A Review on Nanotechnology - Based drug delivery systems in modern pharmacy

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***Abstract*—Nanotechnology is redesigning pharmaceutical research by providing innovative strategies to overcome the limitations of conventional drug delivery systems. Nanotechnology represents one of the most advanced and rapidly evolving fields within pharmaceutical sciences. Nanopharmaceuticals are composed of nanoscale materials whose structural and functional properties can be precisely engineered to improve therapeutic performance. The integration of nanoparticles into tissue engineering, drug delivery, imaging, biosensing, diagnostics, and therapeutic interventions offers tremendous potential for advancing our understanding of biological systems and improving clinical outcomes. A wide range of nanomaterials such as polymeric nanoparticles, magnetic nanoparticles, liposomes, carbon nanotubes, quantum dots, dendrimers, and metallic nanoparticles has contributed to transformative advancements across pharmaceutical and biomedical sectors. By manipulating particle size, morphology, and surface chemistry, researchers can design nanocarriers capable of extended drug release, reduced dosing frequency, and improved penetration into otherwise inaccessible tissues. This chapter provides a comprehensive overview of major classes of nanopharmaceuticals, discussing their properties, fabrication techniques, advantages, and diverse applications in drug delivery and medical science.**

***Index Terms*—Nanotechnology, Nanoparticles, nanomaterials, drug delivery systems, toxicity.**

I.INTRODUCTION

The rise of nanotechnology has profoundly reshaped the field of pharmaceutical sciences and modern medicine in the 21st century. The word *"nano,"* originating from the Greek term *"nanos,"* meaning *dwarf,* refers to materials and structures engineered at the scale of one billionth of a meter (1×10^{-9} m). This nanoscale dimension introduces unique physicochemical properties that have emergenc traditional concepts in drug delivery, diagnostics, and therapeutic interventions. Nanoparticles are taken up by cells more efficiently than larger micromolecules and therefore, could be used as effective transport and delivery systems[1]. Nanoscience is the study of materials and phenomena at the nanoscale typically between 1 and 100 nanometers where unique physical, chemical, and biological properties emerge. Nanotechnology applies this scientific understanding to design, engineer, and develop innovative materials, devices, and systems that harness these nanoscale characteristics for practical use[2].

Nanoscience and nanotechnology focused on understanding, designing, and applying materials and devices at the nanoscale have profoundly influenced numerous industries, particularly the pharmaceutical sector. Recognized as a distinct scientific discipline since the late 20th and 21st century, nanotechnology has transformed approaches to drug development and delivery. A major challenge in the treatment of many diseases is the efficient delivery of therapeutic agents to specific biological targets. Conventional drug administration often suffers from poor biodistribution, limited therapeutic efficacy, non-specific interactions, and undesirable side effects. Controlled drug delivery systems aim to overcome these limitations by transporting the active compound directly to the intended site of action and by protecting it from rapid clearance or biochemical degradation. This targeted approach enhances drug accumulation within diseased tissues, reduces required dosages, and minimizes systemic toxicity. One of the most fundamental and effective applications of nanotechnology in medicine

is the nanoscale reduction of drug formulations, enabling the development of optimized and sophisticated drug-delivery systems[3].

Recent advancements in nanotechnology have highlighted the significant potential of nanoparticles as highly efficient drug-delivery systems. Through various nanoscale engineering and size-reduction techniques, a wide array of nanostructures can be produced, each exhibiting unique physicochemical and biological properties that enhance their performance across multiple pharmaceutical dosage forms. A critical feature of nanoparticles is that their reduced dimensions profoundly influence the physicochemical behaviour of the encapsulated substances. Owing to their diverse sizes, shapes, and surface characteristics, nanoparticles can also exhibit distinctive optical properties, including tunable colours, which make them particularly valuable for biomedical imaging and diagnostic applications[4]. In this review article, we aim to focus on different types, advantages, preparation, characteristics and applications with future scope of nanoparticles. And highlights the significance of nanotechnology in human health with particular emphasis on its nano-medicinal application in imaging, screening, diagnosis, targeted drug delivery systems, and effective treatment strategies for human diseases.

1.1Various type of pharmaceutical nanosystem:

1.Liposomes: Liposomes are spherical, self-assembling vesicular structures formed in aqueous environments and consist of one or more phospholipid bilayers. Typically ranging from 50 to 100 nm in diameter, they offer several advantages due to their versatile composition, high biocompatibility, and biodegradability. Liposomes can encapsulate and protect a wide range of therapeutic biomolecules, exhibiting high entrapment efficiency. Owing to their ability to circulate for extended periods, they support both passive and active delivery of genes, proteins, and peptides. Furthermore, liposomes can be surface-functionalized with targeting ligands to enhance the selective accumulation of therapeutic or diagnostic agents within specific cells or tissues[5].

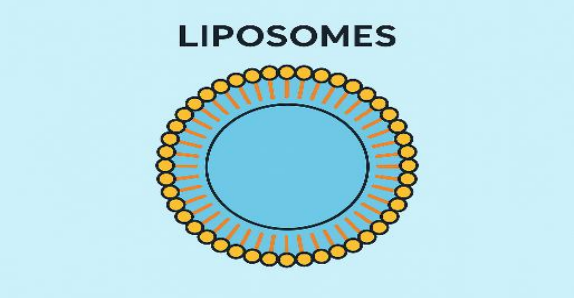

Fig.01 Liposomes.

2.Solid lipid nanoparticles: Solid lipid nanoparticles (SLNs) represent a class of colloidal drug delivery systems composed of physiological lipids that remain solid at both ambient and physiological temperatures. Typically ranging from 50 to 1000 nm in diameter, SLNs combine the advantages of traditional colloidal carriers, such as liposomes and polymeric nanoparticles, while mitigating several of their limitations. They were introduced in the 1990s as a biocompatible and scalable alternative to polymer-based nanocarriers. SLNs are formulated using solid lipids including triglycerides, fatty acids, waxes, and glyceride mixtures forming a solid hydrophobic matrix into which therapeutic agents can be incorporated. The lipid core is stabilized by surfactants such as polysorbates, phospholipids, bile salts, or poloxamers. This architecture enables efficient encapsulation of both lipophilic and certain hydrophilic compounds. Importantly, the solid-state nature of the lipid matrix enhances drug stability by reducing molecular mobility and susceptibility to degradation[6-7]. Solid lipid nanoparticles have a hydrophobic solid core with a monolayer coating of phospholipids, and the drug is typically dissolved or dispersed within the core. These nanoparticles are widely used as adjuvants for vaccines, topical application, cosmetics, anti-tubercular chemotherapy, and targeted brain drug delivery[8].

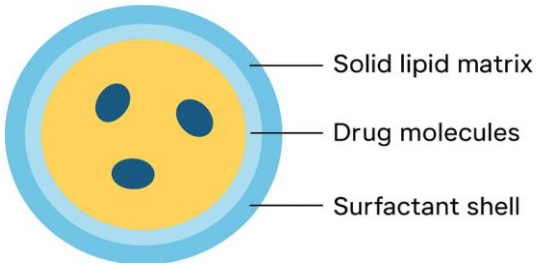

Fig.02 Solid lipid nanoparticles.

3.Carbon nanotubes: Carbon nanotubes (CNTs) are cylindrical nanostructures typically measuring 0.5–3 nm in diameter and 20–1000 nm in length. They are composed of rolled graphene sheets and may exist as single-walled or multi-walled configurations, each representing distinct allotropic forms of carbon. Owing to their extraordinary tensile strength and unique mechanical, thermal, and electrical properties ranging from insulating to semiconductive or conductive CNTs have broad biomedical relevance. Their high aspect ratio and ability to traverse cellular membranes facilitate efficient intracellular delivery, enabling transport of genes, peptides, and other bioactive molecules into the cytoplasm and nucleus. Moreover, their optical and electrical characteristics support their use in early-stage cancer detection and other diagnostic applications[8-9].

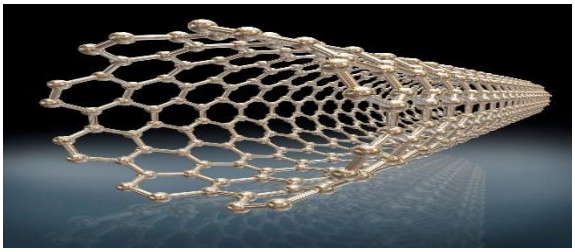

Fig.03 Carbon nanotubes

4)Fullerenes: Fullerenes are carbon-based molecules characterized by their hollow, cage-like structures, which may assume spherical, ellipsoidal, or tubular geometries. Cylindrical fullerenes are classified as carbon nanotubes, whereas the spherical variants are commonly termed buckyballs. Structurally, fullerenes share similarities with graphite, consisting of networks of carbon atoms arranged predominantly in hexagonal rings; however, the incorporation of pentagonal or occasionally heptagonal rings imparts curvature and can generate porous architectures. Molecular clusters composed of fewer than 300 carbon atoms are often referred to as endohedral fullerenes, with the most widely recognized representative being buckminsterfullerene (C_{60}), a spherical molecule renowned for its exceptional symmetry and stability[7-8].

5)Nano shells: Nanoshells are core shell nanostructures composed of a spherical core encapsulated by a thin outer layer, typically 1–20 nm thick. These concentric architectures impart properties distinct from their single-component counterparts or similarly sized homogeneous nanoparticles. The optical, electronic, and chemical behaviors of nanoshells can be precisely tuned by modifying the core shell ratio or by selecting specific constituent materials. Cores are commonly fabricated from dielectric substances such as silica or polystyrene due to their excellent chemical and structural stability, while shells may be composed of metals, insulators, or semiconductors. Among these, metallic nanoshells most notably those consisting of a gold shell surrounding a dielectric core represent a prominent class of composite nanoparticles. Their highly tunable surface plasmon resonance endows them with exceptional optical and photothermal properties, making them valuable in therapeutic interventions, biosensing, and biomedical imaging. Compared with conventional organic dyes, nanoshells exhibit superior photostability, reduced susceptibility to thermal or chemical degradation, and enhanced imaging performance[9].

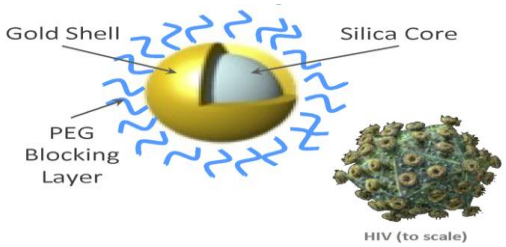

Fig.04 Nano Shell.

6.Quantum dots: Quantum dots (QDs) are fluorescent semiconductor nanocrystals typically ranging from 1–100 nm in diameter. Their unique size-dependent optical properties arising from quantum confinement effects make them highly valuable in biomedical imaging, diagnostics, and drug delivery. QDs can be surface-functionalized with targeting ligands, polymers, or therapeutic agents, enabling simultaneous drug transport and real-time visualization of biodistribution and cellular uptake through their stable, tunable fluorescence. This dual functionality positions quantum dots as powerful tools for theranostic applications[10].

1.2 Properties of Nanoparticles:[11]

1. Enhanced Surface Area: The reduced particle size results in a markedly increased surface-area-to-volume ratio, enabling improved interaction with biological membranes and heightened reactivity. This property facilitates superior drug adsorption, binding efficiency, and more rapid dissolution of poorly water-soluble drugs.

2. Improved Solubility and Dissolution: Nanoparticles can enhance the apparent solubility and dissolution rate of hydrophobic drugs, thereby improving absorption and bioavailability, particularly for orally administered therapeutics.
3. Controlled and Targeted Drug Release:The surface chemistry and structural attributes of nanoparticles allow modulation of drug release profiles, enabling sustained, controlled, or stimuli-responsive release. Functionalization with targeting ligands further permits selective delivery to specific tissues or cells.
4. Reduced Toxicity and Improved Safety: By enabling localized delivery and minimizing systemic distribution, nanoparticles can decrease off-target effects and reduce overall drug toxicity. Biodegradable materials further enhance biocompatibility.
5. Increased Drug Stability: Encapsulation within nanoparticle matrices protects therapeutic molecules from enzymatic degradation, oxidation, photolysis, or hydrolysis, thus improving stability during storage and after administration.
6. Enhanced Cellular and Tissue Penetration: Their nanoscale size allows nanoparticles to navigate biological barriers including cellular membranes, mucosal layers, and in some cases the blood–brain barrier facilitating efficient intracellular and tissue-level delivery.
7. Decreased Dose Frequency and Improved Patient Compliance: Due to sustained-release capabilities and improved bioavailability, nanoparticles can reduce dosing frequency, which enhances therapeutic compliance.
8. Tunable Physicochemical Properties: Nanoparticles can be engineered with specific sizes, shapes, charges, and surface functionalities to optimize biodistribution, circulation time, targeting efficiency, and overall therapeutic performance.

II. DRUGS DEVELOPMENT AND DELIVERY

Oral ingestion or intravascular injection are two methods used in conventional or traditional drug development and delivery systems. Drug circulation inside the body is controlled by the systemic blood circulation. As a result, the organs only receive a slight amount of the active medicinal ingredients[12]. Additionally, the process of creating a new medicinal molecule is costly and time-consuming. Pharmaceutical businesses are now dealing with the following issues and difficulties related to drug development and delivery[12].

Low Solubility: One of the main problems that arises while developing a particular medicinal formulation is low water solubility. The bioavailability of the drug is disadvantaged by poor solubility[13-14]. As a result, it is the main obstacle for novel chemical entities that scientists and industry have found.

Low bioavailability:refers to the reduced fraction of an administered drug that successfully reaches systemic circulation in an active form. Bioavailability is a key pharmacokinetic parameter that determines the therapeutic efficiency of a drug. While intravenous administration provides 100% bioavailability by directly introducing the drug into the bloodstream, other routes particularly oral administration often result in significantly lower bioavailability. This reduction arises from factors such as incomplete gastrointestinal absorption, degradation within the digestive tract, and extensive first-pass metabolism in the liver. Consequently, when drugs are administered via non-intravenous routes, careful consideration of bioavailability is essential for optimizing dosage, ensuring therapeutic efficacy, and minimizing variability in clinical response[15].

Low Efficacy: Efficacy is the highest reaction that a medication dose can produce. A medicine must have a high attraction that causes a tight binding with the target in order to be highly operative. This is referred to as the medication molecule's affinity[16] A low drug affinity for the target molecule will limit the greatest response. One of the main issues with medication molecules that cause treatment of serious diseases to take longer is low efficacy.

III. DRUGS DELIVERY SYSTEM

The idea of a drug delivery system was established in order to address these problems and challenges related with drug development. The process of creating a pharmaceutical molecule and the mechanism by which it is delivered to the body when required.

Drug delivery systems are used to safely accomplish the intended therapeutic impact. This technique involves administering medicine to a patient in a way that raises the drug's concentration in some bodily areas compared to others[17].

3.1 Nanotechnology in Drugs Delivery System:

Nanotechnology has emerged as a transformative platform in modern therapeutics, offering innovative strategies to overcome the limitations of conventional drug delivery. By engineering materials at the nanoscale (typically 1–100 nm), nanotechnology enables precise control over drug transport, release, and targeting, thereby enhancing therapeutic efficacy and reducing systemic toxicity. Nanoparticle-based delivery systems including liposomes, polymeric nanoparticles, dendrimers, solid lipid nanoparticles, nanocrystals, and inorganic nanocarriers are designed to interact with biological environments in ways not achievable with traditional formulations. Their small size, large surface-area-to-volume ratio, and modifiable surface chemistry facilitate improved drug solubility, enhanced permeability across physiological barriers, and prolonged circulation through evasion of rapid clearance mechanisms[18,19-20].

3.2 Action Mechanism of Nano Drug Delivery Systems:

Nanoparticles possess unique physicochemical properties that can be strategically engineered to evade the body's innate defense mechanisms and thereby improve drug delivery. Numerous nanoparticle-based formulations have been incorporated into modern drug development to enhance the efficacy, safety, and tolerability of therapeutic agents. These systems frequently exhibit superior pharmacokinetic and pharmacodynamic profiles, improved solubility of poorly water-soluble drugs, and the ability to provide controlled or sustained release. Critical design parameters including particle size, surface charge, morphology, and surface functionalization play essential roles in determining circulation time, biodistribution, cellular uptake, and overall therapeutic performance. Consequently, careful optimization of these characteristics is fundamental to developing effective nanoparticle-based drug delivery platforms[21].

IV. TOXICITY OF NANOMATERIALS USED AS DRUG DELIVERY SYSTEMS

Although nanomaterials offer significant advantages in drug delivery, their reduced size and enhanced reactivity may also introduce toxicity concerns that must be carefully evaluated during development. The biological interactions of nanoparticles differ substantially from those of bulk materials due to their high surface-area-to-volume ratio, ability to cross biological barriers, and potential for prolonged retention in tissues[22].

The toxicity of nanomaterials is influenced by several key factors, including particle size, shape, surface charge, chemical composition, solubility, and the presence of surface coatings or functional groups. Smaller nanoparticles may penetrate deeply into tissues and cellular compartments, sometimes leading to oxidative stress, mitochondrial dysfunction, inflammation, or DNA damage. Surface charge plays a crucial role as well; highly cationic particles, for example, may disrupt cellular membranes or induce cytotoxicity through strong electrostatic interactions[23] Nanoparticles may also accumulate in organs such as the liver, spleen, lungs, and kidneys, where slow clearance can potentially result in long-term toxicity. Additionally, the degradation products of certain nanomaterials particularly metals or non-biodegradable polymers may elicit immunological responses or interfere with normal cellular pathways[24]. Despite these concerns, many nanomaterials used in drug delivery (e.g., lipids, biodegradable polymers, gold, silica) can be engineered to minimize toxicity through surface modification, controlled degradation, and biocompatible coatings. Comprehensive in-vitro and in-vivo studies, along with advanced toxicological assessments, are essential to ensure the safety of these systems before clinical application[25].

4.1 Interaction of nanoparticles with cells:

Nanoparticles can arrive the human body by ingestion, inhalation, or cutaneal invasion. Once inside the live body, it interacts with several biomolecules, including lipids, proteins, and carbohydrates. They melt in bodily fluids such as blood, lymph, or the interstitial fluid that exists between cells. The instantaneous coating of nanoparticles results in the formation of a novel structure known as the "protein corona" which controls the nanoparticles' biological destiny. Its dynamic composition is determined by the different components' relative concentrations as well as their affinities for the surface of the nanoparticle. Indeed, it is essential to consider nanoparticles as dynamic systems that adjust to different concentrations of the biomolecules in the fluid[26].

4.2 Interaction of nanoparticles with living cells and Key role of the protein corona:

When nanoparticles enter a biological environment, they rapidly interact with a wide range of biomolecules most notably proteins that adsorb onto their surface and form a coating known as the protein corona. This adsorption process effectively confers a new "biological identity" to the nanoparticle, altering its physicochemical properties, cellular interactions, biodistribution, and overall biological fate. The formation of the protein corona adds significant complexity to nanoparticle behavior, as it influences recognition by the immune system, cellular uptake pathways, and pharmacokinetics[27].

Protein corona formation is a highly dynamic and competitive process. Initially, abundant plasma proteins with low affinity bind rapidly to the nanoparticle surface; over time, these are replaced by less abundant but higher-affinity proteins a phenomenon often described by the Vroman effect. The continuously changing composition of the corona reflects the dynamic equilibrium between the nanoparticle surface and surrounding biomolecules[28].

4.3 Mechanism of Toxicity caused by Nanoparticles:

Nanoparticles can induce the formation of reactive oxygen species (ROS), such as superoxide anions and hydroxyl radicals, through direct physicochemical interactions or indirectly via activation of cellular oxidative pathways. This ROS overproduction can overwhelm antioxidant defense mechanisms, leading to oxidative stress, a major contributor to nanoparticle-induced cytotoxicity. Several mechanisms are implicated in ROS generation by nanomaterials. Some nanoparticles inherently possess surface reactivity that enables them to generate oxidants or stimulate ROS production as part of the cellular stress response.Transition metal-based nanoparticles, or trace metal impurities introduced during the synthesis of non-metal nanoparticles, can catalyze redox reactions that promote ROS formation[29].

V. DISCUSSION

Drug delivery is a fundamental aspect of pharmacology, as it determines how effectively a therapeutic agent can be introduced into the body and reach its intended site of action. Modern drug delivery technologies aim to administer medications in a controlled, targeted, and efficient manner to maximize therapeutic outcomes while minimizing systemic side effects. Localized delivery strategies, in particular, offer significant advantages by concentrating the drug at the desired site and reducing exposure to the rest of the body. Despite these advances, conventional drug delivery systems continue to face challenges related to toxicity, limited bioavailability, inadequate control over release kinetics, and poor biocompatibility. Nanomaterials have emerged as promising tools to overcome many of these limitations due to their unique biological and physicochemical properties. Their small size, large surface area, tunable surface chemistry, and ability to encapsulate or conjugate a wide range of therapeutic agents enable precise, controlled, and targeted drug delivery. Many nanocarriers demonstrate excellent biocompatibility, biodegradability, and stealth behavior, along with the capacity for sustained or stimuli-responsive release.

Overall, this review has highlighted both the opportunities and challenges presented by nanomaterials in drug delivery. Understanding the mechanisms through which these materials interact with biological systems is crucial for the rational design of next-generation therapeutics. As research progresses, careful optimization and thorough toxicological assessment will be key to ensuring that nanoparticle-based drug delivery systems achieve their full potential in clinical practice.

VI. CONCLUSION

One of the most critical areas in which biochemistry intersects with medicine is the design, development, and delivery of therapeutic agents. This paper has explored the advantages, limitations, and emerging role of nanotechnology in addressing the shortcomings of conventional drug delivery systems. Nanomaterials are often favored as advanced drug carriers because they enable targeted and sustained release, exhibit favorable biodegradability, and demonstrate high biocompatibility. Despite these advantages, nanomaterials are not inherently benign; their ability to interact intimately with biological systems means they may also exert unintended effects on healthy cells. Consequently, rigorous toxicity assessment is essential to ensure the safe application of nanoparticles in biomedical fields, particularly in drug delivery, gene therapy, and other therapeutic strategies.

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