Review Article

Nanotechnology Based Drug Delivery System: A Comprehensive Review of Design, Mechanism and Future Prospects

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ABSTRACT

Drug delivery methods based on nanotechnology have become a cutting-edge tactic to increase therapeutic efficacy and safety. To improve medication solubility, stability, and controlled release, these systems make use of nanoscale carriers such as liposomes, dendrimers, polymeric nanoparticles, and metallic nanoparticles. They also minimize systemic toxicity by enabling site-specific administration and shielding active medicinal components from deterioration. According to recent research, nanoparticles can improve medication bioavailability and enhance precision medicine techniques by overcoming a variety of biological obstacles, such as cellular and physiological barriers. Both active targeting with ligand-functionalized nanoparticles and passive techniques like the increased permeability and retention (EPR) effect are used to deliver targeted drugs. Clinical translation is still difficult despite tremendous progress because of biological response variability, large-scale production challenges, regulatory concerns, and long-term safety concerns. Nonetheless, the pharmaceutical industry has already effectively used nanotechnology, especially in cancer treatment, where it enhances the safety profile of extremely hazardous medications like chemotherapy medicines.

Keywords: Nanotechnology, Drug delivery, nanoparticles, bioavailability.

BACKGROUND

Plant-based natural products have been utilized extensively in traditional medicine since antiquity and have provided a basis for contemporary pharmacological research. However, there are a number of drawbacks to traditional drug delivery methods, including as low bioavailability, quick clearance, poor solubility, and a lack of site-specific targeting.

By using nanoscale carriers to encapsulate medications and improve their stability and therapeutic efficacy, nanotechnology offers creative alternatives. By enabling tailored administration to particular tissues or cells, these methods increase efficacy and decrease side effects.[1]

The increased permeability and retention (EPR) effect, which makes it easier for nanoparticles to accumulate in tumor tissues because of leaky vasculature and inadequate lymphatic drainage, is a crucial mechanism in nanoparticle-based drug delivery.[3] The EPR effect's practical application is limited, though, as new research suggests that it is highly variable and may not be consistently beneficial in human cancers.[2,4]

As an interdisciplinary link between the biological and physical sciences, nanotechnology advances drug delivery, tissue engineering, biosensors, and microfluidics. Nanomaterials, which are usually between 1 and 100 nm in size, have special physicochemical characteristics that enhance the effectiveness of medication delivery. By overcoming the main drawbacks of traditional drug therapy, such as low stability, restricted membrane permeability, short circulation time, and systemic toxicity, nanomaterial-based drug delivery systems (NBDDS) improve therapeutic outcomes. Additionally, current advancements concentrate on intelligent and stimuli-responsive nanocarriers that can release drugs in a controlled and site-specific manner.[5]

Despite these developments, issues like immune system interactions, scalability, regulatory licensing, and nanoparticle toxicity continue to be significant obstacles to effective clinical translation.[4,5]

INTRODUCTION

Physicist Feynman first presented the idea of nanotechnology in a 1959 lecture titled "There's Plenty of room at the Bottom." Nanotechnology is essentially the core of all scientific fields, including physics, chemistry, biology, engineering, information technology, electronics, and material science. It is the study of incredibly small things. A article about mid-19th-century nanotechnology research was published by Petros and his colleague. They claimed that polymers and pharmaceuticals were conjugated in 1955.[6]

Nanoparticles are defined by the National Nanotechnology Initiative (NNI) as structures that have at least one dimension and range in size from 1 to 100 nm. However, particles as small as a few hundred nanometers are often indicated by the prefix "nano."

Nanocarriers with optimized physicochemical and biological properties can be used as delivery vehicles for currently known bioactive substances since they are more readily absorbed by cells than larger molecules. Liposomes, solid lipid nanoparticles, dendrimers, polymers, silicon or carbon materials, and magnetic nanoparticles are among the

nanocarriers that have been investigated as drug delivery techniques.[7] NPs are commonly used to improve the pharmacological properties of drugs, including plasma distribution, target site accumulation, half-life, and penetration. The physical characteristics of NPs, such as size, shape, charge, and elasticity, contribute to the required pharmacokinetic characteristics for use in drug delivery systems. One of the mechanical properties of NPs is elasticity, which enables improved delivery of cancer medications by bridging biological barriers between the application site and the solid tumor location.

CLASSIFICATION OF NANOPARTICLES

NPs can be categorized into numerous groups according on their size, texture, and features. They are frequently separated into the three basic groups

1. **Organic-Based NPs:** These are the most prevalent kind of NPs and are extensively utilized in the biomedical sector and a variety of cancer treatments. A range of lipids, proteins, carbohydrates, and other organic molecules, including micelles, dendrimers, hollow-core liposomes, and protein complexes like ferritin, make up its actual composition. Although these NPs are biodegradable and non-carcinogenic, they are thermally sensitive to light and electromagnetic radiation. They are also typically made up of non-covalent intramolecular interactions, which make them easily removed from the body and thermally labile. A few essential features, including as size, shape, morphology, stability, and the ability to transport proteins and lipids, define the different types of organic-based NPs.
2. **Inorganic-Based NPs:** These NPs are composed of neither carbon nor any other organic particle. Metallic, ceramic, and semiconductor NPs are the three main subgroups of inorganic NPs.

A) Metal-Based NPs: These are made from metals using chemical and electromechanical processes. Because of their unique thermal and magnetic fields, some metal nanoparticles (NPs) are valuable in a number of fields, such as bioanalytical and environmental investigations, biomolecule detection, and imaging. For instance, gold NPs are administered prior to the material being examined in magnetic NPs such as Fe3O4, gold, and silver NPs for use in these imaging modalities. In order to produce high-quality photos, this is typically done to improve the electrical stream**.** Gold, silver, and magnesium nanoparticles (iron oxide) have been employed and modified many times over the years to make them useful as medicinal and diagnostic agents.

B) Ceramic-Based NPs: These can be amorphous, polycrystalline, dense, porous, or hollow and are typically made by heating and then cooling. They include metal or metalloids like calcium and titanium, as well as oxides, carbonates, carbides, and phosphates. They are incredibly resistant to heat and chemicals. By modifying a number of characteristics, including size, surface area, porosity, and surface-to-volume ratio, ceramic nanoparticles show promise as a drug delivery vehicle. These NPs have been effectively used in medication delivery systems for a number of diseases, such as bacterial infections, cancer, and glaucoma.

C) Semiconductor-Based NPs: These NPs have properties in common with a range of metals and non-metals. They are composed of semiconductor materials such as cadmium telluride or selenide. They are used in water splitting, photocatalysis, electronics, photo-optics, and imaging [44]. However, their possible toxicity and environmental impact are also important considerations when using and developing them.

3. Carbon-Based NPs: These NPs are utilized in place of steel to support constructions.

Carbon quantum dots, fullerenes, and carbon nanotubes (CNTs) are the three primary components of carbon-based nanoparticles. A graphene sheet that has been wrapped into a tube makes up the CNT. Since these materials are 100 times stronger than steel, they are mostly employed for structural reinforcement. CNTs are unique in that they are thermally conductive along their entire length but non-conductive throughout the tube. Carbon allotropes having hollow cage structures made up of at least 60 carbon atoms are known as fullerenes. The structure of C60 is called Buckminsterfullerene, and it looks like a hollow football. However, other fullerenes, such as C70 and C540 fullerenes, have also been made available. They have practical applications due to their structure, high strength, electron affinity, and electrical conductivity. Carbon quantum dots are discrete, quasi-spherical carbon nanoparticles (NPs) smaller than 10 nm. Carbon-based NPs combine the unique properties of sp2-hybridized carbon bonds with exceptional physicochemical features at the nanoscale due to their unique electrical conductivity, strength, electron affinity, optical, thermal, and sorption capabilities.

NANOPARTICLE PROPERTIES

DIMENSIONS: NPs are usually between 1 and 100 nm in size. but this cap isn't precisely defined by a line. because the psychochemical and biological properties of the constituents do not abruptly change at 100 nm, the greatest size at which a material can be categorized as a nanomaterial is arbitrary.[49]

Nps should travel till they arrive to the desired anatomical site. However, because the reticulum endothelial system (res) recognizes nps, the immune system can assist in their removal. Alternatively, NPs can be mechanically filtered out by the spleen, liver, kidneys, or lungs.

one of the most crucial elements in particle removal is size.

Form

Recent studies suggest that NP circulation, distribution within the body, cellular uptake, and general in vivo behavior may be significantly impacted by particle form (sphere, ring, and disc).

In filtering organs or arterial bifurcations, particles with irregular shapes are far more likely to align or change. A spherical particle's diameter must be less than 200 nm in order for it to pass through the spleen. It can, however, pass through this organ if it has a disk-like shape with a diameter of around 7 m and a height of 150 nm**.**

Surface Area

When compared to bulk or micromaterials, nanomaterials exhibit different surface effects. This is primarily caused by three factors: (a) scattered nanomaterials have a large surface area and a high particle number per mass unit; (b) the fraction of atoms at the surface is increased; and (c) the atoms at the surface of nanomaterials have fewer immediate neighbors. Nanomaterials differ from their larger-dimension counterparts in both chemical and physical properties due to each of these distinctions. The reactivity of nanomaterials is often enhanced by larger surface areas and surface-to-volume ratios because of the increased reaction surface, which also has a major impact on the materials' structure. The surface effects are significantly influenced by the dispersity of nanomaterials. Due to very attractive interactions between particles, nanomaterials may aggregate and agglomerate, which adversely affects their surface area and nanoscale characteristics. By raising the zeta potential of nanomaterials, altering the pH and ionic strength of the suspension medium, or maximizing the degree of hydrophilicity/hydrophobicity of the nanomaterial, agglomeration can be minimized.[8]

TYPES OF NANOTECHNOLOGY BASED DRUG DELIVERY SYSTEMS

Liposome

The idea that liposomes can entrap pharmaceuticals and be employed as medication delivery vehicles was established by early pioneers like Gregoriadis and Perrie.

Furthermore, liposomes can contain several lipid bilayers; multilamellar vesicles, or MLVs, are composed of numerous concentric (or onion-like) bilayers and have spherical dimensions of 500–5000 nm. The lipid platform for DepoDur and Exparel, multilamellar liposomes and multivesicular liposomes (MVLs), are fundamentally different. These aggregates have a diameter of 5000–50,000 nm and are made up of hundreds of polyhedral compartments filled with water that are separated by lipid bilayer septa.16,17 Another name for these enormous MVLs is DepoFoam.[9]

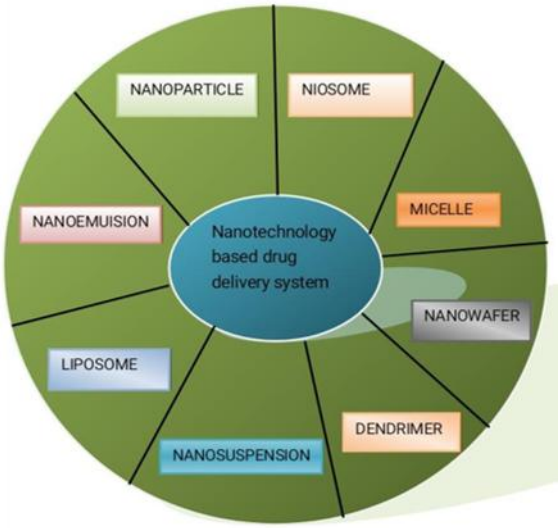
Liposomes are formed by phospholipids, which are amphiphilic molecules having a hydrophilic head and a hydrophobic tail. The hydrophilic part consists of phosphoric acid connected to a water-soluble molecule, whereas the hydrophobic part consists of two fatty acid chains with 10–24 carbon atoms and 0–6 double bonds apiece. They form spherical, vesicle-like structures called liposomes when dispersed in an aqueous solution, with the polar head group facing outward and the fatty acid groups facing one another.[3] Lamellar sheets are created as a result. While the polar part remains in contact with the aqueous environment, the non-polar portion is protected.

Liposome classification

The size and bilayer count of liposomes can be used to classify them. They can be divided into three groups: multilamellar vesicles (MLV), small unilamellar vesicles (SUV), and large unilamellar vesicles (LUV). Based on their composition, they are classified as immuno-liposomes, long circulating liposomes (LCL), cationic liposomes, pH-sensitive liposomes, and conventional liposomes (CL). Depending on the method of synthesis, they are classified as reverse phase evaporation vesicles (REV), French press vesicles (FPV), and ether injection vesicles (EIV).

Liposome Mechanism

Liposome is a region of aqueous solution surrounded by a hydrophobic membrane. Because hydrophobic materials dissolve easily in lipid membranes, liposomes can carry both hydrophilic and hydrophobic compounds. However, the drug's location will depend on its lipid composition and physiochemical characteristics. Essential medicinal compounds are delivered to the site of action more easily when the lipid bilayers fuse with other bilayers of the cell (cell membrane) to release the liposomal content.



Steps in the liposome-based drug delivery process:

1. **Adsorption**: This process allows liposomes to come into contact with cell membranes.

2. **Endocytosis**: Adsorption of liposomes on the cell membrane, internalization, and engulfment within the liposomes.

3. Fusion: When lipid bilayers of liposomes fuse with the lipoidal cell membrane by lateral diffusion and lipid intermingling, direct transport of liposomal contents into the cytoplasm takes place.

4. Lipid exchange: Because the phospholipids in the cell membrane and the liposomal lipid membrane are similar, lipid transfer proteins in the cell membrane may easily recognize liposomes and start lipid exchange.

For example, since cancer cells consume a lot of fat to meet their demand for rapid development, they view liposomes, which are loaded with anti-cancer medications, as a potential source of nutrition. When a liposome targets them, they are absorbed. Once liberated from the liposome, the anti-cancer drugs destroy cancer cells.[10]

Chitosan

Chitosan (CS) is one of the most beneficial natural biopolymers used in the pharmaceutical sector due to its biocompatibility and biodegradability. The pharmaceutical business has been using chitosan, a polysaccharide, as NPs since 20 years ago. CS is a biodegradable, biocompatible, and non-toxic biopolymer made up of β-1→4 linked 2-amino-2-deoxy-glucopyranose and 2-acetamido-2-deoxy-β-Dglucopyranose residues. Chitin, a biopolymer derived from the exoskeleton of crustaceans like crabs and prawns, is produced by alkaline N-deacetylation and utilized to manufacture CS.Only in an acidic media with a pH higher than 6.5 can CS show antibacterial activity.[11]

Chitosan and cellulose are closely related to mucopolysaccharides. Chitosan is created by deacetylating chitin, the main constituent of crab exoskeletons. Chitin from crab and shrimp shells is deacetylated by boiling it in sodium hydroxide after decolorization with potassium permanganate. This process was first described by Rouget in 1859 and 1894, and it was formally named by Hoppe-Seyler.

Nanoparticles of chitosan

According to reports, chitosan is a great material for making microparticles and nanoparticles for controlled drug release. Chitosan, and particularly chitosan nanoparticles, provide several advantages because of their enhanced stability, low toxicity, simple and gentle manufacturing methods, range of administration routes, and growing interest as a drug delivery vehicle. They have the power to control the release of active agents. They avoid utilizing hazardous organic solvents for making the particles because they are soluble in aqueous acidic solution. They avoid utilizing hazardous organic solvents for making the particles because they are soluble in aqueous acidic solution.

Moreover, chitosan is a linear polyamine with several free amine groups that are readily accessible for cross-linking, even if its cationic nature allows ionic cross-linking with multivalent anions.[12]

Alginate

Alginate, a naturally occurring polysaccharide derived from brown seaweed, has grown in importance in nanotechnology-based drug delivery systems due to its remarkable biocompatibility, biodegradability, non-toxicity, and ability to gel in the presence of divalent cations like calcium.[13,15] These qualities allow alginate to be utilized to make a range of nano-carriers that enhance medication stability, regulate release, and improve therapeutic efficacy.[13,14]

Among the most studied systems are alginate nanoparticles, which are often produced by ionic gelation or polyelectrolyte complexation processes.[20] These nanoparticles can contain a variety of medicinal substances, including proteins, nucleic acids, and tiny molecules, to improve their bioavailability and stop decomposition.[17] These are closely related to hydrogels or alginate nanogels, which are three-dimensional crosslinked polymeric networks having a high capacity to absorb water.[13] These systems are particularly useful for controlled and stimuli-responsive drug release, such as pH-sensitive or temperature-sensitive delivery, making them perfect for targeted applications including cancer therapy and wound healing.[19]

In addition to nanoscale systems, alginate is also used to make microspheres and microcapsules, which, despite their larger size, often employ nanotechnology principles to provide sustained and site-specific drug administration.[19] These methods are especially helpful for protecting drugs from serious gastrointestinal disorders and enabling controlled release over extended periods of time.[14] Alginate-based nanocomposites, which combine alginate with other polymers such chitosan or polyethylene glycol to enhance mechanical strength, stability, and mucoadhesive properties, are another important category.[14] These combinations often lead to better drug loading efficiency and more precise control over drug release kinetics. Furthermore, alginate-coated liposomes produce hybrid delivery systems that combine the advantages of liposomal drug encapsulation with the stability provided by alginate coating.[14]

Xanthan Gum

Because of its superior biocompatibility, biodegradability, non-toxicity, and high viscosity, xanthan gum—a high molecular weight extracellular polysaccharide made by the bacterium Xanthomonas campestris—has become a significant biopolymer in drug delivery systems based on nanotechnology.[21,25] It is ideal for creating targeted and regulated drug delivery systems due to its special rheological characteristics and capacity to create stable matrices.[22,23] Xanthan gum nanoparticles are one of the many nanotechnology-based systems that are extensively studied. They are usually made via ionic gelation, nanoprecipitation, or emulsification.[27] These nanoparticles can efficiently encapsulate drugs, proteins, and bioactive compounds, protecting them from degradation and boosting their bioavailability.[27] Furthermore, xanthan gum is used to make hydrogel systems and nanogels, which are three-dimensional crosslinked networks with a high water capacity and long-term, stimuli-responsive drug release, particularly in response to pH and ionic strength variations.[24,26] These qualities make them perfect for uses such as colon-targeted delivery and controlled release formulations.[24]

Furthermore, xanthan gum-based nanoemulsions are utilized to deliver poorly soluble drugs because they improve drug solubility, stability, and absorption.[27] Xanthan

gum is also essential in the development of nanocomposite systems, where it is combined with other polymers such as chitosan, alginate, or synthetic polymers to enhance mechanical strength, mucoadhesion, and drug release control.[27,25] Longer drug release profiles and improved encapsulation efficiency are common characteristics of these nanocomposites.[27] Furthermore, xanthan gum-coated liposomes and nanoparticles are developed to improve the robustness and targeting ability of conventional nanocarriers, reducing drug leakage and increasing therapeutic efficacy.

All things considered, xanthan gum-based nanotechnology drug delivery systems offer several advantages, including targeted dispersion, enhanced bioavailability, controlled and extended drug release, and enhanced stability of therapeutic agents.[25,27] These qualities make xanthan gum a versatile and promising polymer for the development of innovative drug delivery methods in current pharmaceutical research.

Cellulose

The most common natural polysaccharide produced from plant sources, cellulose, has garnered significant attention in nanotechnology-based drug delivery systems due to its high biocompatibility, biodegradability, non-toxicity, and ease of chemical modification.[28,29] Several cellulose derivatives, such as cellulose acetate, hydroxypropyl methylcellulose, and carboxymethyl cellulose, enhance cellulose's utility and compatibility in medicinal formulations.

Because of their large surface area, mechanical strength, and capacity to form stable colloidal systems, cellulose nanoparticles—in particular, cellulose nanocrystals and nanofibers—are extensively researched for drug delivery applications among the various nanotechnology-based systems.[31]

Additionally, cellulose is often combined with other polymers or inorganic materials to improve the stability, release kinetics, and drug loading capacity of nanoemulsions and nanocomposites.[32,34] The enhanced mechanical and mucoadhesion properties of cellulose-based nanocomposites can be advantageous for oral and transdermal drug administration techniques.[34]

All things considered, targeted dispersion, improved drug stability, enhanced bioavailability, and controlled and delayed drug release are just a few advantages of cellulose-based nanotechnology drug delivery systems.[28,32] These qualities make cellulose and its derivatives highly desirable materials for the development of innovative drug delivery methods in current pharmaceutical research.

Polymeric micelle

Polymeric micelle: Amphiphilic block copolymers self-assemble to create polymeric micelles, which are nanoscale colloidal structures in water. They have a hydrophobic core that can contain drugs that are poorly soluble in water and a hydrophilic shell that keeps them stable in biological fluids. This structure facilitates focused and controlled drug administration while also improving drug solubility and bioavailability. High stability and carrier capacity; ability to carry both hydrophilic and hydrophobic medications; non-toxic and biodegradable; ability to modify the surface to target specific tissues; and improved pharmacokinetics by reducing immune clearance and extending drug circulation time. Preparation methods include dispersion polymerization, interfacial polymerization, and emulsion polymerization. The hydrophilic shell stabilizes the hydrophobic core and renders the entire system soluble in water, while hydrophobic drugs like paclitaxel, docetaxel, and camptothecin can be inserted into the hydrophobic core. The EPR effect enables polymeric micelles to concentrate in tumor tissues since they are smaller than 100 nm and frequently have a limited distribution to avoid rapid renal clearance.

Dendrimer

Dendrimers are a kind of nanoscale polymeric structures that are symmetrical and have many branches. They have a core, an internal branching unit, and multiple functional surface groups. Because of this unique architecture, surface chemistry, size, and form may be greatly controlled.

Dendrimers are helpful in drug delivery because they have the ability to encapsulate or adhere medications to their surface or interior. By facilitating focused and controlled drug administration, they increase therapy efficacy and reduce side effects. They are biodegradable and can be made for specific medicinal applications, including as gene transfer and cancer treatment. Dendrimers with a degree of molecular homogeneity, a limited molecular weight distribution, unique size and shape characteristics, and a highly functionalized terminal surface.

Inorganic nanoparticles

Inorganic nanoparticles are solid colloidal particles that have at least one dimension in the nanoscale range (1 to 1000 nm).These particles often contain gold, silver, silica, iron oxide, quantum dots, and other metals or metal oxides. They are fairly stable and have a big carrying capacity. Inorganic nanoparticles can carry both hydrophilic and hydrophobic substances. They offer targeted and controlled drug delivery through a variety of administration methods. These nanoparticles can be surface-functionalized to achieve specific goals. Inorganic nanoparticles include silica, silver, gold, and iron oxide. There aren't as many studies on them as there are on the other kinds of nanoparticles in this field, despite the fact that they have some potential applications. Nanocrystals are solid colloidal particles that have at least one dimension in the nanoscale range (1 to 1000 nm). They are often composed of pure, crystalline drug particles that have been shrunk to the nanoscale. Nanocrystals can improve drug solubility and bioavailability by increasing the surface area available for solvation. These particles offer increased stability and carrier capacity for medication delivery. Nanocrystals can contain both hydrophilic and hydrophobic elements. They can be

administered in a number of ways and offer targeted, controlled drug delivery. Among the methods used to create nanoparticles, including nanocrystals, are polymerization, solvent evaporation, desolvation, and supercritical fluid technologies.

Nanoparticles made of metal

Metallic nanoparticles are solid colloidal particles with at least one dimension in the nanoscale range (1 to 1000 nm) that are usually made of metals like gold, silver, and iron oxide. They can transport both hydrophilic and hydrophobic materials because of their great stability and carrier capacity. Drug distribution can be targeted and regulated by surface-functionalizing metallic nanoparticles. They are used in treatments, imaging, medication delivery, and diagnostics. Techniques like transmission electron microscopy (TEM) and scanning electron microscopy (SEM) are used to examine their size and morphology.

Quantum dots

Quantum dots are tiny semiconductor particles with unique optical and electrical properties due to the effects of quantum mechanics. Typically, they are between one and ten nanometers in size. Because of their high surface-to-volume ratio and size-dependent emission spectra, quantum dots' fluorescence can be tuned by size. These features are helpful for biomedical imaging, medication delivery, and diagnostics. Quantum dots' surface functionalization can improve their targeting and biocompatibility. They are used as fluorescent probes in cellular imaging, targeted therapy, and biosensors.

Protein and polysaccharide nanoparticles

protein nanoparticles made of organic proteins including gelatin, albumin, and soy protein. They are biocompatible and biodegradable, and they can stop the degradation of drugs that have been encapsulated. Protein nanoparticles are used to deliver medications, peptides, and vaccines. often produced by methods such as desolvation, emulsification, or coacervation. Their surface can be engineered for targeted drug delivery and controlled release.

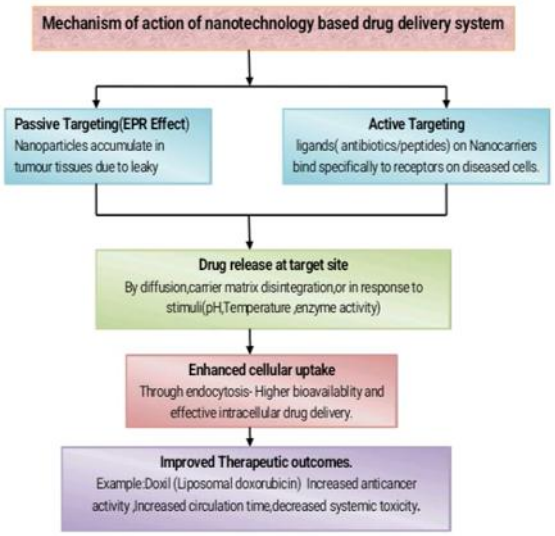
Polysaccharide nanoparticles made from naturally occurring polymers such as cellulose, alginate, chitosan, and dextran are well known for their mucoadhesive, biocompatible, and biodegradable properties. They are widely employed in drug delivery because they can increase the permeability and stability of medications. Produced using techniques such ionic gelation, emulsification, and self-assembly.

The mechanism of action of drug delivery systems based on nanotechnology

nanotechnology-based drug delivery systems improve therapeutic outcomes by improving medicine targeting, stability, and controlled release at the site of action. these systems use nanosized carriers (1–100 nm) such liposomes, polymeric nanoparticles, dendrimers, and micelles to encapsulate or conjugate medications. the primary modes of action are enhanced cellular absorption, controlled drug release, and passive and active targeting. while passive targeting occurs through the enhanced permeability and retention (epr) effect, where nanoparticles accumulate in tumor tissues due to leaky vasculature, active targeting is achieved by attaching ligands (such as antibodies or peptides) to nanocarriers that bind specifically to receptors on diseased cells[35,36].

Once a drug has been localized, it can be released via diffusion, carrier matrix disintegration, or in response to pH, temperature, or enzyme activity.[36,37] Furthermore, nanocarriers provide increased bioavailability and efficient intracellular drug delivery by promoting improved cellular uptake via endocytosis.[37] For example, liposomal formulations such as Doxil® (liposomal doxorubicin) enhance anticancer activity by prolonging circulation length and reducing systemic toxicity, particularly cardiotoxicity associated with conventional doxorubicin therapy.

NANOTECHNOLOGY APPLICATION



1.Targeted Administration of Drugs

Targeted drug delivery, which reduces effects on healthy tissues by precisely delivering the medication to the location of illness, makes extensive use of nanotechnology-based drug delivery devices. Liposomes, polymeric nanoparticles, and dendrimers are examples of nanocarriers that can be functionalized with ligands to identify certain receptors on target cells. This strategy lowers systemic toxicity while improving therapeutic efficacy. For instance, the increased permeability and retention (EPR) effect may cause liposomal formulations such as Doxil to build up in tumor tissues during cancer treatment.[39,40]

2. Sustained and Regulated Drug Release

Another important use that helps maintain drug concentration within the therapeutic range for a longer period of time is controlled and sustained pharmaceutical release. Polymeric nanoparticles, especially those made from biodegradable polymers like PLGA, are widely used for this purpose. These technologies reduce the frequency of

dosages and improve patient compliance by providing a longer pharmacological impact.[41]

3. Cancer Treatment

Nanotechnology-based devices are frequently employed in cancer treatment because they can specifically target tumor cells and reduce the side effects of conventional chemotherapy.

4. Improvement of Bioavailability and Solubility

When it comes to increasing the solubility and bioavailability of medications that are poorly soluble in water, nanotechnology is essential. Increased surface area from nanosizing results in improved absorption and dissolution rates. To get around solubility restrictions, lipid-based nanoparticles, nanocrystals, and nanoemulsions are frequently used.[42]

5. Delivery of Genes and Vaccines

Gene delivery and vaccination applications employ nanocarriers such dendrimers and lipid nanoparticles. They make it easier for genetic material to enter target cells and shield them from deterioration. In recent years, this application has drawn a lot of interest for the creation of cutting-edge treatments and vaccines.[43]

6. Drug Administration Through Biological Barriers

Nanoparticles can be utilized to treat diseases of the central nervous system because they can cross complex biological barriers like the blood–brain barrier. This application has made it possible to administer drugs that were previously unable to effectively reach brain tissues.[44]

LIMITATIONS OF NANOTECHNOLOGY DRUG DELIVERY SYSTEMS

1. Issues with Biocompatibility and Toxicity

Despite their advantages, nanocarriers may be hazardous due to their small size, large surface area, and ability to interact with biological systems at the molecular level. By inducing oxidative stress, inflammation, or immunological responses, some nanoparticles may be cytotoxic. The absence of long-term safety evidence raises questions about their clinical use.[45]

2. Storage and Stability Problems

For nanoparticle formulations, aggregation, sedimentation, or drug leakage during storage are typical stability issues. These factors may affect the shelf life and efficacy of the formulation, making it challenging to maintain consistent product quality over time.[46]

3. High Production Costs and Scale-Up Challenges

Nanotechnology-based drug delivery systems require sophisticated equipment, specialized techniques, and strict process control. The challenge and expense of scaling these systems from the laboratory to the industrial level limits their widespread commercial application.[47]

4. Limited Drug Loading Capacity

Certain nanocarriers can only partially encapsulate drugs, especially hydrophilic molecules. Their therapeutic usage may be limited since greater doses may be required to achieve the desired effect.[49]

5. Problems with Biodistribution and Quick Clearance

Nanoparticles can be swiftly detected and removed by the reticuloendothelial system (RES), particularly the liver and spleen. As a result, their ability to effectively reach target tissues is limited and their bloodstream circulation time is shortened.[50]

6. Regulatory and Safety Concerns

The lack of precise regulatory standards complicates the approval procedure for nanomedicines. Quality control, reproducibility, and long-term safety evaluation issues need to be fixed before widespread clinical use.

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