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The Future of Medicine: Nanotechnology in Drug Delivery Systems

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Abstract

Nanotechnology has revolutionized modern drug delivery systems by enabling the design of nanoscale materials that enhance therapeutic efficacy, minimize toxicity, and enable targeted delivery. The ability to engineer nanocarriers with controlled size, surface characteristics, and functionalization has opened new avenues for overcoming limitations of conventional therapies, such as poor solubility, rapid clearance, and lack of site-specificity. This review provides an overview of recent advances in nanotechnology-driven drug delivery systems, including polymeric nanoparticles, liposomes, dendrimers, micelles, and solid lipid nanoparticles. The discussion highlights how nanocarriers improve bioavailability, facilitate controlled or stimuli-responsive release, and traverse biological barriers such as the blood–brain barrier. Additionally, emerging trends in green nanomedicine, personalized nano therapy, and theragnostic are explored as key directions shaping future biomedical applications. Despite significant progress, translation to clinical practice remains challenged by scalability, regulatory hurdles, and incomplete understanding of long-term biocompatibility. Overall, nanotechnology continues to hold transformative potential in precision medicine by enabling safer, more effective, and sustainable drug delivery platforms.

Keywords*:*

Nanotechnology, Drug delivery, Nanocarriers, Liposomes, Polymeric nanoparticles, Theragnostic, Green nanomedicine, Targeted therapy.

1. INTRODUCTION

Over the past two decades, nanotechnology has emerged as a transformative discipline in medicine, particularly in drug delivery, offering new strategies to overcome limitations of conventional therapeutics such as poor solubility, off-target effects, limited bioavailability, and toxicity. The design of nanoscale carriers—typically in the size range below ~100 nm in at least one dimension—enables improved pharmacokinetics, enhanced delivery to target tissues, and controlled release profiles. [1,2,3]

A variety of nanocarrier systems have been developed: polymeric nanoparticles, liposomes, solid lipid nanoparticles (SLNs), micellar systems, dendrimers, inorganic nanoparticles, and biomimetic/hybrid systems.[4,5,6] Polymeric nanoparticles allow tenable degradation and surface functionalization; liposomes offer biocompatibility and ability to encapsulate both hydrophilic and hydrophobic drugs; inorganic nanoparticles (such as gold, iron oxide) bring additional features like imaging contrast or magnetic guidance.[7,8,9] Moreover, recent advances emphasize self-assembled nanocarriers capable of stimuli-responsive release and dual targeting, enhancing therapeutic efficacy while reducing side effects.[10]

Another important direction is the integration of green chemistry principles in nanomedicine, using biocompatible and renewable materials, minimizing toxic reactants and waste during synthesis, which is essential for safety and sustainability.[11]

Nanotechnology has already found success in areas such as cancer therapy (targeted delivery of chemotherapeutics), gene therapy (delivery of siRNA, DNA), vaccine delivery, and overcoming biological barriers including the blood-brain barrier. [12,13,14] Despite these promising advances, challenges persist: understanding nanoparticle biodistribution, long-term toxicity, large scale-manufacturing reproducibility, regulatory approval pathways, and precise targeting in vivo. This review aims to provide a comprehensive overview of the current state of nanotechnologies in drug delivery, their mechanisms, diverse applications in medicine, and the challenges and future directions in the field. [15,16]

2. NANOTECHNOLOGY AND DRUG DELIVERY IN THE FIELD OF MEDICINE

Drug delivery is one of the several applications of nanotechnology in the medical profession. In addition to being utilized to deliver proteins, antibiotics, and vaccines, nanoparticles have been employed as medication delivery vehicles for radiation, AIDS, cancer, and gene therapy. Nanotechnology is regarded as a novel and quickly developing sector in medicine and pharmaceuticals. Nanoparticles offer a number of benefits as medication delivery machinery, including greater efficacy and less adverse drug effects [17]. Virtually challenging to overlook the humble beginnings of nanomedicine when reviewing the immense domains of biotechnology, medicine, and biological sciences. Within the larger context of nanobiotechnology, nanotechnology is already beginning to transcend the realm of the imagination. As a result of the successful use of the technology of nanotechnology in medicine, which has continuously improved human life quality, an entirely novel discipline of nanomedicine has sprung up, assisting researchers to nurture improved methods for disease prevention, screening, diagnosis, treatment, and proactive healthcare measures. Combining advancements in tissue engineering, gene therapy, and nano-based genomics, these procedures may also include drug design, conjugation, manufacturing, and efficient delivery methods [18].

1. CARBON NANOTUBES

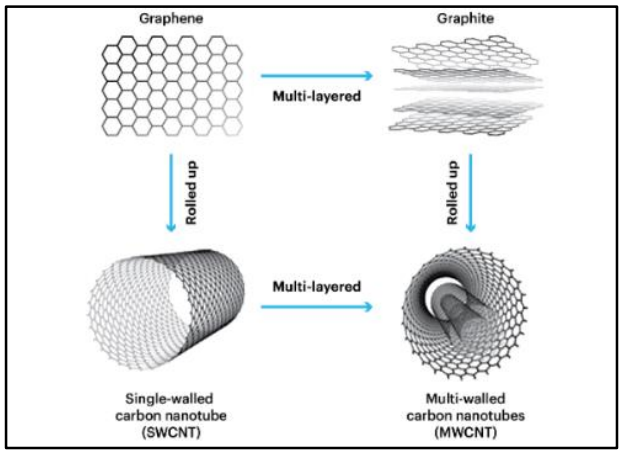

Fig – 1: Carbon nanotube.

Carbon nanotubes (CNTs) are materials that resemble tubes and are composed of carbon. Their diameter is measured in nanometres. Originating from graphite sheets, these graphite layers resemble an indestructible hexagonal mesh structure that is constantly rolled up, with carbon molecules appearing at the apexes of the hexagonal structures. Single-walled carbon nanotubes (SWCNTs), double-walled carbon nanotubes (DWCNTs), and multi-walled carbon nanotubes (MWCNTs) are distinguished by the number of carbon layers they contain. There are three primary techniques for creating carbon nanotubes (CNTs): chemical vapor deposition, electric arc deposition, and laser deposition. Among the many distinctive qualities of carbon nanotubes are their high flexibility, high thermal conductivity, low density, and greater chemical inertness. These intriguing characteristics have made carbon nanotubes important in the disciplines of materials science, electronics, optics, and nanotechnology.

Applications for carbon nanotubes include water purification, medication delivery, and sensing. When their surface is functionalized, extremely soluble materials can be produced. These materials can then be further derivatized with active molecules to make them compatible with biological systems. Adsorption or attachment of different molecules or antigens is made possible by surface functionalization, and these molecules or antigens can then be directed towards the target cell population for immunological recognition or a therapeutic impact [19,20 image].

2. DENDRIMERS

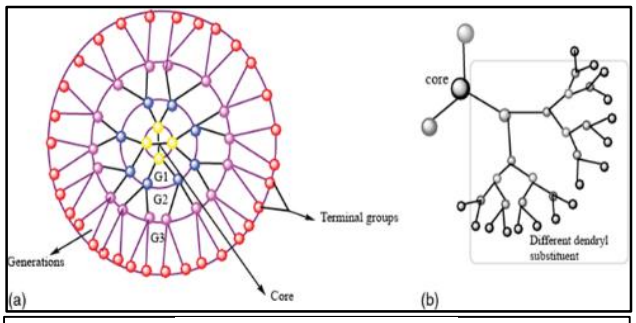

Fig – 2: Dendrimers.

Dendrimers are radially symmetric, nanoscale molecules with a characteristic symmetric core, inner shell, and outer shell. They have a well-defined, uniform, and monodisperse structure. Their three

conventional macromolecular architectural classes are known to produce fairly polydisperse products with varying molecular weights. Numerous dendrimers are known to possess biological characteristics, including solubility, low cytotoxicity, electrostatic interactions, polyvalency, self-assembly, and chemical stability. In the medical field, dendrimers are an excellent choice because of these diverse qualities [21]. Cancer treatment is one of the primary areas of research into the biological uses of dendrimers. The bioactive substance can be delivered precisely to cancer tissues by conjugating such nanocarriers to targeting groups, which lessens the off-target effects. Targeted administration is made possible by the aberrant components that cancer cells typically exhibit, such as increased protein expression of transferring and epidermal growth factor receptors and folate [22,23 image].

3. NANOCAPSULES

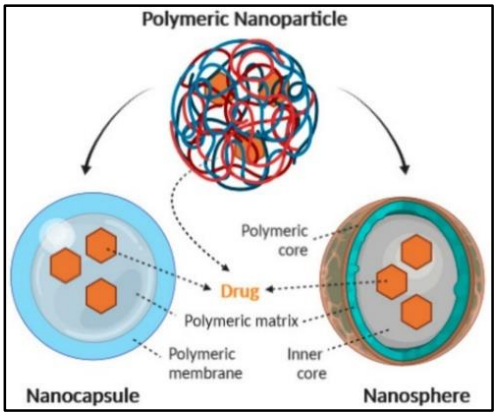

Fig – 3: Nano capsules.

Nano capsules (NCs) are small colloidal systems with an aqueous or oily core surrounded by a thin polymeric membrane that are used to deliver medications. They are distinguished by their protective coating, which shields the medication from adverse circumstances and frequently extends the release of active chemicals. Nano capsules are made using a variety of technological techniques, the most popular of which is interfacial polymerization. The most important aspect of their manufacturing is their size distribution, which may be evaluated using a variety of methods, including transmission electron microscopy, scanning electron microscopy, and X-ray diffraction. A reliably reproducible nano capsule is appropriate for a wide range of biological uses. They are useful in many different fields, including as adhesives, cleaning products, cosmetics, genetic modification, botanical insecticides, and wastewater treatment [24]. Nano capsules are of biological relevance due to their ability to target and release drugs in prescribed amounts while sustaining enzymes, proteins, foreign cells, etc [25, 26 image].

4. NANOEMULSION

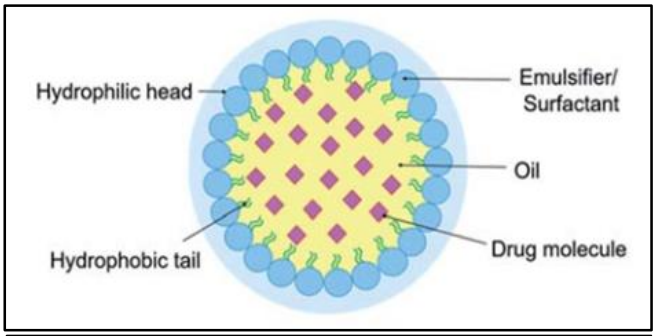

Fig – 4: Nano-emulsion.

Nano-emulsions are a colloidal atom system in the submicron size range acting as carriers of medicinal molecules. Their size varies from 10 to 1,000 nm. These carriers are solid spheres with an amorphous, lipophilic, negatively charged surface. Site specificity can be improved by using magnetic nanoparticles. As a medication delivery mechanism, they reduce toxic reactions and side effects while increasing the drug's therapeutic efficacy. Major uses include reticuloendothelial system (RES) infection treatment, liver enzyme replacement therapy, cancer treatment, and immunization [26]. The NE's ability to alter the surface electrical charge of ionic medicines or boost drug thermodynamic activity was thought to be responsible for the easier transport of these permeants. The solubilization of sebum by the NE components, which facilitated the follicular distribution of hydrophilic medicines, was occasionally given as an explanation for the same improvement [28, 29 image].

5. SOLID LIPID NANOPARTICLES

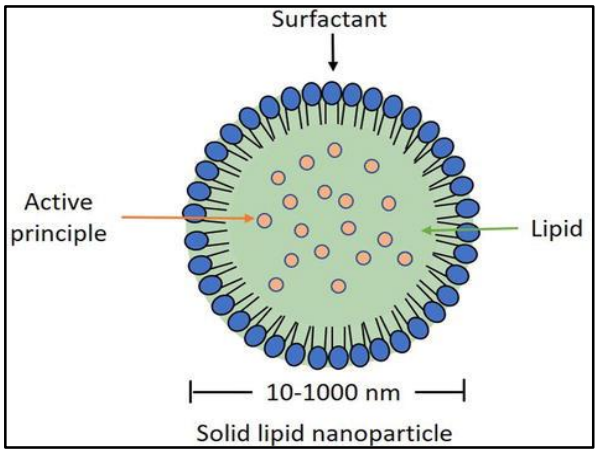

Fig – 5: Solid lipid nanoparticles.

Solid lipid nanoparticles (SLNs) are composed of lipid phase and surfactant, and are formed by O/W nano-emulsions. They are prepared using melted lipid molecules and active ingredients, dispersed in an aqueous medium containing an emulsifier. The emulsifier is used to solidify the lipid phase (fully or partly) by one or a mixture of solid lipids. In SLNs, the lipid phase includes physiological lipid-like triglycerides or saturated fatty acids. SLNs show an advantage over other lipid-based nano systems as they offer high encapsulation efficiency, stability, loading capacity, and target-specific release

properties. SLNs offer greater protection to both lipophilic and hydrophilic compounds from environmental stress. SLNs have higher bioavailability, prolonged-release profile and flexible application. In contrast to other lipid-based nano systems, SLNs are easy to produce, scalable, affordable, and suitable for industrial use. However, SLNs have a number of disadvantages, including restricted loading capacity, a strong propensity to aggregate during the drying process, and poor stability in acidic environments [30, 31 image].

6. POLYMERIC MICELLES

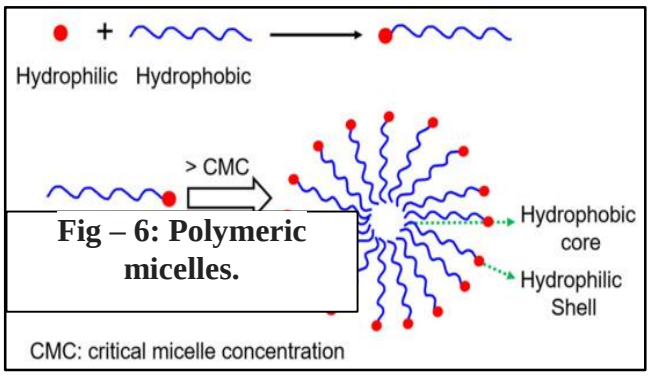

Fig – 6: Polymeric micelles.

Polymeric micelles are amphiphilic block copolymers that create nanoscopic core/shell structures. For medication delivery, polymeric micelles are especially well-suited due to their intrinsic and adjustable characteristics. The methods used to describe and characterize the physical characteristics of polymeric micelles have been emphasized in this review. Size, stability, morphology, and micellar association are among the pertinent characteristics that are covered. To put the recognized benefits and uses of polymeric micelles for drug delivery in context, certain characteristics and characteristics [32, 33 image].

3. NANOPARTICLE AND DRUG DELIVERY INCORPORATING MECHANISM

A novel method in medicine is nanoparticle-based drug delivery, in which medications are administered by nanoparticles, which are minuscule carriers that are usually between one and a thousand nanometres in size. A variety of medicinal substances, including proteins, nucleic acids, and small molecule medications, can be encapsulated in these nanoparticles through engineering. Enhancing the accuracy, release, and effectiveness of medications is the primary benefit of using nanoparticle-based drug delivery, especially when treating complicated illnesses like brain and spinal cord disorders [34].

Some of the Nanoparticle Drug Delivery Mechanisms:

1. TARGETED DELIVERY:

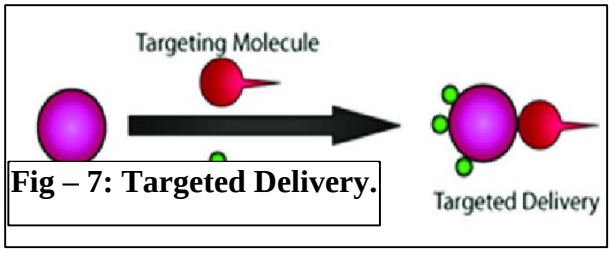

Fig – 7: Targeted Delivery.

Targeted delivery methods can accurately and efficiently deliver the majority of medications to tumour cells or tissues rather than healthy cells or tissues. Utilizing nanotechnology, such delivery methods can be accomplished. Because nanoparticles can accumulate at tumour sites through the EPR effect, nanoparticle-based medication delivery has generally gained more attention. The "targeting fraction," which can connect with particular moieties or receptors at the target region, is a key part of targeted drug delivery systems. Furthermore, because of its low dosage, excellent efficacy, and few side effects, targeted medication delivery can help individualized therapy reach its objective. Through a variety of targeting methods, tailored nanocarriers have been shown to efficiently increase the bioavailability and efficacy of medications [35, 36 image].

Example: Targeting ligands, such as antibodies, that precisely recognize antigens expressed on tumour cells can be attached to the surface of nanoparticles to enable them to target tumour cells in cancer therapy. By doing this, systemic toxicity is decreased and the drug concentration at the tumour site is raised [34].

2. PASSIVE TARGETING VIA THE ENHANCED PERMEABILITY AND RETENTION (EPR) EFFECTS:

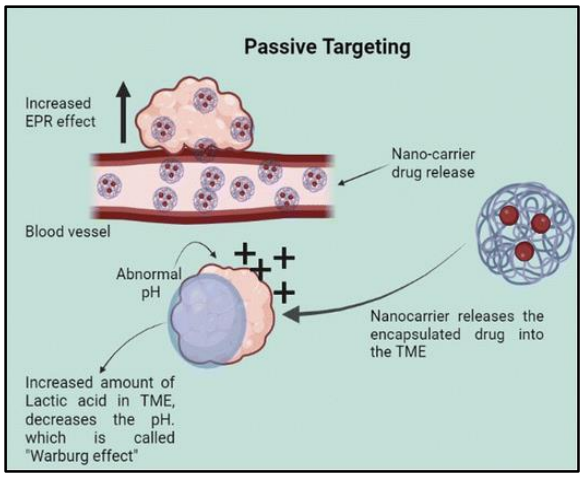

Fig – 8: Passive Targeting.

A universal pathophysiological phenomenon and mechanism known as the enhanced permeability and retention effect (EPR effect) demonstrates the way macromolecular substances like albumin and other polymer-conjugated medications that are larger than a certain size (above 40 kDa) can gradually accumulate in the tumour vascularized area, achieving targeted delivery and retention of anticancer compounds into solid tumour tissue. Since the EPR effect's strength varies according to the type and location of tumours, the state of blood circulation in tumours, and the physical-chemical characteristics of macromolecular anticancer medicines, targeting therapy using the EPR effect in clinical practice is not always successful [37, 38 image].

Example: This process is frequently used by liposomes and polymer-based nanoparticles to concentrate medications in tumours or inflammatory tissues, enhancing therapeutic results [34].

3. ACTIVE TARGETING WITH SURFACE MODIFICATIONS:

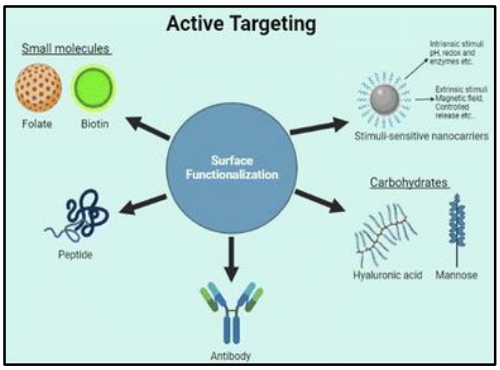

Fig – 9: Active Targeting.

Active targeting is the process of conjugating targeting moieties on the surface of nanocarriers, including as aptamers, ligands, and antibodies, to specifically recognize tumour cells. Receptor-mediated endocytosis to internalize nanocarriers is triggered by selectively identifying overexpressed receptors on the surface of tumour cells, increasing the effectiveness of treatment. Targets like integrins, vascular endothelial growth factor receptors (VEGFRs), and folate receptors have all been used in nano-drug delivery systems to target osteosarcoma (OS) [39, 38 image].

Example: Chemotherapeutic drugs can be delivered directly to the tumour while preserving healthy tissue by using nanoparticles functionalized with antibodies that target antigens linked to brain tumours [34].

4. CONTROLLED AND SUSTAINED RELEASES:

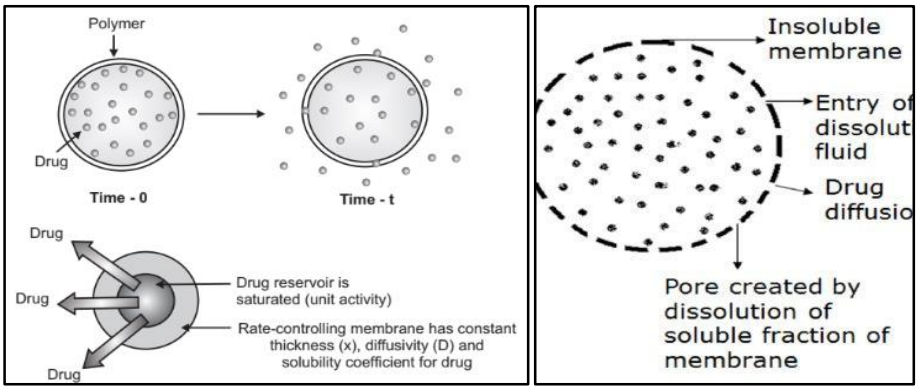

Fig – 10: (a) Controlled release and (b) Sustained release.

A controlled drug delivery system is one that delivers the medication from the dosage form either locally or systemically over a certain amount of time at a predefined rate. The kind of system known as sustained drug delivery releases medication continuously over a long period of time following the administration of a single dose, resulting in a lasting therapeutic impact [40, 41 image, 42 image].

Example: Biodegradable nanoparticles are frequently employed in drug delivery systems that release the medication gradually, decreasing the need for frequent administration and increasing patient compliance [34].

5. CROSSING BIOLOGICAL BARRIERS (BLOOD-BRAIN BARRIER)

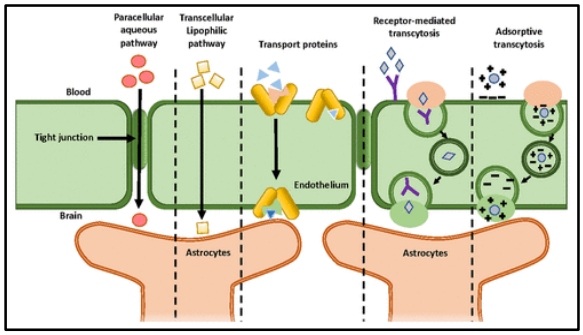

Fig – 11: Crossing biological barriers.

The majority of medications are kept out of the brain by the blood-brain barrier (BBB), a microvascular network. The BBB's impermeability limits the treatment of brain cancers, and as a result, the prognosis for malignant brain tumours is still dismal. Because of their small size and ability to target tumour cells, nanoparticles (NPs) offer a viable approach to enhance drug transport to brain tumours. The processes of NP transport across the BBB, such as paracellular transport, carrier-mediated transport, and adsorptive- and receptor-mediated transcytosis, are covered here, along with a review of the special physical and chemical characteristics of NPs that support BBB transport. Multifunctional nanoparticles (NPs) that can target malignancies for both therapeutic and imaging applications can be created [43, 44 image].

Drugs for diseases including Parkinson's, Alzheimer's, and brain cancers can be delivered through the blood-brain barrier using lipid-based nanoparticles or polymeric nanoparticles functionalized with peptides or antibodies [34].

4. ON GOING RESEARCHES:

1. To shield astronauts from the effects of radiation, NASA created bio-capsules.
2. To enhance the immune system, endeavour to introduce antigens to the body.
3. Enhance implants for dentistry by embedding nanotubes onto the implant matrix's surface.
4. To increase circulation time, strategy to bind RNA to the NP surface.

5. FUTURE OPPORTUNITIES

In the future, DDS based on nanotechnology can be used to treat anticancer therapy, gene therapy, radiation, and the BBB for the administration of proteins, antibiotics, vaccines, and vesicles. Scientists will be able to design drug loading, targeting, transporting, releasing, interaction with the barriers, low toxicity, and safe settings if they first research the mechanism and fate of NP-drugs using animal models. the knowledge that medications can enhance NPs to treat bone disorders and promote bone regeneration when administered to delicate organelles like the nucleus. Multifunctional nanoparticles could be created

that can identify cancerous cells, distribute many medications simultaneously, use imaging agents to see the area, destroy cancer cells with minimal side effects, and simultaneously monitor and treat. These nanoparticles have the potential to be improved to treat conditions like HIV and cancer, and they can even be used to create robots to treat conditions like heart disease. When combined with a computer programming system, the nanoparticles can autonomously control human homeostasis, including blood glucose and calcium levels. In the future, we can make these NPs even more effective at shielding the body from foreign particles [45].

6. CONCLUSION

Nanotechnology has fundamentally reshaped the landscape of drug delivery by enabling precisely engineered nano systems that enhance the efficacy, specificity, and safety of therapeutic agents. As demonstrated in numerous studies, polymeric nanoparticles, liposomes, dendrimers, solid lipid nanoparticles, and self-assembled nanocarriers have improved drug bioavailability, facilitated targeting (both passive and active), and enabled stimuli-responsive release for a wide variety of disease contexts, especially oncology, infectious diseases, and neurological disorders.

The adoption of green nanomedicine strategies further promises safer, more sustainable systems, reducing potential environmental and biological toxicity. However, translation into clinical practice still faces critical hurdles: variability in nanoparticle behaviour in vivo, immunogenicity, off-target effects, scale-up and reproducibility, regulatory uncertainty, and cost barriers.

Looking forward, the field is likely to benefit from advances in multifunctional nanocarriers (capable of combined therapeutic and diagnostic functions— “theragnostic”), precise targeting through ligands or stimuli, smart release controlled by environmental cues (pH, temperature, redox etc.), and more rigorous preclinical models that mimic human physiology. Moreover, stronger integration of safety assessment, regulatory science, and standardization in characterization will be essential for wider adoption.

In summary, while nanotechnology in drug delivery holds enormous promise and has already yielded significant progress, concerted efforts across material science, biology, engineering, and regulation are required to fully realise its potential in routine medical practice.

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