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Nanotechnology-Based Drug Delivery Systems: A Comprehensive Review

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ABSTRACT :

Because they can improve the solubility, stability, bioavailability, and targeted delivery of pharmaceutical agents, nanotechnology-based drug delivery systems (NDDS) have become a revolutionary platform in contemporary therapeutics. By enabling controlled and site-specific drug release, nanocarriers—such as liposomes, polymeric nanoparticles, dendrimers, solid lipid nanoparticles, nanoemulsions, and inorganic nanomaterials—improve therapeutic efficacy and lower systemic toxicity. Precise interaction with biomolecules and biological barriers is made possible by the special physicochemical properties of nanostructures, such as their large surface area, tunable size, and modifiable surface chemistry. The transition to personalized nanomedicine is indicated by recent developments in gene-delivery vectors, hybrid nanosystems, stimuli-responsive nanocarriers, and theranostic platforms. Despite these developments, problems still exist, The types, mechanisms, applications, benefits, drawbacks, and prospects for the future of NDDS are highlighted in this review, which is backed by a substantial body of scientific research.

Keywords :- Nanotechnology, Nanomedicine , Drug Delivery system, Nanocarriers, Liposomes, Dendrimers etc.

1. Overview

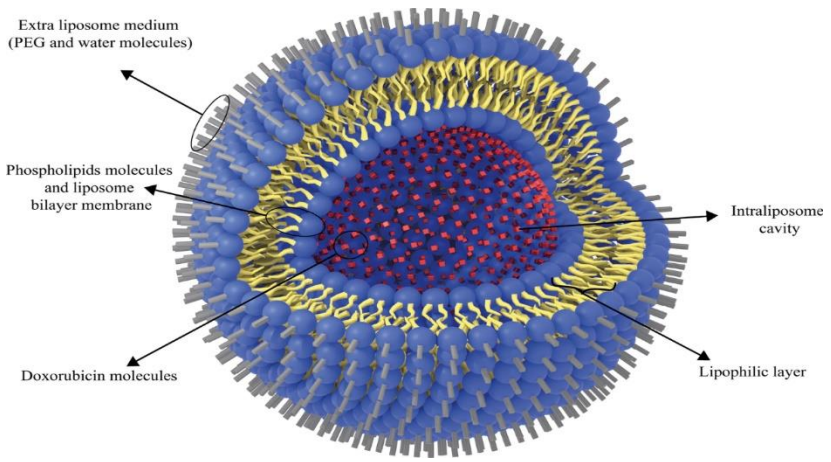
Poor solubility, a short half-life, quick clearance, systemic toxicity, and an inability to pass through physiological barriers like the blood–brain barrier (BBB) are common problems with conventional drug delivery methods [1,2]. By creating drug carriers at the nanoscale, usually between 1 and 1000 nm, nanotechnology provides solutions that improve pharmacokinetics, biodistribution, and targeted delivery [3]. Nanocarriers facilitate controlled and prolonged drug release, improve cellular uptake, and shield therapeutic compounds from degradation [4,5]. Applications of NDDS in oncology, infectious diseases, neurological disorders, chronic inflammatory disorders, gene therapy, and vaccine delivery have been extensively investigated [6]. A new frontier in personalized and precision medicine is represented by their potential for theranostics, which combines diagnostic and therapeutic functions [7].

2. Drug Delivery Systems Based on Nanotechnology

2.1 Liposomes

Both hydrophilic and hydrophobic medications can be encapsulated in liposomes, which are spherical vesicles made of phospholipid bilayers [8]. Numerous clinically approved formulations have resulted from their biocompatibility, biodegradability, and capacity to lessen systemic toxicity [9]. Instability, leakage, and quick clearance by the reticuloendothelial system (RES) are obstacles, though [10].

Fig 1 Liposomes



2.2 Nanoparticles

made of polymers Biodegradable polymers like PLGA, PLA, and chitosan are used to create polymeric nanoparticles, such as nanospheres and nanocapsules [11]. They provide enhanced stability, controlled release, and protection for labile medications [12]. By lowering opsonization, surface modification with PEG (PEGylation) increases circulation time [13].

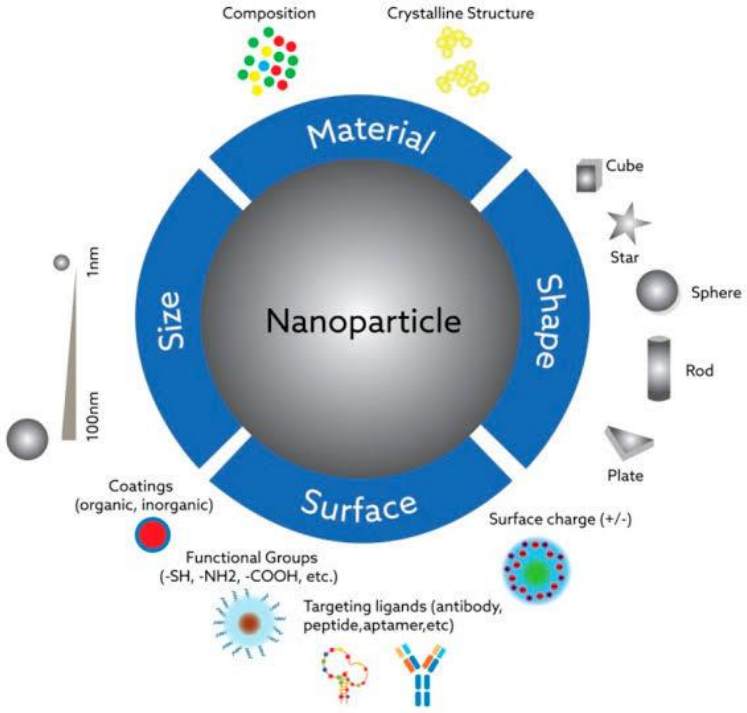


Fig 2 Nanoparticle

2.3 Micelles

made of polymers Amphiphilic block copolymers create polymeric micelles, which are ideal for solubilizing poorly soluble medications [14]. Improved stability, tumor accumulation, and low toxicity are made possible by their hydrophilic shell and hydrophobic core [15]. Dilution-induced instability and early drug release are limitations [16].

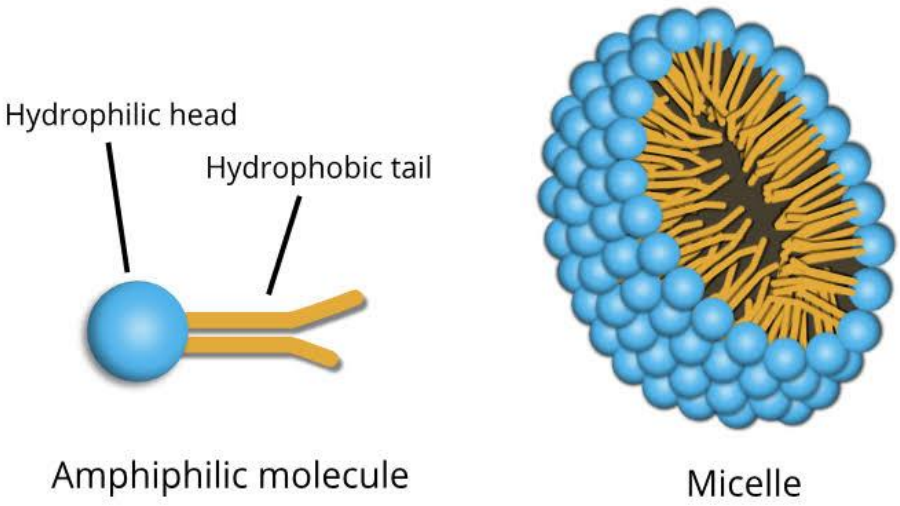


Fig 3 Micelle

2.4 Dendrimers

Drug conjugation or encapsulation is made possible by dendrimers, which are highly branched, monodisperse macromolecules with many functional groups [17]. They exhibit potential in combination therapy, imaging, and gene delivery [18]. Nevertheless, some cationic dendrimers are cytotoxic, and their synthesis is complicated [19].

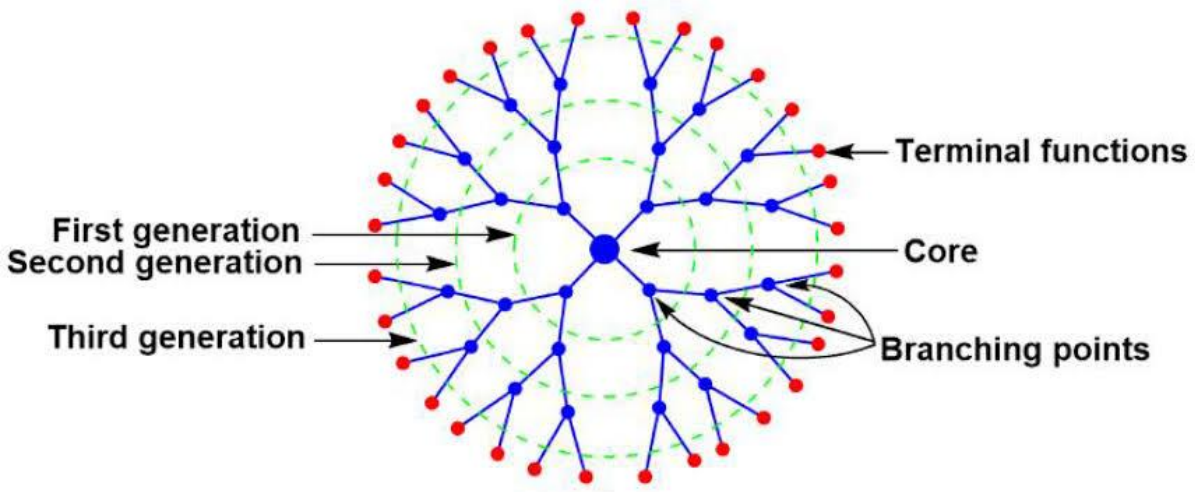


Fig 4 Dendrimers

2.5 SLNs, or solid lipid nanoparticles Compared to liposomes, SLNs provide better physical stability and controlled release by entraping drugs in solid-state lipids [20]. Limited drug loading and possible gelation during storage are their main disadvantages [21].

2.6 Nanoemulsions

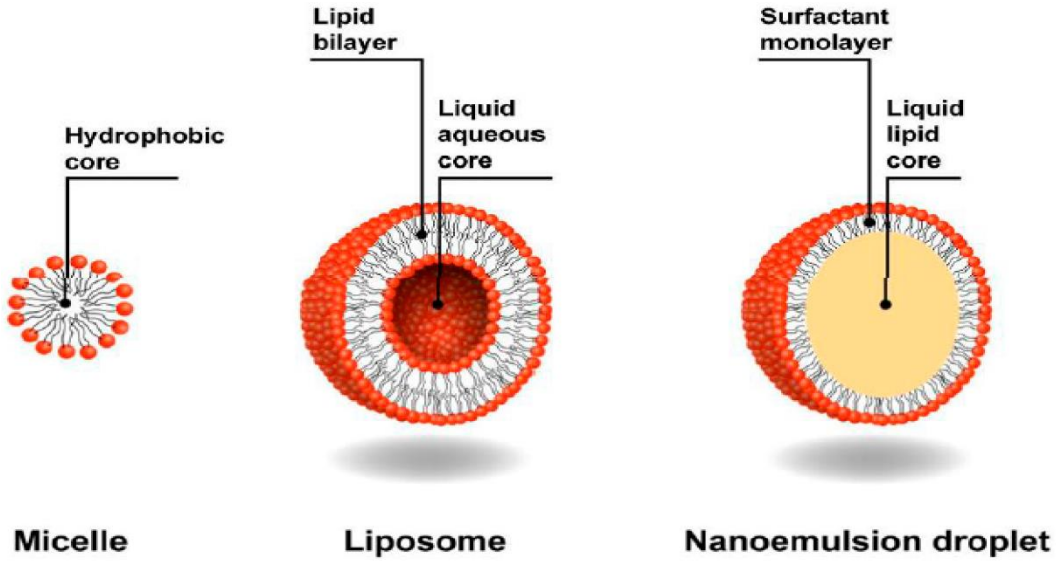


Fig 5 Nanoemulsion

Nanoemulsions are colloidal dispersions that are kinetically stable and typically have droplet sizes between 20 and 200 nm [22]. They can be administered orally, topically, or parenterally due to their high solubilization capacity and simplicity of production [23].

2.7 Inorganic and Metallic Nanoparticles Applications for gold, silver, silica, and magnetic nanoparticles include targeted chemotherapy, gene delivery, photothermal therapy, and imaging [24]. Long-term toxicity and biodegradability are issues, despite the fact that it provides precise control and stimuli-responsiveness [25, 26].

2.8 Nanomaterials Based on Carbon High drug-loading capacity and substantial potential in cancer treatment and biosensing are provided by carbon nanotubes, graphene oxide, and fullerenes [27]. However, clinical translation is limited by their long retention times, risk of inflammation, and potential toxicity [28].

2.9 Nanocarriers that are hybrid Polymers, lipids, and inorganic materials are combined in hybrid nanocarriers to combine the benefits of each system, allowing for regulated release, imaging, and multifunctional drug delivery [29, 30].

3. Drug Targeting and Delivery Mechanisms

3.1 Using Passive Targeting Because of the enhanced permeability and retention (EPR) effect brought on by leaky vasculature and inadequate lymphatic drainage, nanoparticles build up in tumor tissues [31].

3.2 Using Active Targeting Functionalization with ligands like folic acid, peptides, or antibodies improves specificity by increasing binding to particular cellular receptors [32, 33].

3.3 Delivery that Responds to Stimuli Drugs are released by stimuli-triggered nanocarriers in reaction to pH, temperature, enzymes, redox state, magnetic fields, or light [34].

3.4 Barrier Penetration and Transcytosis Through receptor-mediated transcytosis and increased membrane permeability, some nanocarriers can get past biological barriers (like the blood-brain barrier) [35].

3.5 Systems of Co-delivery Multiple therapeutic agents (such as two chemotherapeutics or a drug plus siRNA) can be encapsulated in nanocarriers to reduce drug resistance and enable synergistic effects [36].

4. Therapeutic Uses

4.1 Treatment for Cancer Chemotherapeutics with improved tumor targeting and decreased toxicity, such as paclitaxel, doxorubicin, and cisplatin, are being extensively investigated for delivery via NDDS [37]. Real-time drug distribution imaging is made possible by theranostic nanocarriers [38].

4.2 Delivery of Genes and RNA mRNA vaccines are one example of how lipid nanoparticles (LNPs) have transformed mRNA delivery [39]. Additionally, siRNA and DNA are delivered via polymeric nanoparticles and dendrimers [40].

4.3 Neurological Conditions Alzheimer's, Parkinson's, and brain tumors can all be treated thanks to nanocarriers' ability to cross the blood-brain barrier [41].

4.4 Contagious Illnesses Targeted delivery of antiviral, antibacterial, and antifungal agents is made possible by NDDS, which also increases antimicrobial efficacy and decreases resistance [42].

4.5 Autoimmune and Inflammatory Conditions Nanocarriers lessen intestinal disease and systemic toxicity while improving targeting to inflammatory tissues [43].

5.Benefits of Drug Delivery

Using Nanotechnology Improved bioavailability and solubility [44] sustained and regulated drug release [45] Targeted treatment with fewer adverse effects [46] enhanced labile drug stability [47] Capacity to administer vaccines, proteins, peptides, and genes [48] Therapeutic and imaging multifunctionality (theranostics) [49]

6. Difficulties and Restrictions

Biodegradability and long-term toxicity issues [50] Certain nanocarriers have short circulation times and RES clearance [51]. High production costs and complicated synthesis [52] Absence of uniform regulations [53] Leakage, aggregation, and unstable storage [54] Limited clinical translation as a result of manufacturing challenges [55]

7. Prospects for the Future NDDS's future is in:

customized nanomedicine based on the genetic makeup of the patient [56] AI-assisted design of nanocarriers [57] Intelligent nanocarriers that respond to multiple stimuli [58] Synthesis of "green" nanoparticles with microbial or plant agents [59] increased non-invasive delivery methods (ocular, transdermal, and intranasal) [60]

8. Conclusion

Drug delivery methods based on nanotechnology have shown great promise in enhancing treatment results for a variety of illnesses. Even though there are still many obstacles to overcome, primarily in the areas of toxicity, scale-up, regulation, and long-term stability, the quick development of materials science, engineering, and biomedicine guarantees further advancements. Leading the way in next-generation treatments, NDDS will probably be crucial to precision and personalized medicine.

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