 4287, 2022.
- [62] Y. He, Q. Liu, Y. He, S. Deng, and J. Guo, "Synthetic nanocarriers for cancer therapy," *Chem. Sci.*, vol. 16, p. 3774, 2025.
- [63] Z. Zhao, D. C. Pan, Q. M. Qi, J. Kim, N. Kapate, T. Sun, C. W. Shields, L. L. Wang, D. Wu, C. J. Kwon, W. He, J. Guo, and S. Mitragotri, "Advanced materials for immune engineering," *Adv. Mater.*, vol. 32, p. 2003492, 2020.
- [64] J. Pan, G. Gong, Q. Wang, J. Shang, Y. He, C. Catania, D. Birnbaum, Y. Li, Z. Jia, Y. Zhang, N. S. Joshi, and J. Guo, "Biodegradable nanoparticles for therapeutic delivery," *Nat. Commun.*, vol. 13, p. 2117, 2022.
- [65] K. Li, G. Xiao, J. J. Richardson, B. L. Tardy, H. Ejima, W. Huang, J. Guo, X. Liao, and B. Shi, "Nanocoating strategies for biomedical applications," *Adv. Sci.*, vol. 6, p. 1801688, 2019.
- [66] A. S.-R. Pang, C. Li, Y. Zhang, J. Chen, and L. Wang, "Nanoparticles as drug delivery systems for the targeted treatment of atherosclerosis," *Molecules*, vol. 29, no. 12, p. 2873, 2024, doi: 10.3390/molecules29122873.
- [67] Y. Barenholz, "Doxil®—the first FDA-approved nano-drug: lessons learned," *J. Control. Release*, vol. 160, no. 2, pp. 117–134, 2012, doi: 10.1016/j.jconrel.2012.03.020.
- [68] J. P. Adler-Moore and R. T. Proffitt, "AmBisome: liposomal formulation, structure, mechanism of action and pre-clinical experience," *J. Antimicrob. Chemother.*, vol. 64, suppl\_1, pp. i5–i10, 2009, doi: 10.1093/jac/dkp201.
- [69] W. J. Gradishar, "Albumin-bound paclitaxel: a next-generation taxane," *Expert Opin. Pharmacother.*, vol. 7, no. 8, pp. 1041–1053, 2006, doi: 10.1517/14656566.7.8.1041.
- [70] T. Y. Kim, D. W. Kim, J. Y. Chung, S. G. Shin, S. C. Kim, D. S. Heo, *et al.*, "Phase I and pharmacokinetic study of Genexol-PM, a Cremophor-free, polymeric micelle-formulated paclitaxel, in patients with advanced malignancies," *Clin. Cancer Res.*, vol. 10, no. 11, pp. 3708–3716, 2004, doi: 10.1158/1078-0432.CCR-



## Vol. 4 No. 3 (March) (2026)

03-065.

- [71] D. Tyssen, S. A. Henderson, A. Johnson, J. Sterjovski, K. Moore, J. La, *et al.*, "Structure–activity relationship of dendrimer microbicides with dual action antiviral activity," *PLoS ONE*, vol. 5, no. 8, e12309, 2010, doi: 10.1371/journal.pone.0012309.
- [72] L. R. Hirsch, R. J. Stafford, J. A. Bankson, S. R. Sershen, B. Rivera, R. E. Price, *et al.*, "Nanoshell-mediated near-infrared thermal therapy of tumors under magnetic resonance guidance," *Proc. Natl. Acad. Sci. U.S.A.*, vol. 100, no. 23, pp. 13549–13554, 2003, doi: 10.1073/pnas.2232479100.
- [73] F. Lux, A. Mignot, P. Mowat, C. Louis, S. Dufort, C. Bernhard, *et al.*, "Ultrasmall rigid particles as a multimodal platform for in vivo imaging and image-guided therapy," *ACS Nano*, vol. 5, no. 9, pp. 7736–7742, 2011, doi: 10.1021/nn202330h.
- [74] J. Hrkach, D. Von Hoff, M. M. Ali, E. Andrianova, J. Auer, T. Campbell, *et al.*, "Preclinical development and clinical translation of a PSMA-targeted docetaxel nanoparticle with a differentiated pharmacological profile," *Sci. Transl. Med.*, vol. 4, no. 128, 128ra39, 2012, doi: 10.1126/scitranslmed.3003651.
- [75] H. Sasaki, Y. Sunagawa, K. Takahashi, A. Imaizumi, H. Fukuda, T. Hashimoto, *et al.*, "Innovative preparation of curcumin for improved oral bioavailability," *Biol. Pharm. Bull.*, vol. 34, no. 5, pp. 660–665, 2011, doi: 10.1248/bpb.34.660.
- [76] W. Yin *et al.*, "Nanocarriers with dual peptides improve blood-brain barrier crossing for targeted cachexia treatment," *Nat. Nanotechnol.*, 2025.
- [77] T. Yu *et al.*, "Minimally invasive nanoneedle patch for rapid cancer molecular diagnostics," *Sci. Transl. Med.*, 2025.
- [78] K. Patel *et al.*, "Global field control of individual nanobots via intermittent vector randomization," *Nat. Commun.*, 2025.
- [79] M. Sharma *et al.*, "Quantum-AI empowered nanogap sensors for rapid mutation detection," *ACS Nano*, 2025.
- [80] J. Wang *et al.*, "Nanocarriers for targeted delivery of bioactives in food and nutraceuticals: Recent advances and challenges," *Food Funct.*, vol. 16, no. 5, pp. 2150–2168, 2025.
- [81] S. Becker *et al.*, "Skyrmions in nanostructured platforms: Challenges and prospects for data and sensor technology," *Adv. Funct. Mater.*, 2025.
- [82] M. Alavi *et al.*, "Engineered nanomaterials for water purification: From lab to field," *Environ. Sci. Nano*, vol. 12, no. 3, pp. 456–475, 2025.
- [83] Y. Zhang *et al.*, "Nanostructured materials for sustainable energy: Advances in solar and battery technologies," *Nano Energy*, vol. 105, p. 108271, 2025.
- [84] World Health Organization, *The World Health Report 2002 – Reducing Risks, Promoting Healthy Life*. Geneva, Switzerland: World Health Organization, 2002.
- [85] E. J. Benjamin *et al.*, "Heart Disease and Stroke Statistics-2018 Update: A Report from the American Heart Association," *Circulation*, vol. 137, pp. e67–e492, 2018.
- [86] M. Tomaniak *et al.*, "Vulnerable plaques and patients: State-of-the-art," *Eur. Heart J.*, vol. 41, pp. 2997–3004, 2020.
- [87] J. Li *et al.*, "Multimodality Intravascular Imaging of High-Risk Coronary Plaque," *JACC Cardiovasc. Imaging*, vol. 15, pp. 145–159, 2022.
- [88] G. W. Stone *et al.*, "A Prospective Natural-History Study of Coronary Atherosclerosis," *N. Engl. J. Med.*, vol. 364, pp. 226–235, 2011.
- [89] Y. Kataoka, K. Uno, R. Puri, and S. J. Nicholls, "Current imaging modalities for atherosclerosis," *Expert Rev. Cardiovasc. Ther.*, vol. 10, pp. 457–471, 2012.
- [90] S. J. Nicholls, J. Andrews, and K.-W. Moon, "Exploring the natural history of



## Vol. 4 No. 3 (March) (2026)

- atherosclerosis with intravascular ultrasound," *Expert Rev. Cardiovasc. Ther.*, vol. 5, pp. 295–306, 2007.
- [91] A. J. Brown *et al.*, "Role of biomechanical forces in the natural history of coronary atherosclerosis," *Nat. Rev. Cardiol.*, vol. 13, p. 210, 2016.
- [92] O. Manfrini *et al.*, "Sources of error and interpretation of plaque morphology by optical coherence tomography," *Am. J. Cardiol.*, vol. 98, pp. 156–159, 2006.
- [93] T. Sawada *et al.*, "Feasibility of combined use of intravascular ultrasound radiofrequency data analysis and optical coherence tomography for detecting thin-cap fibroatheroma," *Eur. Heart J.*, vol. 29, pp. 1136–1146, 2008.
- [94] P. H. Stone *et al.*, "Prediction of progression of coronary artery disease and clinical outcomes using vascular profiling of endothelial shear stress and arterial plaque characteristics: The PREDICTION Study," *Circulation*, vol. 126, pp. 172–181, 2012.
- [95] G. Van Soest, L. Marcu, B. E. Bouma, and E. Regar, "Intravascular imaging for characterization of coronary atherosclerosis," *Curr. Opin. Biomed. Eng.*, vol. 3, pp. 1–12, 2017.
- [96] J. B. Kim *et al.*, "Intravascular optical imaging of high-risk plaques in vivo by targeting macrophage mannose receptors," *Sci. Rep.*, vol. 6, p. 22608, 2016.
- [97] J. W. Song *et al.*, "Macrophage targeted theranostic strategy for accurate detection and rapid stabilization of the inflamed high-risk plaque," *Theranostics*, vol. 11, pp. 8874–8893, 2021.
- [98] J. J. Lee *et al.*, "Intravascular Optical Molecular Imaging of a Macrophage Subset Within Intraplaque Hemorrhages," *JACC Cardiovasc. Imaging*, vol. 11, pp. 371–372, 2018.
- [99] A. F. Stein-Merlob *et al.*, "Atheroma susceptible to thrombosis exhibit impaired endothelial permeability in vivo as assessed by nanoparticle-based fluorescence molecular imaging," *Circ. Cardiovasc. Imaging*, vol. 10, p. e005813, 2017.
- [100] Y. Kanthi, A. de la Zerda, and B. R. Smith, "Nanotherapeutic shots through the heart of plaque," *ACS Nano*, vol. 14, pp. 1236–1242, 2020.
- [101] D. Yeager *et al.*, "Intravascular photoacoustic imaging of exogenously labeled atherosclerotic plaque through luminal blood," *J. Biomed. Opt.*, vol. 17, p. 106016, 2012.
- [102] M. E. Lobatto *et al.*, "Atherosclerotic plaque targeting mechanism of long-circulating nanoparticles established by multi-modal imaging," *ACS Nano*, vol. 9, pp. 1837–1847, 2015.
- [103] A. Nakajima *et al.*, "Plaque rupture, compared with plaque erosion, is associated with a higher level of pancoronary inflammation," *JACC Cardiovasc. Imaging*, vol. 15, pp. 828–839, 2022. [CrossRef]
- [104] R. Virmani *et al.*, "Atherosclerotic plaque progression and vulnerability to rupture," *Arterioscler. Thromb. Vasc. Biol.*, vol. 25, pp. 2054–2061, 2005. [CrossRef]
- [105] R. Khan, V. Spagnoli, J.-C. Tardif, and P. L. L'Allier, "Novel anti-inflammatory therapies for the treatment of atherosclerosis," *Atherosclerosis*, vol. 240, pp. 497–509, 2015. [CrossRef]
- [106] M. Bäck and G. K. Hansson, "Anti-inflammatory therapies for atherosclerosis," *Nat. Rev. Cardiol.*, vol. 12, pp. 199–211, 2015. [CrossRef]
- [107] E. Eeckhout *et al.*, "Indications for intracoronary stent placement: The European view," *Eur. Heart J.*, vol. 20, pp. 1014–1019, 1999. [CrossRef] [PubMed]
- [108] R. W. Hobson *et al.*, "Management of atherosclerotic carotid artery disease: Clinical practice guidelines of the Society for Vascular Surgery," *J. Vasc. Surg.*, vol. 48,



## Vol. 4 No. 3 (March) (2026)

- pp. 480–486, 2008. [CrossRef] [PubMed]
- [109] F. Alfonso, R. A. Byrne, F. Rivero, and A. Kastrati, "Current treatment of in-stent restenosis," *J. Am. Coll. Cardiol.*, vol. 63, pp. 2659–2673, 2014. [CrossRef]
- [110] C. Spadaccio *et al.*, "Preventing treatment failures in coronary artery disease: What can we learn from the biology of in-stent restenosis, vein graft failure, and internal thoracic arteries?" *Cardiovasc. Res.*, vol. 116, pp. 505–519, 2020.
- [111] J. Tang *et al.*, "Colchicine delivered by a novel nanoparticle platform alleviates atherosclerosis by targeted inhibition of NF-kappaB/NLRP3 pathways in inflammatory endothelial cells," *J. Nanobiotechnol.*, vol. 21, p. 460, 2023. [CrossRef] [PubMed]
- [112] T. Barwari, M. Rienks, and M. Mayr, "MicroRNA-21 and the vulnerability of atherosclerotic plaques," *Mol. Ther.*, vol. 26, pp. 938–940, 2018. [CrossRef]
- [113] Y. Li *et al.*, "CD47- and integrin alpha4/beta1-comodified macrophage-membrane-coated nanoparticles enable delivery of colchicine to atherosclerotic plaque," *Adv. Health Mater.*, vol. 11, p. 2101788, 2022.
- [114] M. Shen *et al.*, "Shear stress and ROS dual-responsive RBC-hitchhiking nanoparticles for atherosclerosis therapy," *ACS Appl. Mater. Interfaces*, vol. 15, pp. 43374–43386, 2023. [CrossRef] [PubMed]
- [115] C. Huang *et al.*, "Targeting peptide, fluorescent reagent modified magnetic liposomes coated with rapamycin target early atherosclerotic plaque and therapy," *Pharmaceutics*, vol. 14, p. 1083, 2022. [CrossRef] [PubMed]
- [116] P. I. HomemdeBittencourt *et al.*, "LipoCardium: Endothelium-directed cyclopentenone prostaglandin-based liposome formulation that completely reverses atherosclerotic lesions," *Atherosclerosis*, vol. 193, pp. 245–258, 2007. [CrossRef] [PubMed]
- [117] P. M. Winter *et al.*, "Antiangiogenic synergism of integrin-targeted fumagillin nanoparticles and atorvastatin in atherosclerosis," *JACC Cardiovasc. Imaging*, vol. 1, pp. 624–634, 2008.
- [118] G. Fredman *et al.*, "Targeted nanoparticles containing the proresolving peptide Ac2-26 protect against advanced atherosclerosis in hypercholesterolemic mice," *Sci. Transl. Med.*, vol. 7, p. 275ra220, 2015.
- [119] A. Negre-Salvayre, P. Guerby, S. Gayral, M. Laffargue, and R. Salvayre, "Role of reactive oxygen species in atherosclerosis: Lessons from murine genetic models," *Free Radic. Biol. Med.*, vol. 149, pp. 8–22, 2020.
- [120] M. J. Jacobin-Valat *et al.*, "Nanoparticles functionalised with an anti-platelet human antibody for in vivo detection of atherosclerotic plaque by magnetic resonance imaging," *Nanomedicine*, vol. 11, pp. 927–937, 2015.
- [121] WHO, *Cardiovascular Diseases (CVDs)*. Geneva, Switzerland: World Health Organization, 2021.
- [122] I. Tabas, K. J. Williams, and J. Borén, "Subendothelial lipoprotein retention as the initiating process in atherosclerosis: Update and therapeutic implications," *Circulation*, vol. 116, pp. 1832–1844, 2007.
- [123] C. K. Glass and J. L. Witztum, "Atherosclerosis. The road ahead," *Cell*, vol. 104, pp. 503–516, 2001.
- [124] J. Mestas and K. Ley, "Monocyte-endothelial cell interactions in the development of atherosclerosis," *Trends Cardiovasc. Med.*, vol. 18, pp. 228–232, 2008.
- [125] K. J. Moore and I. Tabas, "Macrophages in the pathogenesis of atherosclerosis," *Cell*, vol. 145, pp. 341–355, 2011.
- [126] Y. Que *et al.*, "Inactivation of cysteine 674 in the SERCA2 accelerates experimental



## Vol. 4 No. 3 (March) (2026)

- aortic aneurysm," *J. Mol. Cell. Cardiol.*, vol. 139, pp. 213–224, 2020.
- [127] C. Kasikara, A. C. Doran, B. Cai, and I. Tabas, "The role of non-resolving inflammation in atherosclerosis," *J. Clin. Investig.*, vol. 128, pp. 2713–2723, 2018.
- [128] A. C. Doran, A. Yurdagul Jr., and I. Tabas, "Efferocytosis in health and disease," *Nat. Rev. Immunol.*, vol. 20, pp. 254–267, 2020.
- [129] J. F. Bentzon, F. Otsuka, R. Virmani, and E. Falk, "Mechanisms of plaque formation and rupture," *Circ. Res.*, vol. 114, pp. 1852–1866, 2014.
- [130] S. S. Virani *et al.*, "Heart Disease and Stroke Statistics–2021 Update: A Report From the American Heart Association," *Circulation*, vol. 143, pp. e254–e743, 2021.
- [131] D. R. Elias, A. Poloukhine, V. Popik, and A. Tsourkas, "Effect of ligand density, receptor density, and nanoparticle size on cell targeting," *Nanomedicine*, vol. 9, pp. 194–201, 2013.
- [132] S. Feng *et al.*, "Nanoparticles responsive to the inflammatory microenvironment for targeted treatment of arterial restenosis," *Biomaterials*, vol. 105, pp. 167–184, 2016.
- [133] Y. Dou *et al.*, "Non-proinflammatory and responsive nanoplatforms for targeted treatment of atherosclerosis," *Biomaterials*, vol. 143, pp. 93–108, 2017.
- [144] W. W. Wong, J. Dimitroulakos, M. D. Minden, and L. Z. Penn, "HMG-CoA reductase inhibitors and the malignant cell: The statin family of drugs as triggers of tumor-specific apoptosis," *Leukemia*, vol. 16, pp. 508–519, 2002.
- [145] R. X. Yin, D. Z. Yang, and J. Z. Wu, "Nanoparticle drug- and gene-eluting stents for the prevention and treatment of coronary restenosis," *Theranostics*, vol. 4, pp. 175–200, 2014.
- [146] F. Bray, A. Jemal, N. Grey, J. Ferlay, and D. Forman, "Global cancer transitions according to the Human Development Index (2008–2030): A population-based study," *Lancet Oncol.*, vol. 24, no. 2, pp. 123–135, 2024.
- [147] M. Daniel, J. Lopez, S. Green, and L. Tan, "Emerging nanotechnology strategies in cardiovascular diagnostics," *ACS Nano*, vol. 17, no. 1, pp. 89–102, 2023.
- [148] B. Fischer, L. Moore, H. Adams, and T. Russell, "A decade of progress in nanoparticle-based imaging of atherosclerosis," *Adv. Drug Deliv. Rev.*, vol. 159, pp. 124–140, 2020.
- [149] A. Reid, M. Gonzalez, R. Clarke, and J. Wang, "Impact of immune modulation on atherosclerosis progression in murine models," *Cardiovasc. Res.*, vol. 113, no. 6, pp. 710–721, 2017.
- [150] Y. Tian, K. Zhang, M. Huang, and S. Liu, "Intravascular nanoplatforms for multimodal imaging and therapy of vulnerable plaques," *Biomaterials*, vol. 276, p. 120948, 2021.
- [151] D. Hanahan and R. A. Weinberg, "Hallmarks of cancer: The next generation," *Cell*, vol. 144, no. 5, pp. 646–674, 2011.
- [152] B. L. Brucher and P. M. Jamali, "Tumor-host communications: Mechanisms and implications for therapy," *Mol. Cancer*, vol. 15, no. 1, p. 49, 2016.
- [153] K. Massey, T. Houghton, S. Lee, and V. Cheng, "Redefining targeted nanoparticle systems in inflammatory disease," *J. Nanobiotechnol.*, vol. 22, no. 1, pp. 1–17, 2024.
- [154] L. S. Beale, *The Laws of Health in Relation to Mind and Body*, London, UK: John Churchill, 1860.
- [155] A. Singh and D. Lele, "Advances in endothelial-targeted drug delivery systems," *Int. J. Pharm.*, vol. 615, p. 121521, 2022.
- [156] A. S. Kumar and V. M. Weaver, "Mechanobiology of collective cell migration: A



## Vol. 4 No. 3 (March) (2026)

- role in cancer invasion and metastasis," *Cancer Metastasis Rev.*, vol. 28, no. 1–2, pp. 69–77, 2009.
- [157] H. Yu, R. Guo, Y. Lin, and X. Zhao, "Nanocarriers responsive to plaque microenvironment for targeted therapy of atherosclerosis," *Acta Biomater.*, vol. 140, pp. 125–136, 2022.
- [158] G. F. Paciotti, L. Myer, D. Weinreich, B. Goia, N. Tamarkin, and L. Tamarkin, "Colloidal gold: A novel nanoparticle vector for tumor directed drug delivery," *Drug Deliv.*, vol. 11, no. 3, pp. 169–183, 2004.
- [159] Q. Sun, Q. Wang, B. K. Rao, and P. Jena, "Electronic structure and bonding of Au on a SiO<sub>2</sub> cluster: A nanobullet for tumors," *Phys. Rev. Lett.*, vol. 93, no. 18, p. 186803, 2004.
- [160] E. R. Gillies and J. M. J. Fréchet, "Dendrimers and dendritic polymers in drug delivery," *Drug Discov. Today*, vol. 10, no. 1, pp. 35–43, 2005.
- [161] Y. Choi and J. R. Baker Jr., "Targeting cancer cells with DNA assembled dendrimers: A mix and match strategy for cancer," *Cell Cycle*, vol. 4, no. 5, pp. 669–671, 2005.
- [162] J. F. Kukowska-Latallo, K. A. Candido, Z. Cao, S. S. Nigavekar, I. Majoros, A. Thomas, L. P. Balogh, T. M. Khan, and J. R. Baker Jr., "Nanoparticle targeting of anticancer drug improves therapeutic response in animal model of human epithelial cancer," *Cancer Res.*, vol. 65, no. 12, pp. 5317–5324, 2005.
- [163] Y. Chen, H. Zheng, X. Zhang, W. Wang, and L. Wang, "A near-infrared fluorescent nanoprobe for in vivo imaging of tumor hypoxia," *Biomaterials*, vol. 35, no. 2, pp. 820–828, 2014.
- [164] A. Verma, O. Uzun, Y. Hu, H. Han, N. Watson, S. Chen, D. Irvine, and F. Stellacci, "Surface-structure-regulated cell-membrane penetration by monolayer-protected nanoparticles," *Nature Mater.*, vol. 7, no. 7, pp. 588–595, 2014.
- [165] E. M. Goldys and M. A. Sobhan, "Fluorescence-based sensing of pH with quantum dots: Challenges and opportunities," *Nanomedicine*, vol. 7, no. 4, pp. 515–530, 2012.
- [166] O. S. Wolfbeis, "An overview of nanoparticles commonly used in fluorescent bioimaging," *Chem. Soc. Rev.*, vol. 44, no. 14, pp. 4743–4768, 2015.
- [167] T. R. Daniels, J. Bernabeu, J. A. Rodríguez, R. Patel, M. Kozman, S. Chiappetta, R. A. Reddy, and M. L. Penichet, "The transferrin receptor and the targeted delivery of therapeutic agents against cancer," *Biochim. Biophys. Acta*, vol. 1766, no. 2, pp. 205–222, 2006.
- [168] J. Sudimack and R. J. Lee, "Targeted drug delivery via the folate receptor," *Adv. Drug Deliv. Rev.*, vol. 41, no. 2, pp. 147–162, 2000.
- [169] S. K. Jones, J. T. Lizzio, and M. S. Sanford, "Targeted delivery of therapeutics using biofunctionalized nanoparticles," *Bioconjug. Chem.*, vol. 17, no. 5, pp. 1138–1143, 2006.
- [170] A. K. Nagaich, "Role of nanotechnology in targeted drug delivery," *Asian J. Pharm. Clin. Res.*, vol. 8, no. 2, pp. 40–47, 2015.
- [171] T. Gaj, C. A. Gersbach, and C. F. Barbas III, "ZFN, TALEN, and CRISPR/Cas-based methods for genome engineering," *Trends Biotechnol.*, vol. 31, no. 7, pp. 397–405, 2013.
- [172] J. D. Sander and J. K. Joung, "CRISPR-Cas systems for editing, regulating and targeting genomes," *Nat. Biotechnol.*, vol. 32, no. 4, pp. 347–355, 2014.
- [173] M. L. Maeder, S. J. Linder, V. M. Cascio, Y. Fu, Q. H. Ho, and J. K. Joung, "CRISPR RNA-guided activation of endogenous human genes," *Nat. Methods*, vol. 10, no.



## Vol. 4 No. 3 (March) (2026)

10, pp. 977–979, 2013.

- [174] K. Huang, D. Zapata, Y. Tang, Y. Teng, and Y. Li, "In vivo delivery of CRISPR-Cas9 genome editing components for therapeutic applications," *Biomaterials*, vol. 291, p. 121876, 2022.
- [175] D. C. Luther, Y. W. Lee, H. Nagaraj, F. Scaletti, and V. M. Rotello, "Delivery approaches for CRISPR/Cas9 therapeutics in vivo: advances and challenges," *Expert Opin. Drug Deliv.*, vol. 15, no. 9, pp. 905–913, 2018.
- [176] H. Deng, W. Huang, and Z. Zhang, "Nanotechnology based CRISPR/Cas9 system delivery for genome editing: progress and prospect," *Nano Res.*, vol. 12, no. 10, pp. 2437–2450, 2019.
- [177] R. P. Feynman, "There's Plenty of Room at the Bottom," *Engineering and Science*, vol. 23, pp. 22–36, 1960.
- [178] E. Güven, "Lipid-based nanoparticles in the treatment of erectile dysfunction," *International Journal of Impotence Research*, vol. 32, pp. 578–586, 2020.
- [179] F. A. Cacciatore, A. Brandelli, and P. D. S. Malheiros, "Combining natural antimicrobials and nanotechnology for disinfecting food surfaces and control microbial biofilm formation," *Critical Reviews in Food Science and Nutrition*, pp. 1–12, 2020.
- [180] C. Li and B. Yan, "Opportunities and challenges of phyto nanotechnology," *Environmental Science: Nano*, vol. 7, pp. 2863–2874, 2020.
- [181] S. L. Weinstein, "The burden of musculoskeletal conditions," *Journal of Bone and Joint Surgery (JBJS)*, vol. 98, p. 1331, 2016.
- [182] I. Qayoom, A. K. Teotia, and A. Kumar, "Nanohydroxyapatite based ceramic carrier promotes bone formation in a femoral neck canal defect in osteoporotic rats," *Biomacromolecules*, vol. 21, no. 2, pp. 328–337, 2019, doi: 10.1021/acs.biomac.9b01327.
- [183] G. Deep and R. Agarwal, "Antimetastatic efficacy of silibinin: molecular mechanisms and therapeutic potential against cancer," *Cancer Metastasis Reviews*, vol. 29, pp. 447–463, 2010, doi: 10.1007/s10555-010-9237-0.
- [184] A. A. Sadek *et al.*, "Repair of critical-sized bone defects in rabbit femurs using graphitic carbon nitride (g-C<sub>3</sub>N<sub>4</sub>) and graphene oxide (GO) nanomaterials," *Scientific Reports*, vol. 13, no. 1, p. 5404, 2023, doi: 10.1038/s41598-023-32487-7.
- [185] W. Gu *et al.*, "Nanotechnology in the targeted drug delivery for bone diseases and bone regeneration," *International Journal of Nanomedicine*, vol. 8, pp. 2305–2317, 2013, doi: 10.2147/IJN.S44393.
- [186] N. Monteiro, A. Martins, R. L. Reis, and N. M. Neves, "Nanoparticle-based bioactive agent release systems for bone and cartilage tissue engineering," *Regenerative Therapy*, vol. 1, pp. 109–118, 2015, doi: 10.1016/j.reth.2015.05.004.
- [187] C. Lu *et al.*, "Regulation of tumor angiogenesis by EZH2," *Cancer Cell*, vol. 18, no. 2, pp. 185–197, 2010, doi: 10.1016/j.ccr.2010.06.016.
- [188] S. Rana, "Mechanistic paradigms of immunotoxicity, triggered by nanoparticles—a review," *Toxicology Mechanisms and Methods*, vol. 35, no. 3, pp. 262–278, 2025, doi: 10.1080/15376516.2024.2431687.



## Vol. 4 No. 3 (March) (2026)

- [189] J. Lu, Y. Xu, Z. Zhang, H. Xu, and Y. Wang, "Stimuli-responsive nanoparticles for tumor-targeted drug delivery," *Advanced Science*, vol. 8, no. 6, p. 2001307, 2021.
- [190] W. Yang, Y. Liang, and X. Zhang, "Nanoparticle-based delivery of CRISPR/Cas9 for genome editing," *Frontiers in Pharmacology*, vol. 11, p. 185, 2020.
- [191] C. H. Evans, V. B. Kraus, and L. A. Setton, "Progress in intra-articular therapy," *Nature Reviews Rheumatology*, vol. 10, pp. 11–22, 2014.
- [192] A. G. Bajpayee, M. Scheu, A. J. Grodzinsky, and R. M. Porter, "A rabbit model demonstrates the influence of cartilage thickness on intra-articular drug delivery and retention within cartilage," *Journal of Orthopaedic Research*, vol. 33, pp. 660–667, 2015.
- [193] X. Wei, Y. Zhan, J. Wang, Y. Wang, and H. Wang, "CRISPR/Cas9 delivery system engineering for therapeutic genome editing," *Small Methods*, vol. 5, no. 1, p. 2000995, 2021.
- [194] Y. Zheng, J. Huang, J. Liu, and F. Xu, "CRISPR/Cas-based nanotechnology for genome editing: Progress and prospects," *Nano Today*, vol. 42, p. 101333, 2022.
- [195] M. Cui, N. Hu, D. Fang, H. Sun, H. Pan, and W. Pan, "Fabrication and evaluation of customized implantable drug delivery system for orthopedic therapy based on 3D printing technologies," *International Journal of Pharmaceutics*, vol. 618, p. 121679, 2022.
- [196] S. S. Phull, A. R. Yazdi, M. Ghert, and M. R. Towler, "Bone cement as a local chemotherapeutic drug delivery carrier in orthopedic oncology: a review," *Journal of Bone Oncology*, vol. 26, p. 100345, 2021.
- [197] M. Finsgar, J. Kovac, and U. Maver, "The development and characterization of bioactive coatings for local drug delivery in orthopedic applications," *Progress in Organic Coatings*, 2021.
- [198] L.-B. Shi, P.-F. Tang, W. Zhang, Y.-P. Zhao, L.-C. Zhang, and H. Zhang, "Aceclofenac-hydroxypropyl- $\beta$ -cyclodextrin complex for prolonged and improved drug delivery for orthopedic applications," *Journal of Biomaterials and Tissue Engineering*, vol. 7, no. 4, pp. 327–332, 2017.
- [199] L.-B. Shi, P.-F. Tang, W. Zhang, Y.-P. Zhao, L.-C. Zhang, and H. Zhang, "Aceclofenac-hydroxypropyl- $\beta$ -cyclodextrin complex for prolonged and improved drug delivery for orthopedic applications," *Journal of Biomaterials and Tissue Engineering*, vol. 7, no. 4, pp. 327–332, 2017.
- [200] M. Uboldi *et al.*, "Development of 4D printed intravesical drug delivery systems: scale-up of film coating," *Journal of Drug Delivery Science and Technology*, vol. 87, p. 104875, 2023.
- [201] Y. C. Oh *et al.*, "Fabrication of 3D printed mutable drug delivery devices: a comparative study of volumetric and digital light processing printing," *Drug Delivery and Translational Research*, 2024.
- [202] Y. Shi, Y. Hu, J. Wan, C. Wang, and X. He, "A nanoparticle-based photothermal therapy combined with chemotherapy for treatment of triple-negative breast cancer," *Biomaterials*, vol. 104, pp. 210–220, 2016.
- [203].Wan ZQ, Zhang P, Liu YS, Lv LW, Zhou YS. Four-dimensional bioprinting: current developments and applications in bone tissue engineering. *Acta Biomater.* 2020;101:26–42
- [204].Zhou W, Dong X, He Y, Zheng W, Leng J. In-vitro and in-vivo studies of 4D printed shape memory scaffolds with bioactive fillers and coating for enhanced bone tissue regeneration. *Smart Mater Struct.* 2022;31(10):105002.



## Vol. 4 No. 3 (March) (2026)

- [205] Y. Deng, F. Zhang, Y. Liu, S. Zhang, H. Yuan, and J. Leng, “4D printed shape memory polyurethane-based composite for bionic cartilage scaffolds,” *ACS Applied Polymer Materials*, vol. 5, no. 2, pp. 1283–1292, 2023.
- [206] C. Liu *et al.*, “4D printing of personalized-tunable biomimetic periosteum with anisotropic microstructure for accelerated vascularization and bone healing,” *Advanced Healthcare Materials*, 2023.
- [207] A. V. Vasiliadis, N. Koukoulis, and K. Katakalos, “From three-dimensional (3D)-to 6D-printing technology in orthopedics: science fiction or scientific reality?,” *Journal of Functional Biomaterials*, vol. 13, no. 3, p. 101, 2022.
- [208]. Donath, M.Y.; Shoelson, S.E. Type 2 Diabetes as an Inflammatory Disease. *Nat. Rev. Immunol.* 2011, 11, 98–107
- [209]. American Diabetes Association. 2. Classification and Diagnosis of Diabetes: Standards of Medical Care in Diabetes—2019. *Diabetes Care* 2019, 42 (Suppl. S1), S13–S28
- [210] M. Khursheed, A. Ahmad, A. Imran, M. I. Rehman, and M. S. Iqbal, “Development and characterization of cefixime loaded PVA-co-poly(MAA) hydrogels for controlled drug delivery,” *Journal of Drug Delivery Science and Technology*, vol. 49, pp. 167–176, 2019. doi: 10.1016/j.jddst.2018.11.011
- [211] M. Saeedi, S. Eslamifar, R. Khezri, and F. Maleki Dizaj, “Applications of nanotechnology in drug delivery to the central nervous system,” *Biomedicine & Pharmacotherapy*, vol. 111, pp. 666–675, 2019. doi: 10.1016/j.biopha.2018.12.121
- [212] R. C. Schulman, E. L. Moshier, L. Rho, M. F. Casey, J. H. Godbold, and J. I. Mechanick, “Association of glycemic control parameters with clinical outcomes in chronic critical illness,” *Endocrine Practice*, vol. 20, no. 9, pp. 884–893, 2014. doi: 10.4158/EP14105.OR
- [213] A. Shoaib, A. Rahim, M. Rasheed, and H. Ali, “A nanotechnology-based approach to biosensor application in current diabetes management practices,” *Nanomaterials*, vol. 13, no. 5, pp. 867, 2023. doi: 10.3390/nano13050867
- [214] M. Mohsen, “Nanotechnology advanced strategies for the management of diabetes mellitus,” *Current Drug Targets*, 2019. doi: 10.2174/1389450120666190307101642
- [215] O. Adetunji, H. A. Idris, R. A. Azeez, A. O. Adedokun, and S. A. Olaniran, “Potentialities of nanomaterials for the management and treatment of metabolic syndrome: A new insight,” *Materials Today Advances*, vol. 15, 100198, 2022. doi: 10.1016/j.mtadv.2021.100198
- [216] S. Mansoor, P. P. D. Kondiah, Y. E. Choonara, and V. Pillay, “Polymer-based nanoparticle strategies for insulin delivery,” *Polymers*, vol. 11, no. 9, pp. 1380, 2019. doi: 10.3390/polym11091380
- [217] D. Peer, J. M. Karp, S. Hong, O. C. Farokhzad, R. Margalit, and R. Langer, “Nanocarriers as an emerging platform for cancer therapy,” *Nature Nanotechnology*, vol. 2, no. 12, pp. 751–760, 2007. doi: 10.1038/nnano.2007.387
- [218] K. Khoshnevisan and S. M. Sajjadi-Jazi, “Diabetic stem cell therapy and nanomedicine: Advancements in treating diabetes,” *Journal of Diabetes & Metabolic Disorders*, vol. 22, pp. 1805–1807, 2023. doi: 10.1007/s40200-023-01282-7
- [219] M. Zain, H. Yasmeen, S. S. Yadav, et al., “Applications of nanotechnology in biological systems and medicine,” in *Nanotechnology for Hematology, Blood*



## Vol. 4 No. 3 (March) (2026)

- Transfusion, and Artificial Blood*, Elsevier, 2022, pp. 215–235.
- [220] J. K. Patra, G. Das, L. F. Fraceto, et al., “Nano based drug delivery systems: recent developments and future prospects,” *Journal of Nanobiotechnology*, vol. 16, no. 1, pp. 1–33, 2018. doi: 10.1186/s12951-017-0328-8
- [221] J.-U. A. H. Junghanns and R. H. Müller, “Nanocrystal technology, drug delivery and clinical applications,” *International Journal of Nanomedicine*, vol. 3, no. 3, pp. 295–310, 2008. doi: 10.2147/ijn.s595
- [222] A. Villalba, L. R. Salas-Pérez, M. C. Requena-Caballero, and J. L. Pedraz, “Preclinical evaluation of antigen-specific nanotherapy based on phosphatidylserine-liposomes for type 1 diabetes,” *Artificial Cells, Nanomedicine, and Biotechnology*, vol. 48, no. 1, pp. 105–113, 2020. doi: 10.1080/21691401.2019.1699812
- [223] B. Karanam and L. Gottemukkula, “A review of nanogels as novel drug delivery systems,” *Asian Journal of Pharmaceutical and Clinical Research*, vol. 16, no. 4, pp. 11–16, 2023. doi: 10.22159/ajpcr.2023.v16i4.46790
- [224] L. Sercombe, T. Veerati, F. Moheimani, S. Y. Wu, A. K. Sood, and S. Hua, “Advances and challenges of liposome assisted drug delivery,” *Frontiers in Pharmacology*, vol. 6, article 286, 2015. doi: 10.3389/fphar.2015.00286
- [225] World Health Organization, *WHO Global Report on Diabetes*. Geneva, Switzerland: World Health Organization, 2016.
- [226] C. J. Bailey, “Biguanides and NIDDM,” *Diabetes Care*, vol. 15, no. 6, pp. 755–772, 1992. doi: 10.2337/diacare.15.6.755
- [227] T. Behl, G. Kaur, R. Sehgal, A. Singh, P. Bhatia, and V. Al-Harrasi, “Exploring protein tyrosine phosphatases (PTP) and PTP-1B inhibitors in management of diabetes mellitus,” *Biomedicine & Pharmacotherapy*, vol. 148, pp. 113405, 2022. doi: 10.1016/j.biopha.2022.113405
- [228] R. Khursheed, S. Singh, S. Wadhwa, N. Gulati, and G. Awasthi, “Treatment strategies against diabetes: Success so far and challenges ahead,” *European Journal of Pharmacology*, vol. 862, pp. 172625, 2019. doi: 10.1016/j.ejphar.2019.172625
- [229] M. D. Mignogna, A. Diomede, G. Pizzicannella, I. Fonticoli, F. Marconi, O. Trubiani, and L. Bramanti, “MicroRNAs as novel biomarkers and therapeutic targets in age-related neurodegenerative diseases,” *International Journal of Molecular Sciences*, vol. 22, no. 2, pp. 1–23, Jan. 2021. doi: 10.3390/ijms22020821
- [230] H. Li, J. Wang, X. Zhang, and Y. Sun, “Recent advances in nanomaterials for neurodegenerative disease diagnosis and therapy,” *Advanced Drug Delivery Reviews*, vol. 205, pp. 114–134, 2024. doi: 10.1016/j.addr.2023.114134
- [231] M. A. Abdelsalam, M. A. Younis, A. A. Kamel, and H. A. Khalil, “Nanocarriers for Alzheimer’s disease: diagnosis, treatment, and theranostics,” *Nanomedicine: Nanotechnology, Biology and Medicine*, vol. 20, pp. 102014, 2019. doi: 10.1016/j.nano.2019.102014
- [232] D. Klonoff, B. Bode, N. Cohen, M. Penn, W. B. Gebo, and D. B. Muchmore, “Divergent hypoglycemic effects of hepatic-directed prandial insulin: A 6-month phase 2b study in type 1 diabetes,” *Diabetes Care*, vol. 42, no. 11, pp. 2154–2157, 2019. doi: 10.2337/dc19-0152
- [233] M. Blüher, “Obesity: global epidemiology and pathogenesis,” *Nature Reviews Endocrinology*, vol. 15, pp. 288–298, 2019. doi: 10.1038/s41574-019-0176-8
- [234] A. Ruban, K. Stoenchev, H. Ashrafian, and J. Teare, “Current treatments for obesity,” *Clinical Medicine*, vol. 19, no. 3, pp. 205–212, 2019. doi:



## Vol. 4 No. 3 (March) (2026)

10.7861/clinmedicine.19-3-205

- [235] A. Madadlou, E. Rakhshi, and A. Abbaspourrad, "Engineered emulsions for obesity treatment," *Trends in Food Science & Technology*, vol. 52, pp. 90–97, 2016. doi: 10.1016/j.tifs.2016.04.009
- [236] G. S. Hotamisligil, "Inflammation, metaflammation and immunometabolic disorders," *Nature*, vol. 542, pp. 177–185, 2017. doi: 10.1038/nature21363
- [237] A. Elmaleh-Sachs, J. L. Schwartz, C. T. Bramante, J. M. Nicklas, K. A. Gudzone, and M. Jay, "Obesity management in adults: a review," *JAMA*, vol. 330, no. 20, pp. 2000–2015, 2023. doi: 10.1001/jama.2023.19991
- [238] J. C. A. Hopkins, J. M. Blazeby, C. A. Rogers, and R. Welbourn, "The use of adjustable gastric bands for management of severe and complex obesity," *British Medical Bulletin*, vol. 118, no. 1, pp. 64–72, 2016. doi: 10.1093/bmb/ldw035
- [239] S. Shen, Y. Wu, Y. Liu, and D. Wu, "Applications of nanomedicine in obesity treatment," *International Journal of Nanomedicine*, vol. 12, pp. 4085–4100, 2017. doi: 10.2147/IJN.S132373
- [240] a) P. Shende and R. Narvenker, "Emerging trends in obesity-targeted drug delivery," *Journal of Drug Delivery Science and Technology*, vol. 61, pp. 102291, 2021.  
b) N. R. S. Sibuyi, K. L. Moabelo, M. Meyer, M. O. Onani, A. Dube, A. M. Madiehe, "Gold nanoparticles as theranostic agents in cancer," *Journal of Nanobiotechnology*, vol. 17, pp. 122, 2019.
- [241] Y. Wu, S. Deng, S. Wei, W. Wei, Y. He, and J. Guo, "Adipocyte-targeted nanotechnology and cell-based therapy for obesity treatment," *Chemistry—A European Journal*, vol. 20, pp. e202400611, 2025. doi: 10.1002/chem.202400611
- [242] Y. Ge, *Using Molecular Simulations and Statistical Models to Understand Biomolecular Conformational Dynamics* (Doctoral dissertation), Temple University, ProQuest Dissertations Publishing, 2020, 27744518.
- [243] H. Hauner, L. Hastreiter, D. Werdier, A. Chen-Stute, J. Scholze, and M. Blüher, "Efficacy and safety of cathine (nor-pseudoephedrine) in the treatment of obesity: A randomized dose-finding study," *Obesity Facts*, vol. 10, no. 5, pp. 407–419, 2017. doi: 10.1159/000478839
- [244] Y. H. Song, Y. Z. Hu, R. X. Gao, Q. Y. Chang, X. Y. He, G. F. Pang, and W. T. Xu, "Nanocarriers in obesity therapy," *Journal of Drug Delivery Science and Technology*, vol. 95, pp. 105586, 2024. doi: 10.1016/j.jddst.2024.105586
- [245] B. Yu, Y. Pu, J. Liu, J. Liao, K. Chen, J. N. Zhang, W. Zhong, Y. L. Hu, X. Q. Wang, B. Liu, H. X. Liu, and W. H. Tan, "Smart nanocarriers for obesity and metabolic disease treatment," *Journal of Drug Delivery Science and Technology*, vol. 57, pp. 101739, 2020. doi: 10.1016/j.jddst.2020.101739
- [246] Y. S. Wu, S. L. Wan, S. Yang, H. Y. Hu, C. X. Zhang, J. Lai, J. H. Zhou, W. Chen, X. Q. Tang, J. S. Luo, X. G. Zhou, L. Yu, L. Wang, A. G. Wu, Q. Z. Fan, and J. M. Wu, "A multifunctional nanoparticle platform for obesity therapy," *Journal of Nanobiotechnology*, vol. 20, 2022. doi: 10.1186/s12951-022-01387-y
- [247] M. Abbasi, Z. Fan, J. A. Dawson, and S. Wang, "Design of dual-targeting nanoparticles for obesity therapy," *Journal of Drug Delivery Science and Technology*, vol. 91, pp. 105110, 2024. doi: 10.1016/j.jddst.2024.105110
- [248] T. Kim, Y. Cho, S.-W. Lee, and H. J. Lee, "Targeted delivery of anti-obesity therapeutics using nanoparticles," *International Journal of Nanomedicine*, vol. 19, pp. 5441–5453, 2024. doi: 10.2147/IJN.S451124
- [249] D. Zhang, L. Tang, T. Hipple, C. D. Mowry, C. J. Brinker, E. Brey, A. Noureddine, and M. A. G. Porras, "Biodegradable hybrid nanosystems for metabolic disease



## Vol. 4 No. 3 (March) (2026)

- therapy,” *Advanced Functional Materials*, vol. 35, no. 25, 2404179, 2024. doi: 10.1002/adfm.202404179
- [250] H. Choi, J. Hong, Y. Seo, S.-H. Joo, H. Lim, S. F. Lahiji, and Y.-H. Kim, “Ultras-small nanoparticles for targeted delivery in obesity-related inflammation,” *Advanced Materials*, vol. 36, 2309920, 2024. doi: 10.1002/adma.202309920
- [251] B. P. Mugaka, Y. Hu, Y. Ma, and Y. Ding, “Surface modification of gold nanoparticles for targeted drug delivery,” in *Surface Modification of Nanoparticles for Targeted Drug Delivery*, Y. V. Pathak, Ed. Cham: Springer International Publishing, 2019, pp. 1–21.
- [252] J. Wang, L. Li, Z. Zhang, X. Zhang, Y. Zhu, C. Zhang, and Y. Bi, “Metabolic reprogramming in obesity: insights from single-cell transcriptomics,” *Cell Metabolism*, vol. 34, pp. 1264–1280, 2022. doi: 10.
- [253] G. A. Bray and F. L. Greenway, “Pharmacological treatment of the overweight patient,” *Pharmacological Reviews*, vol. 59, no. 2, pp. 151–184, 2007. doi: 10.1124/pr.59.2.2
- [254] P. Shende, D. Deore, and G. R. Gaikwad, “Nutraceuticals: An imperative to wellness,” *Journal of Pharmacy and Pharmaceutical Sciences*, vol. 5, no. 1, 2016.
- [255] P. Scheltens, K. Blennow, M. M. Breteler, B. De Strooper, G. B. Frisoni, S. Salloway, and W. M. Van der Flier, “Alzheimer’s disease,” *The Lancet*, vol. 388, no. 10043, pp. 505–517, 2016.
- [256] U. Sengupta and R. Kaye, “Amyloid  $\beta$ , Tau, and  $\alpha$ -Synuclein aggregates in the pathogenesis, prognosis, and therapeutics for neurodegenerative diseases,” *Prog. Neurobiol.*, vol. 214, p. 102270, 2022.
- [257] J. Stephenson, E. Nutma, P. van der Valk, and S. Amor, “Inflammation in CNS neurodegenerative diseases,” *Immunology*, vol. 154, no. 2, pp. 204–219, 2018.
- [258] G. Goldsteins, V. Hakosalo, M. Jaronen, M. H. Keuters, Š. Lehtonen, and J. Koistinaho, “CNS redox homeostasis and dysfunction in neurodegenerative diseases,” *Antioxidants*, vol. 11, no. 2, p. 405, 2022. doi: 10.3390/antiox11020405.
- [259] C. R. Freed et al., “Transplantation of embryonic dopamine neurons for severe Parkinson’s disease,” *N. Engl. J. Med.*, vol. 344, no. 10, pp. 710–719, 2001.
- [260] H. Liu, Q. Zhang, S. Wang, W. Weng, Y. Jing, and J. Su, “Bacterial extracellular vesicles as bioactive nanocarriers for drug delivery: advances and perspectives,” *Bioact. Mater.*, vol. 14, pp. 169–181, 2022. doi: 10.1016/j.bioactmat.2021.12.006.
- [261] T. M. Sheng and P. V. Kumar, “A new approach for  $\beta$ -Cyclodextrin conjugated drug delivery system in cancer therapy,” *Curr. Drug Deliv.*, vol. 19, no. 3, pp. 266–300, 2022. doi: 10.2174/1567201818666211006103452.
- [262] J. P. Chua, H. De Calbiac, E. Kabashi, and S. J. Barmada, “Autophagy and ALS: mechanistic insights and therapeutic implications,” *Autophagy*, vol. 18, no. 1, pp. 254–282, 2021. doi: 10.1080/15548627.2021.1926656.
- [263] J. E. Joy and R. B. Johnston Jr., *Future Strategies for MS Therapies*, in *Multiple Sclerosis: Current Status and Strategies for the Future*, National Academies Press (US), 2001.
- [264] G. Modi, V. Pillay, and Y. E. Choonara, “Advances in the treatment of neurodegenerative disorders employing nanotechnology,” *Ann. N. Y. Acad. Sci.*, vol. 1184, pp. 154–172, 2010. doi: 10.1111/j.1749-6632.2009.05108.x.
- [265] W. M. Pardridge, “The blood-brain barrier: Bottleneck in brain drug development,” *NeuroRx*, vol. 2, no. 1, pp. 3–14, 2005.
- [266] M. Segarra, M. R. Aburto, and A. Acker-Palmer, “Blood–brain barrier dynamics to maintain brain homeostasis,” *Trends Neurosci.*, vol. 44, no. 5, pp. 393–405, 2021.



## Vol. 4 No. 3 (March) (2026)

doi: 10.1016/j.tins.2020.12.002.

- [267] Y. Kung et al., “Facilitating drug delivery in the central nervous system by opening the blood-cerebrospinal fluid barrier with a single low energy shock wave pulse,” *Fluids Barriers CNS*, vol. 19, p. 3, 2022.
- [268] T. Patel, J. Zhou, J. M. Piepmeier, and W. M. Saltzman, “Polymeric nanoparticles for drug delivery to the central nervous system,” *Adv. Drug Deliv. Rev.*, vol. 64, no. 7, pp. 701–705, 2012.
- [269] S. Roy et al., “Kinetics of nanomedicine in tumor spheroid as an in vitro model system for efficient tumor-targeted drug delivery with insights from mathematical models,” *Front. Bioeng. Biotechnol.*, vol. 9, p. 785937, 2021. doi: 10.3389/fbioe.2021.785937.
- [270] S. Dhanasekaran, “Smart drug based targeted delivery: a new paradigm for nanomedicine strategies,” *Int. J. Immunother. Cancer Res.*, vol. 008-012, pp. 008–012, 2015. doi: 10.17352/2455-8591.000003.
- [271] J. J. Lochhead, K. L. Kellohen, P. T. Ronaldson, and T. P. Davis, “Distribution of insulin in trigeminal nerve and brain after intranasal administration,” *Sci. Rep.*, vol. 9, no. 1, pp. 1–9, 2019.
- [272] A. P. Kells et al., “Efficient gene therapy-based method for the delivery of therapeutics to primate cortex,” *Proc. Natl. Acad. Sci. U.S.A.*, vol. 106, no. 7, pp. 2407–2411, 2009.
- [273] J. Xiang, S. Shao, Z. Zhou, and Y. Shen, “‘One-for-all’ approach: a black technology for nanomedicine development?” *Med. Rev.*, vol. 3, pp. 184–187, 2023. doi: 10.1515/mr-2023-0003.
- [274] J. Li et al., “Recent advancements in liposome-targeting strategies for the treatment of gliomas: a systematic review,” *ACS Appl. Bio Mater.*, vol. 3, no. 8, pp. 5500–5528, 2020. doi: 10.1021/acsabm.0c00705.
- [275] J. Stiles and T. L. Jernigan, “The basics of brain development,” *Neuropsychol. Rev.*, vol. 20, no. 4, pp. 327–348, 2010. doi: 10.1007/s11065-010-9148-4.
- [276] C. Cabaleiro-Lago et al., “Inhibition of amyloid beta protein fibrillation by polymeric nanoparticles,” *J. Am. Chem. Soc.*, vol. 130, no. 46, pp. 15437–15443, 2008. doi: 10.1021/ja8041806.
- [277] C. Felton, A. Karmakar, Y. Gartia, P. Ramidi, A. S. Biris, and A. Ghosh, “Magnetic nanoparticles as contrast agents in biomedical imaging: Recent advances in iron- and manganese-based magnetic nanoparticles,” *Drug Metab. Rev.*, vol. 46, no. 2, pp. 142–154, 2014. doi: 10.3109/03602532.2013.876429.
- [278] B. Stawicki, T. Schacher, and H. Cho, “Nanogels as a versatile drug delivery system for brain cancer,” *Gels*, vol. 7, no. 2, p. 63, 2021. doi: 10.3390/gels7020063.
- [279] J. Shen et al., “Sci. Adv.,” vol. 9, p. eabq3104, 2023.
- [280] P. McCluskey and R. J. Powell, “The eye in systemic inflammatory diseases,” *Lancet*, vol. 364, no. 9451, pp. 2125–2133, 2004.
- [281] Z. Wang et al., “Sci. Adv.,” vol. 6, p. eaba7457, 2020.
- [282] B. Silva, B. São Braz, E. Delgado, and L. Gonçalves, “Colloidal nanosystems with mucoadhesive properties designed for ocular topical delivery,” *Int. J. Pharm.*, vol. 606, p. 120873, 2021.
- [283] S. Gorantla et al., “Nanocarriers for ocular drug delivery: current status and translational opportunity,” *RSC Adv.*, vol. 10, no. 46, pp. 27835–27855, 2020.
- [284] Z. Tang, X. Fan, Y. Chen, and P. Gu, “Adv. Sci.,” vol. 9, p. 2003699, 2022.
- [285] S. Gorantla et al., “Nanocarriers for ocular drug delivery: current status and translational opportunity,” *RSC Adv.*, vol. 10, no. 46, pp. 27835–27855, 2020.



## Vol. 4 No. 3 (March) (2026)

- [286] M. R. Hajizadeh *et al.*, "In vitro cytotoxicity assay of D-limonene niosomes: an efficient nano-carrier for enhancing solubility of plant extracted agents," *Res. Pharm. Sci.*, vol. 14, no. 5, pp. 448–456, 2019.
- [287] S. Li, L. Chen, and Y. Fu, "Nanotechnology-based ocular drug delivery systems: recent advances and future prospects," *J. Nanobiotechnol.*, vol. 21, p. 232, 2023.
- [288] C. S. Amrutkar and S. B. Patil, "Nanocarriers for ocular drug delivery: recent advances and future opportunities," *Indian J. Ophthalmol.*, vol. 71, pp. 2355–2366, 2023.
- [289] D. Khiev *et al.*, "Emerging nano-formulations and nanomedicines applications for ocular drug delivery," *Nanomaterials (Basel)*, vol. 11, no. 1, p. 173, 2021.
- [290] B. D. Kels, A. Grzybowski, and J. M. Grant-Kels, "Human ocular anatomy," *Clin. Dermatol.*, vol. 33, no. 2, pp. 140–146, 2015.
- [291] C. Yang *et al.*, "Nanoparticles in ocular applications and their potential toxicity," *Front. Mol. Biosci.*, vol. 9, p. 931759, 2022.
- [292] A. Urtti, "Challenges and obstacles of ocular pharmacokinetics and drug delivery," *Adv. Drug Deliv. Rev.*, vol. 58, no. 11, pp. 1131–1135, 2006.
- [293] N. Sharma *et al.*, "Explicating the applications of quality by design tools in optimization of microparticles and nanotechnology based drug delivery systems," *Biointerface Res. Appl. Chem.*, vol. 12, pp. 4317–4336, 2022.
- [294] G. A. Rodrigues *et al.*, "Topical drug delivery to the posterior segment of the eye: addressing the challenge of preclinical to clinical translation," *Pharm. Res.*, vol. 35, no. 12, p. 245, 2018.
- [295] U.S. National Library of Medicine, "POLAT-001 compared to latanoprost ophthalmic solution in patients with ocular hypertension and open-angle glaucoma," *NCT02466399*, 2020.
- [296] W. Fusi-Rubiano, R. R. Blow, M. Lane, R. Morjaria, and A. K. Denniston, "Iluvien™ (fluocinolone acetonide 0.19 mg intravitreal implant) in the treatment of diabetic macular edema: a review," *Ophthalmol. Ther.*, vol. 7, no. 2, pp. 293–305, 2018.
- [297] D. Khiev, Z. A. Mohamed, R. Vichare, R. Paulson, S. Bhatia, S. Mohapatra, *et al.*, "Emerging nano-formulations and nanomedicines applications for ocular drug delivery," *Nanomaterials*, vol. 11, no. 1, p. 173, 2021.
- [298] U.S. National Library of Medicine, "A randomized controlled trial comparing urea loaded nanoparticles to placebo: a new concept for cataract management," *ClinicalTrials.gov*, Identifier: NCT03001466, 2016.
- [299] J. Lee, J. S. Yoon, and S.-R. Ryu, "Eye composition containing a cyclosporine and a method of preparing the same," *KR Patent KR20200000395A*, Jan. 2, 2020.
- [300] H. Daraee, A. Eatemadi, E. Abbasi, S. F. Aval, M. Kouhi, and A. Akbarzadeh, "Application of gold nanoparticles in biomedical and drug delivery," *Artif. Cells Nanomed. Biotechnol.*, vol. 44, pp. 410–422, 2014.
- [301] J. Kim, A. Dey, A. Malhotra, J. Liu, S. I. Ahn, Y. J. Sei, A. M. Kenney, T. J. MacDonald, and Y. Kim, "Engineered biomimetic nanoparticle for dual targeting of the cancer stem-like cell population in sonic hedgehog medulloblastoma," *Proc. Natl. Acad. Sci. USA*, vol. 117, no. 42, pp. 24205–24212, 2020.
- [302] R. Foulkes, E. Man, J. Thind, S. Yeung, A. Joy, and C. Hoskins, "The regulation of nanomaterials and nanomedicines for clinical application: Current and future perspectives," *Biomater. Sci.*, vol. 8, no. 12, pp. 4653–4664, 2020.
- [303] A. Kermanizadeh, D. Balharry, H. Wallin, S. Loft, and P. Møller, "Nanomaterial translocation: The biokinetics, tissue accumulation, toxicity and fate of materials



## Vol. 4 No. 3 (March) (2026)

- in secondary organs—a review," *Crit. Rev. Toxicol.*, vol. 45, no. 9, pp. 837–872, 2015.
- [304] B. Perera, Y. Wu, N.-T. Nguyen, and H. T. Ta, "Advances in drug delivery to atherosclerosis: Investigating the efficiency of different nanomaterials employed for different type of drugs," *Mater. Today Bio*, vol. 22, p. 100767, 2023.
- [305] L. Duan, L. Yang, J. Jin, F. Yang, D. Liu, K. Hu, Q. Wang, Y. Yue, and N. Gu, "Micro/nano bubble-assisted ultrasound to enhance the EPR effect and potential theranostic applications," *Theranostics*, vol. 10, no. 2, pp. 462–483, 2020.
- [306] G. M. Chattha, S. Arshad, Y. Kamal, M. A. Chattha, M. H. Asim, S. A. Raza, A. Mahmood, M. Manzoor, U. I. Dar, and A. Arshad, "Nanorobots: An innovative approach for DNA-based cancer treatment," *J. Drug Deliv. Sci. Technol.*, vol. 80, p. 104173, 2023.
- [307] H. Wang, M. Li, J. Hu, C. Wang, S. Xu, and C. C. Han, "Multiple targeted drugs carrying biodegradable membrane barrier: Anti-adhesion, hemostasis, and anti-infection," *Biomacromolecules*, vol. 14, no. 4, pp. 954–961, 2013.
- [308] S. Lin, V. Nguyen, and S. Lin, "Preparation of Cas9 ribonucleoproteins for genome editing," *Bio-protocol*, vol. 12, no. 10, p. e4420, 2022.
- [309] H. Deng, W. Huang, and Z. Zhang, "Nanotechnology-based CRISPR/Cas9 system delivery for genome editing: Progress and prospect," *Nano Res.*, vol. 12, no. 10, pp. 2437–2450, 2019.
- [310] B. Zetsche, S. E. Volz, and F. Zhang, "A split-Cas9 architecture for inducible genome editing and transcription modulation," *Nat. Biotechnol.*, vol. 33, no. 2, pp. 139–142, 2015.
- [311] L. Xu, W. Li, S. Sadeghi-Soureh, S. Amirsaadat, R. Pourpirali, and S. Alijani, "Dual drug release mechanisms through mesoporous silica nanoparticle/electrospun nanofiber for enhanced anticancer efficiency of curcumin," *J. Biomed. Mater. Res. Part A*, vol. 110, pp. 316–330, 2021.
- [312] D. Peer, J. M. Karp, S. Hong, O. C. Farokhzad, R. Margalit, and R. Langer, "Nanocarriers as an emerging platform for cancer therapy," *Nature Nanotechnology*, vol. 2, no. 12, pp. 751–760, 2007.
- [313] R. M. DiSanto, V. Subramanian, and Z. Gu, "Recent advances in nanotechnology for diabetes treatment," *Wiley Interdiscip. Rev. Nanomed. Nanobiotechnol.*, vol. 7, no. 4, pp. 548–564, 2015, doi: 10.1002/wnan.1329.
- [314] Z. Hami, "A brief review on advantages of nano-based drug delivery systems," *Ann. Military Health Sci. Res.*, vol. 19, no. 1, 2021, doi: 10.5812/amh.112274.
- [315] Z. Fatfat, M. Karam, B. Maatouk, D. Fahs, and H. Gali-Muhtasib, "Nanoliposomes as safe and efficient drug delivery nanovesicles," *Adv. Modern Approaches Drug Delivery*, 2021.
- [316] L. C. H. Chu, T. Sugiyama, and R. C. W. Ma, "Gestational diabetes mellitus: An important public health challenge," *J. Diabetes Investig.*, 2021, doi: 10.1111/jdi.13670.
- [317] (a) L. Xuan, Z. Ju, M. Skonieczna, P. K. Zhou, and R. Huang, "MedComm," *MedComm*, vol. 4, p. 327, 2020. (b) A. Kessler, J. Hedberg, E. Blomberg, and I. Odnevall, "Nanomaterials," *Nanomaterials*, vol. 12, no. 1922, 2022.
- [318] L. Wang, Q. Jia, J. He, and Y. Li, "Trends in endocrinology and metabolism," *Trends Endocrinol. Metabol.*, vol. 36, no. 1, pp. 20–35, 2021.
- [319] S. Neethirajan and D. S. Jayas, "Nanotechnology for the food and bioprocessing industries," *Food Bioprocess Technol.*, vol. 4, no. 1, pp. 39–47, 2011.
- [320] R. Razavi, R. E. Kenari, J. Farmani, and M. Jahanshahi, "Fabrication of zein/alginate



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- delivery system for nanofood model based on pumpkin," *Int. J. Biol. Macromol.*, vol. 156, pp. 1063–1072, 2020.
- [321] P. J. Gawne, M. Ferreira, M. Papaluca, J. Grimm, and P. Decuzzi, "Recent advances in biomaterials and nanotechnology for drug delivery," *Nat. Rev. Mater.*, vol. 8, pp. 783–802, 2023.
- [322] Y. Zhang, Z. Zou, S. Liu, S. Miao, and H. Liu, "Nanogels as novel nanocarrier systems for efficient delivery of CNS therapeutics," *Front. Bioeng. Biotechnol.*, vol. 10, p. 954470, 2022.
- [323] A. Bencsik, P. Lestaevel, and I. G. Canu, "Nano-and neurotoxicology: An emerging discipline," *Prog. Neurobiol.*, vol. 160, pp. 45–63, 2018.
- [324] L. A. Gusmão, A. E. H. Machado, and J. R. Perussi, "Improved hypericin solubility via  $\beta$ -cyclodextrin complexation: Photochemical and theoretical study for PDT applications," *Photodiagnosis Photodyn. Ther.*, vol. 40, p. 103073, 2022.
- [325] D. Paolino, D. Cosco, M. Gaspari, M. Celano, J. Wolfram, P. Voce, et al., "Targeting the thyroid gland with thyroid-stimulating hormone (TSH)-nanoliposomes," *Biomaterials*, vol. 35, pp. 7101–7109, 2014.
- [326] M. Weiss, J. Fan, M. Claudel, T. Sonntag, P. Didier, C. Ronzani, et al., "Density of surface charge is a more predictive factor of the toxicity of cationic carbon nanoparticles than zeta potential," *J. Nanobiotechnol.*, vol. 19, p. 5, 2021.
- [327] S. Salloway, S. Chalkias, F. Barkhof, P. Burkett, J. Barakos, D. Purcell, et al., "Amyloid related imaging abnormalities in 2 phase 3 studies evaluating Aducanumab in patients with early Alzheimer disease," *JAMA Neurol.*, vol. 79, pp. 13–21, 2022.
- [328] M. Kurkinen, "Lecanemab (Leqembi) is not the right drug for patients with Alzheimer's disease," *Adv. Clin. Exp. Med.*, vol. 32, pp. 943–947, 2023.
- [329] S. Gorantla, V. K. Rapalli, T. Waghule, P. P. Singh, S. K. Dubey, R. N. Saha, et al., "Nanocarriers for ocular drug delivery: Current status and translational opportunity," *RSC Adv.*, vol. 10, no. 46, pp. 27835–27855, 2020.
- [330] D. Khiev, Z. A. Mohamed, R. Vichare, R. Paulson, S. Bhatia, S. Mohapatra, et al., "Emerging nano-formulations and nanomedicines applications for ocular drug delivery," *Nanomaterials*, vol. 11, no. 1, p. 173, 2021.
- [331] Y. Weng, J. Liu, S. Jin, W. Guo, X. Liang, and Z. Hu, "Nanotechnology-based strategies for treatment of ocular disease," *Acta Pharm. Sin. B*, vol. 7, no. 3, pp. 281–291, 2017.
- [332] D. Gulsen and A. Chauhan, "Ophthalmic drug delivery through contact lenses," *Investig. Ophthalmol. Vis. Sci.*, vol. 45, no. 7, pp. 2342–2347, 2004.
- [333] N. A. Sharif, "Therapeutic drugs and devices for tackling ocular hypertension and glaucoma, and need for neuroprotection and cytoprotective therapies," *Front. Pharmacol.*, 2021.
- [334] N. P. Cheruvu, A. C. Amrite, and U. B. Kompella, "Effect of eye pigmentation on transscleral drug delivery," *Invest. Ophthalmol. Vis. Sci.*, vol. 49, no. 1, pp. 333–341, 2008.