Application of Nanocomposites in Drug Delivery: A Review

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Abstract

In drug delivery, nanocomposites now play a key role, addressing barriers found in conventional carriers such as poor absorption, fast break-up and a lack of targeting. Because they are made with small organic and inorganic molecules, those systems add improved drug stability, controlled release and targeted action to specific tissues or cells. The focus of this review is on polymer, lipid, inorganic and carbon-based nanocomposites, exploring how they function in drug delivery and how drugs are loaded, unloaded and delivered to target organs. The discussion highlights how nanomedicine reduces toxic effects, increases treatment performance and is sensitive to different stimuli. Also, recent progress and look ahead show that nanocomposites could lead to significant improvements in personalized medicine and push forward new therapies in nanomedicine.

Keywords: Nanocomposites,Drug Delivery System**,** Tageted Drug delivery, Controlled Release.

Introduction

Whether a drug is successful and safe depends largely on how it is delivered. Conventional drugs commonly have poor solubility, fast decomposition, reduced oral bioavailability and affect any cells they come in contact with, affecting their results and leading to side effects (Torchilin, 2014). Thanks to nanotechnology, researchers can now make materials that store medicines securely, prevent them from breaking down early and allow medicines to be delivered only to the parts of the body that need them. Because of nanotechnology, researchers can now create nanomaterials to hold drugs, save them from being damaged too early and release them exactly where needed (Danhier, 2016). Because nanoparticle medicines have received Food and Drug Administration (FDA) clearance, it is clear that this type of treatment can work in the clinic (Bobo et al., 2016). Hybrid composites made of two or more nanoscale components have become popular since they exhibit new functions and improved physical and chemical characteristics (Khan et al., 2020).

Nanocomposites take the good properties of polymers, lipids, inorganic nanoparticles or carbon materials, making them suitable vehicles for delivering drugs. Such materials can solve problems with solubility, maintain the drug in the blood for longer and be directed to specific tissues through surface coating and triggered mechanisms (Zhang et al., 2019). For instance, both polymer-based and inorganic nanocomposites have benefits; biocompatibility and control over drug release for the first ones and magnetic or photothermal function for use in site-specific therapy for the second ones (Gupta & Gupta, 2019).

These characteristics allow nanocomposites to fix several issues seen in typical drug delivery, for example, overcoming resistance to many drugs, boosting drug penetration and improving how the drugs behave in the body (Patra et al., 2018). We will discuss various kinds of nanocomposites, the ways they work for drug delivery, the reasons they are better than traditional carriers and the trends in their current clinical use.

Types of Nanocomposites Used in Drug Delivery

Drug delivery nanocomposites are grouped mainly by what they are made of and how they are structured. Among the main types are polymer-based, lipid-based, inorganic and carbon-based nanocomposites, all suited to particular therapeutic functions.

1.Polymer-based nanocomposites

Many drug delivery systems utilize polymeric nanocomposites because they are safe, will dissolve in the body and can be tweaked for various applications. Examples of such materials are chitosan, alginate, PLGA and PEG. The materials ensure the drug is distributed how and when it should be and help target only particular cells or parts of the body (Szyk et al., 2023). Special molecules such as antibodies or peptides, can be attached to their surfaces so the drug goes where it needs to work. The body's natural signals such as pH or temperature, may trigger the release of drugs from some polymer-based forms. Evidently, research now uses these types of systems to administer many drugs at once which brings benefits in the treatment of diseases such as cancer.

2.Lipid-based nanocomposites

Many scientists choose to use liposomes and solid lipid nanoparticles as lipid-based nanocomposites. Fats make them up and the body likes to use them during digestion. They have the capacity to move water-based (hydrophilic) drugs and water-walling (hydrophobic) drugs at the same time. It is particularly helpful that you attach ligands or antibodies to them which directs them to exact spots at the cancer site (Matei et al., 2021). A number of lipid-based systems, including Doxil for cancer treatment, can already be found in real medicines.

3.Inorganic nanocomposites

Common materials for inorganic nanocomposites include silica, gold and iron oxide. They are hardy and have the ability to bring more than drugs to the surface. Magnetic fields can line up magnetic particles where needed in the body and exposing them to light causes gold particles to heat and kill tumor cells (Gupta & Gupta, 2005). Silica particles are commonly used since they can load a lot of drug and can be adjusted to react to bodily changes, including changes in pH.

4.Carbon-based nanocomposites

Carbon nanocomposites, including carbon nanotubes and graphene oxide, have a large total surface area and are extremely durable. It aids in transporting lots of drugs into cells. Nevertheless, using these materials directly can be dangerous, so their surfaces are usually treated with PEG to avoid harm and improve stability (Debnath & Srivastava, 2021). Carbon materials are being investigated for use in cancer treatment, genetic medicine and for heating and treating tumor cells with laser light.

Each kind of nanocomposite can be modified to enhance drug delivery, making them essential in today's drug systems.

The main categories of nanocomposites for drug delivery are shown in **Table 1** and their key benefits and advantages are discussed together with the efficiency of nanoparticles in drug delivery in **Figure 1**.

Table 1. Types of Nanocoposites Used in Drug Delivery

Type of Nanocomposite	Description	Applications / Advantages	Reference
Polymer-based	Composed of natural or synthetic polymers like PLGA, PEG, chitosan	Biodegradable, controlled release, surface modification for targeting	Szyk et al., 2023
Lipid-based	Includes liposomes and solid lipid nanoparticles	High drug encapsulation, biocompatible, useful for hydrophobic drugs	Matei et al., 2021
Inorganic-based	Made of silica, gold, or iron oxide nanoparticles	Magnetic targeting, imaging capabilities, stimuli-responsive release	Gupta & Gupta, 2005
Carbon-based	Includes carbon nanotubes and graphene oxide	High surface area, excellent drug loading, cell penetration	Debnath & Srivastava, 2021

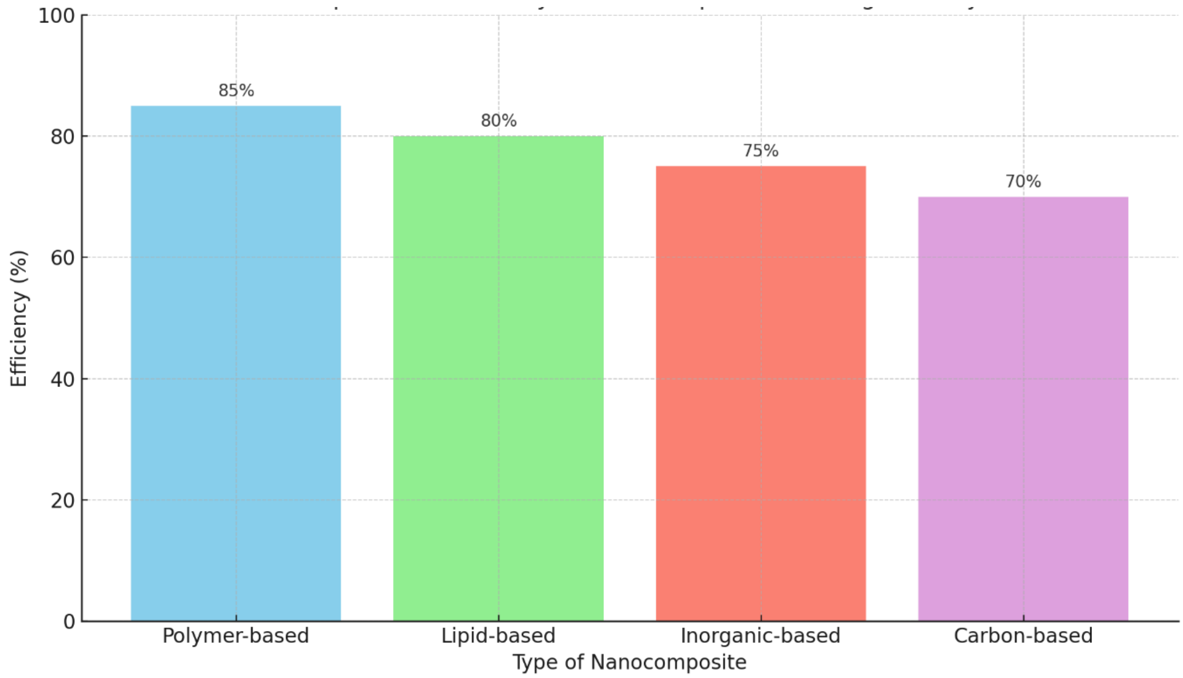

Figure 1. Comparative Efficiency of Nanocomposites in Drug Delivery

Mechanism of Nanocomposites in Drug Delivery

Improvements in drug delivery have been made possible by using nanocomposites because of their useful physicochemical features. These traits help nanocomposites fix a number of problems seen in standard drug delivery systems, leading to more accurate and reliable healing. In general, the key ways nanocomposites support drug delivery involve increasing how the drugs are taken into cells, managing the time drug release occurs and directing the drugs toward a particular part of the body.

Nanocomposites enhance the ability of cells to take up molecules, using processes such as clathrin-mediated endocytosis, caveolae-mediated endocytosis and macropinocytosis (Sahay et al., 2010). How tiny they are, on the scale of nanometers, means they can move into cells that other drugs cannot reach. Better, nanocomposites rely on the EPR effect, where poor blood vessels and lymph system in tumors or inflammation allow them to build up inside the tumors, so drugs are delivered in higher concentrations (Fang et al., 2021).

Secondly, nanocomposites are built to deliver drugs in response to certain conditions, making treatment more accurate. When nanocomposites respond to factors such as pH, temperature or enzymes or redox changes, they can control when to release the medication more precisely. An example is polymeric nanocomposites which deliver their drug load only in the acidic microenvironment of tumors or lysosomes, so that the therapy is localized and less harmful throughout the body (Xiang et al., 2023). For patients such adjustable drug release improves treatment efficiency, as they can still benefit from steady, on-demand or regular drug supply (Khan et al., 2020).

Also, adding special molecules known as ligands, antibodies or peptides to the surface of nanocomposites supports directed targeting. The changes at the surface allow nanocomposites to attach to particular overexpressed receptors on unhealthy cells (Debnath & Srivastava, 2021). This type of targeting both increases the specific delivery of drugs and has a big reduces off-target effects and systemic toxicity by minimizing drug uptake by healthy tissues.

All in all, nanocomposites target the body passively using the EPR effect, can be targeted actively by adding special molecules to their surface, are taken up easily by cells and slowly release their drugs in response to specific stimuli. When used together, these special properties allow nanocomposites to deliver drugs more easily, increase their usefulness and have fewer unwanted effects, making them an excellent option for future drug delivery systems.

Table 2 and **Figure 2** offer a detailed explanation of this mechanism.

Table 2. Various Mechanism of Nanocomposite in Drug Delivery

Mechanism	**Description**	**Advantages**
Cellular Uptake	Nanocomposites enter cells via endocytosis and accumulate at target sites using the EPR effect.	Efficient internalization and targeted accumulation.

Controlled Release	Drug release triggered by pH, temperature, enzymes, or redox conditions.	Site-specific action with minimal toxicity.
Targeted Delivery	Surface modified with ligands or antibodies to bind specific receptors.	High specificity and reduced side effects.

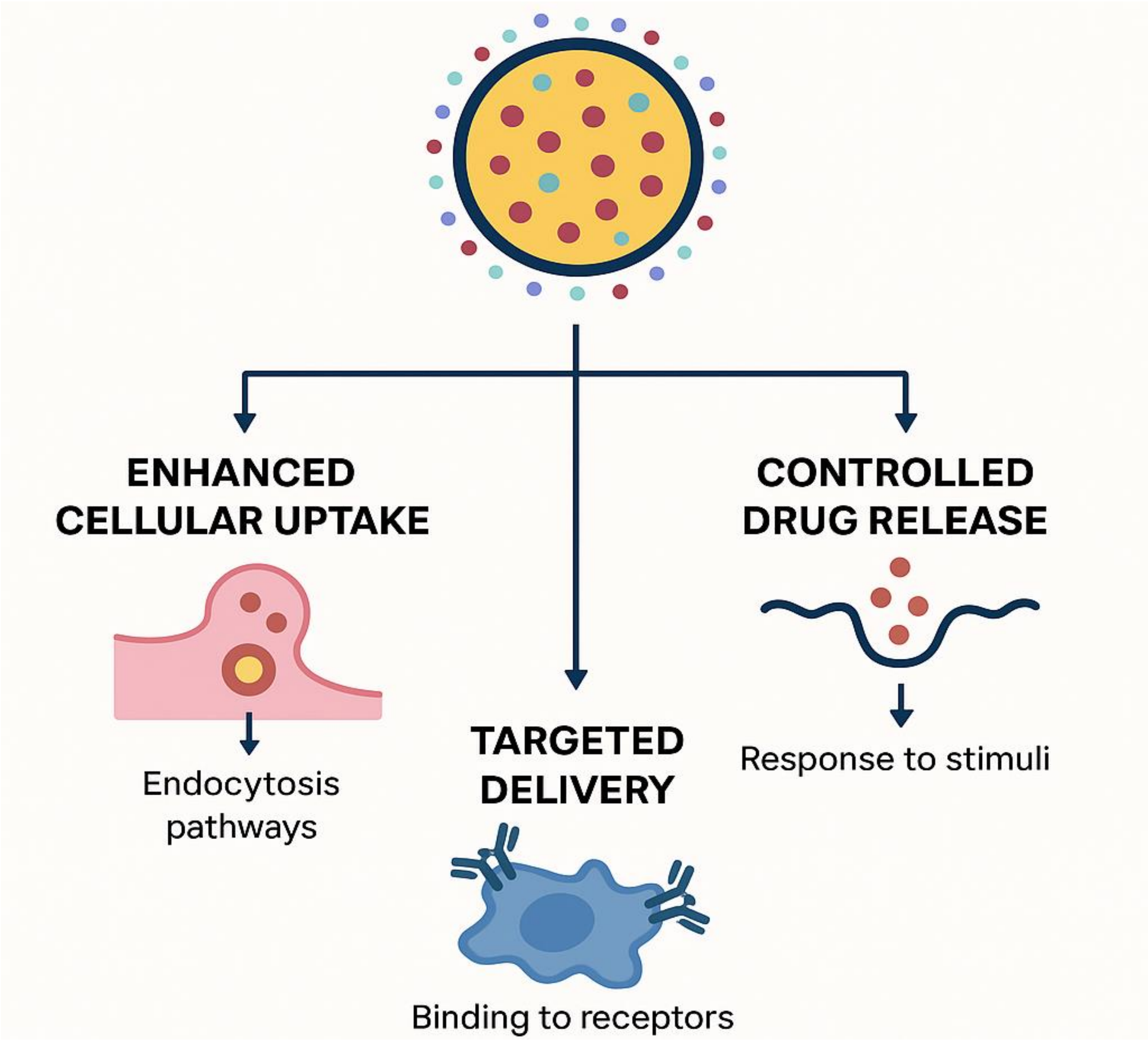

Figure 2. Mechanism of Nanocomposites in Drug Delivery

Advantages and Challenges of Nanocomposites in Drug Delivery

For their special features, multifunction and tunability, nanocomposites are transforming drug delivery. Compared to others, these physical approaches have higher drug encapsulation and a better chance of reaching the target, both of which reduce unwanted side effects and enhance the effectiveness of treatment (Xiang et al., 2021). Stimulation by pH, temperature, enzymes or redox changes triggers their properties and makes drug release more precise at specific locations (Liu et al., 2021). Also, because of their durability and solubility, nanocomposites often make it easier for drugs that do not mix well with water to be given less often and accepted better by patients (Roy et al., 2010).

At the same time, numerous obstacles make it difficult to translate preclinical research outcomes to clinical use (See Figure 3). Creating and manufacturing nanocomposites in larger amounts pose problems for industry. Furthermore, how well plastic degrades and if it is toxic are important issues, mainly because of the buildup of materials that do not break down (Wang et al., 2022). It is unclear in many cases how long the metabolites stay in a person's system and how they clear once the drugs are gone. Extra regulations, a high price to produce and strict quality standards make it hard for large-scale growth.

In the future, researchers ought to pay attention to making effective, green and affordable nanocomposites and carry out wide-ranging in-person studies and clinical trials to determine their safety and effectiveness. Overcoming these difficulties will be crucial for making the most of nanocomposites in modern drug delivery.

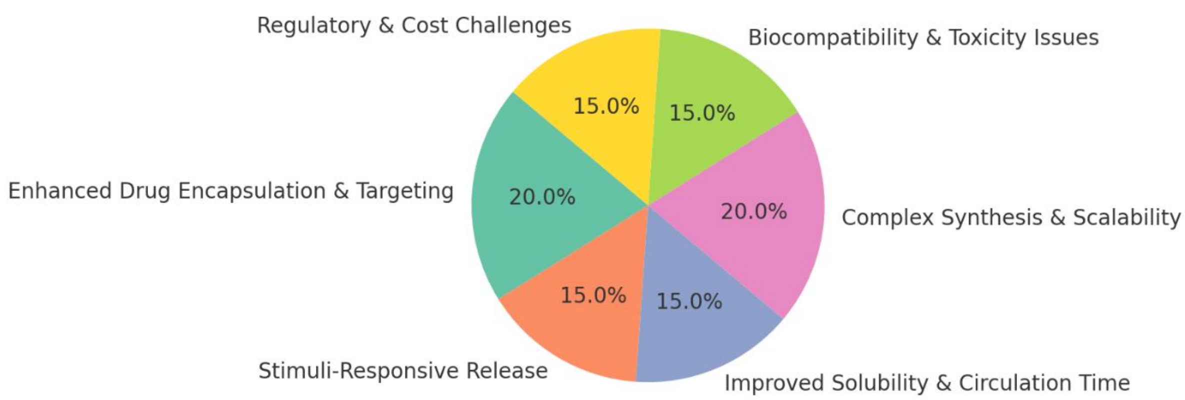

Figure 3. Advantages & Challenges of Nanocomposites in Drug Delivery

Conclusion

Thanks to nanocomposites, drug delivery is now capable of fine-tuned drug release, goal-directed targeting and better accessibility for the body. Therapeutics delivered in liposomes are powerful for precision medicine, because they hold several types of substances and react appropriately according to changes in the body. Although synthetic polymers offer many benefits, it is still difficult to overcome synthetic difficulties, the hazards of toxicity, obstacles in their making and problems with regulations. Nevertheless, new studies and advances in technology are addressing these problems, making better and more secure use of nanocomposites for drug delivery possible. With advances, nanocomposites are likely to support the growth of important therapeutic solutions, especially for chronic and complicated diseases such as cancer and neurological disorders. Adding them to common medical uses could lead to better results for patients and help shape upcoming personalized medicine.

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