REVIEW PAPER

From Concept to Clinic: Evolution and Impact of Carrier-Based Drug Delivery Systems

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ABSTRACT
In the present scenario drug delivery technology growing in rapid speed significantly influenced the rapid progress of drug-delivery technologies is greatly advancing the development of more precise and effective therapeutic options. Among the various delivery strategies, biocompatible drug carriers shown a pivotal model in enhancing the delivery of drug molecules. These carriers ranging from nanoparticles to liposomes, polymers, and dendrimers offer distinct advantages by ensuring the safe and controlled release of drugs, thereby improving the stability, and efficacy in treatment. The main objective of this study is to explore the current trends and innovations in biocompatible drug carriers, examining their potential to revolutionize drug delivery in both the clinical and preclinical stages. The study reviews the design principles, synthesis methods, and biocompatibility evaluations of these carriers, highlighting their application in various therapeutic areas, including cancer treatment, gene therapy, and chronic disease management. Furthermore, the study addresses the challenges and limitations associated with these systems, such as their scalability, safety, and regulatory concerns. By investigating the promising approaches and materials in the field, this work aims to contribute to the ongoing development of efficient, patient-specific in delivery that maximize therapeutic outcomes with low adverse effects. The work aims to provide a clearer understanding of how drug carriers are selected and developed to optimize therapeutic efficacy.
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INTRODUCTION

Drug carrier systems are cutting-edge technologies created to improve therapeutic agent delivery and effectiveness. By enhancing medication's bioavailability, stability, and targeted distribution, these systems hope to reduce harmful effects and enhance patient outcomes[1]. The growing need for tailored medicines is expected to propel the global drug delivery industry, with a special emphasis on drug carrier systems, to reach about $1.5 trillion by 2028[2]. Research and markets have out that developments in nanotechnology are greatly advancing the creation of medication carriers, which will improve bioavailability and lessen negative effects for a range of therapies. Drug carrier system advancements are being fuelled by the growth of customized medicine, that will allow for more individualized treatments that are tailored to each patient's specific needs.

Vehicles that make it easier for active pharmaceutical ingredients (APIs) to reach particular bodily locations are known as drug carrier systems. They are able to manage the release, encapsulation, and protection of medications. Zhang, stress that improving drug delivery methods is essential to overcoming issues such some medications' poor solubility and quick metabolism. Drug delivery is made safer and more effective with the use of drug carrier systems by providing a number of noteworthy benefits. Targeted medication delivery, enhanced bioavailability, controlled release, fewer adverse effects, and application diversity are some advantages of drug carriers. Drug characteristics (solubility, stability, and molecular weight), carrier material properties (size, shape, and surface charge), and environmental factors (pH, temperature, and the presence of particular enzymes or biomolecules) can all have an impact on how well a drug is delivered by a drug carrier system. Additionally, drug carriers must pass through a number of biological barriers, such as cell membranes and vascular endothelium, in order to deliver the drug. Drug carriers can be categorized according to their structure, composition, and mode of action. The selection of suitable carriers for particular therapeutic applications are aided by this classification. Drug carriers are categorized as dendrimers, conjugates, viral vectors, nanoparticles, microspheres, and hydrogels. In pilot-scale research as well as in lab settings, drug carriers are essential. Their application can significantly enhance the drug researcher's testing, and

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formulation. Drug carriers use a variety of tactics to enable targeted, prolonged, or controlled drug release. With its capacity to deliver medicines in a focused, regulated, and effective manner while minimizing adverse effects, drug carriers are a major improvement over conventional drug delivery technique[3].

CLASSIFICATION OF DRUG CARRIERS[4]

Based on their nature and characteristics, drug carriers may be broadly categorized in Table 1.

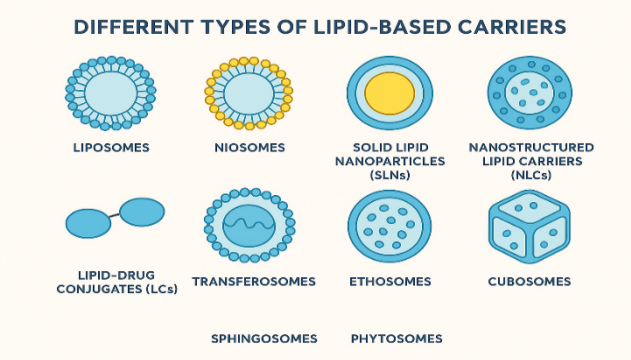
Table 1. Classification of drug carriers

Lipid based carriers	Polymeric carriers	Protein-mediated carriers	Inorganic drug carriers	Hybrid carriers
Liposomes	Polymer Micelles	Protein Micelles and Protein Based Hydrogels	Nanoparticles	Nanoparticles
SLN & NLC	Dendrimers	Silk Fibroin Nanoparticles and Elastin-Like Polypeptides	Quantum Dots	Polymeric Nano capsules
Transferosomes & Ethosomes	Nanogels	Protein Nanotubes and Ferritin Nanocages	Carbon Nanotubes	Bio-Nanocomposite Drug Carriers
Niosomes	Polymeric Nanoparticles	Transferrin Conjugates and Protein – Lipid Hybrid Nanoparticles		
Micro emulsion & Nano Emulsion	Hydrogels			
Lipid Nano capsules	Polymersomes			
SMEDDS	Biodegradable Polymeric Implants			

LIPID – BASED CARRIERS

These innovative medication delivery vehicles include liposomes, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLCs), all of which are made to encapsulate and protect active pharmaceutical compounds while enabling their regulated release. Additionally, lipid emulsions and exosomes have emerged as promising platforms for delivering nutrients and therapeutics, capitalizing on their biocompatibility and ability to mimic natural cellular processes. Lipid-based carrier is, on the whole, transforming medicine delivery by improving treatment efficacy and lowering adverse effects, making them a crucial field of study in pharmaceutical development. Lipid-based carriers fall into one of several categories (Fig.No.1).

Fig.No.1 Different types of lipid-based carriers



Liposomes

The first description of enlarged phospholipid systems was published in 1965 by a group of researchers. A number of encapsulated phospholipid bilayer structures, first known as "bangosomes" and then known as liposomes, were described in a matter of years[5]. Since liposomes have an aqueous core, they have core – self structures. By adjusting their size, composition, and degree of lamellarity, liposomes may be tailored to a variety of experimental and practical requirements, and they are also rather simple to create. By allowing for the incorporation of nanoparticles (NPs) of different sizes and natures, liposomes broaden the range of potential applications with unique features and traits. A good liposomal formulation product has three key ingredients: lipids to make a liposome, molecules to functionalize it, and a drug molecule that will be encapsulated. Liposomal formulations are used in a variety of therapeutic areas, including cancer treatment, fungal infections, analgesia, viral vaccines, and photodynamic therapy.

Solid – lipid nanoparticles (SLNs)

SLNs combine lipid-based parenteral emulsions' non-toxic and biodegradable properties with NPs' metallic and polymeric properties. They offer a safer, stable, and less expensive alternative to phospholipid-based liposomes for drug release. SLN are biodegradable, colloidal carrier systems with potential benefits such as targeted medication release, chemical degradation defense, carrier bio toxicity, organic solvent avoidance, and large-scale manufacturing issues. They can be generated using micro emulsion methods. SLNs, made of solid phase lipid and surfactant, are attractive commercial choices due to their natural

components. They range from 40 to 1000 nm, consisting of complex glyceride combinations, triglycerides, or waxes[6].

Nano structured lipid carrier (NLCs)

The NLC have the properties like enhanced drug entrapment efficiency, morphological characterization, and topical application, which are made of a solid lipid matrix with a specific amount of liquid lipid. The solubility and bioavailability of insoluble medications are two parameters that formulations like NLCs can enhance. NLCs are a novel kind of DDS and formulation that offers improved stability and loading along with the capacity to generate concentrated dispersions. There are several methods for making NLCs, including solvent displacement and micro emulsification[7].

Transferosomes

Since skin is permeable to tiny molecules and lipophilic pharmaceuticals but impermeable to big molecules and hydrophilic drugs, its permeability presents a problem for TDDS. Researchers have looked into vesicular systems like ethosomes, liposomes, niosomes, and transfersomes in an effort to get beyond this obstacle. Because of their flexible membrane and deformability, transfersomes stand out among these vesicular systems as being especially promising for non-invasive drug delivery. Numerous studies have examined their capacity to deliver anticancer drugs, insulin, corticosteroids, NSAIDs, and herbal therapeutics administered via the skin. The primary constituents of transfersomes, which are elastic nanovesicles, are phospholipids and edge activators (EAs). Cevc was the first to introduce this kind of vesicle in 1992. The carrier characteristics and the permeability enhancing abilities work in concert to allow these elastic vesicles to penetrate and penetrate the skin[8]. Extremely flexible and strong under stress, these are a complex aggregate. The vesicle's local composition and bilayer form independence allow it to be both self-regulating and self-optimizing. Transferosomal carriers are capable of transporting therapeutic compounds extending over a large area of solubility. Transfersomes are helpful as phospholipid vesicles for transdermal drug delivery. Their ultra-flexible and self-optimized membrane features allow them to deliver the medication through or into the skin with great efficiency, depending on how it is administered or applied.

Ethosomes

A vesicular nanocarriers with a comparatively high ethanol content (20–45%) is called an Ethosomes. One well-known permeation enhancer, ethanol, gives Ethosomes special qualities including strong flexibility and deformability, which enable them to deeply enter the skin and improve drug deposition and permeation. The impact of Ethosomes on the skin's ultrastructure was assessed using fluorescence microscopy[34]. These are pliable, squishy vesicles designed to improve active drug distribution. A new field of vesicular research for transdermal medication administration has been sparked by Ethosomes[10].

Niosomes

In recent years, niosomes have been developed, which are bilayer structures composed of lipid components (mainly cholesterol) and nonionic surfactants. They have an amazing array of uses. These vesicles offer a practical way to provide a range of medicinal substances., including gene materials, protein therapies, and chemical pharmaceuticals, because they have the potential to enhance the absorption of medications, based on research studies. This method provides desirable targeting effectiveness with low toxicity. Due to their non-immunogenic properties, niosomes can be engineered to deliver controlled release medications that promote therapeutic effectiveness by reducing adverse effects[11].

Nano emulsions

Nano emulsions, due to their beneficial traits like extensive surface area and nanoscale size for each volume unit, facilitate better distribution of active hydrophobic elements, promote greater absorption, and offer numerous benefits. in pharmaceutics, food, and cosmetics. High-pressure homogenization (HPH), micro fluidization, and ultra-sonication are examples of high-energy emulsification technologies that need to introduce significant mechanical force into the system to create droplets that are monodisperse. Nano emulsions exhibit improved component penetration, efficacy and low surface tension of the entire emulsion system[12].

Micro emulsions

Oil, water, a surfactant, and a co-surfactant are the ingredients of micro emulsions, which are thermodynamically stable mixtures. A range of micro emulsion formulations were developed and optimized using a 32-factorial design based on drug release, globule size, zeta potential, skin permeability, and transmittance percentage. Micro emulsions are the ideal alternative to oral drug administration. Furthermore, micro emulsions' increased thermodynamic activity helps to speed up the absorption of drugs[13].

Lipid Nano capsules

Because of their many benefits, lipid Nano capsules become a flexible platform to address those obstacles and effectively deliver various pharmacological payloads. Their properties can be adjusted to create the best possible brain drug delivery vehicle, and they can be made quickly, solvent-free, and scaled up. Because of their structural features and morphological traits, lipid Nano capsules (LNCs), which are lipid-based nanocarriers with uses in drug administration, diagnostics, and theranostic. They are made up of a hard outer layer composed of saturated fats and mixing agents surrounding a liquid center. A layer of water-attracting and water-repelling surfactants surrounds a fatty center composed of medium chain triglycerides in lipid Nano capsules, which are tiny particles created through a solvent-free, energy-efficient phase inversion method[14].

Self – micro emulsifying drug delivery system (SMEDDS)

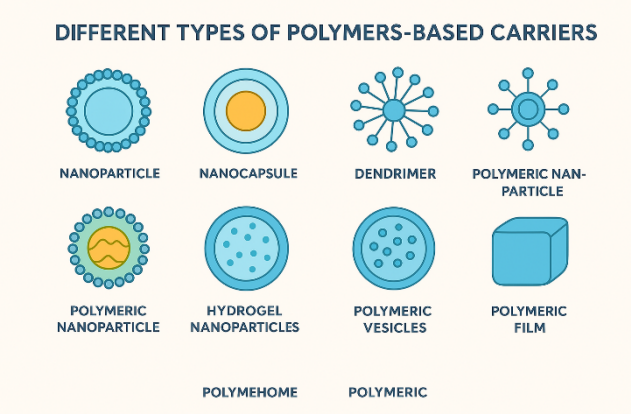
When an isotropic mixture of lipid, surfactant, and co-surfactant comes into contact with an aqueous medium with modest agitation, the SEDDS generates a fine emulsion. SEDDS is a type of oral lipid dosage. After being diluted with the aqueous phase, this blend of oils and surfactants can be gently stirred to make fine oil in water (o/w) emulsions. Because of this characteristic, For the oral delivery of hydrophobic drugs that are adequately soluble in

oils or oil/surfactant mixes, SEDDS are a helpful choice. SEDDS improves the solubility of drugs by providing a large surface area for the drug to divide between the oil and gastrointestinal fluids, as it spontaneously forms an emulsion in the stomach, releasing the drug in the form of tiny oil droplets. In 1985, SEDDSs were introduced as the first practical way to enhance lipophilic drug distribution through oral ingestion. The cutaneous route has largely remained unaffected by the decades spent developing SEDDS for the oral, rectal, vaginal, ophthalmic, and nasal modes of delivery. (SEDDS) are a promising method for self-emulsifying drugs to improve their oral bioavailability. The size of droplets in the SEDDS was illustrated utilizing a ternary phase diagram[15].

POLYMER – BASED CARRIERS

In modern drug delivery, polymer-based carriers provide improved solubility, stability, targeted delivery, and controlled release. Different systems include polymeric micelles that encapsulate hydrophobic drugs within their core, dendrimers with highly branched architectures for multiple drug attachments, nanogels that act as cross-linked networks responsive to environmental stimuli, and Polymersomes that resemble vesicles capable of carrying both hydrophilic and hydrophobic drugs (Fig.No. 2). In addition, polymer-drug conjugates enhance drug stability and circulation, while implantable systems such as reservoir and monolithic types allow sustained release. The release of drugs from stimuli-responsive polymers is triggered by factors such as pH or temperature, and nano sponges exhibit high drug-loading capacity with prolonged release times. Together, these polymer-based nanocarriers represent advanced strategies for efficient and targeted therapeutic delivery.

Fig.No. 2 Different types of polymers-based carriers[16]



Polymer micelles

At the CMC, amphiphilic polymers spontaneously organize into micelles. A polymeric micelle is formed when an amphiphilic polymer combines a water-attracting head with a water-repelling tail. The shapes of micelles can vary, including spheres, tubes, reversed micelles, bottle-brush structures, among others, influenced by solvent conditions and the characteristics of the hydrophilic and hydrophobic parts. Various methods such as dilution, freeze-drying, evaporation of solvents, dialysis, and oil-in-water emulsification are employed to create micelles. Micelles arise through the self-organization of grafted polymers, block copolymers, and random block copolymers. The micelles are characterized using dynamic light scattering (DLS), Atomic force microscopy (AFM), small-angle X-ray scattering (SAXS), small-angle neutron scattering (SANS), transmission electron microscopy (TEM). Furthermore, it is believed that polymeric micelles are advantageous because of their kinetic stability and robust core–shell structure. Because of its great efficacy in retaining drugs in tissue, preventing enzyme breakdown, and increasing the cellular absorption mechanism. Changes in solvent polarity and temperature promote copolymer micelle self-assembly in an experimental setting. Through the conversion of polymeric micelles, self-assembly occurs in this thermodynamically directed process[17].

Dendrimers

The Greek words "dendron" and "meros," which translate to "tree" and "parts," are combined to form the name "dendrimer," which explains their branching structure. Dendrimers' nanometric size has led to their consideration as potential new drug delivery mechanisms since their early stages. The relationship between drugs and dendrimers can be covalent or non-covalent. Non-covalent interactions include electrostatic interactions between charged medications (or DNA, RNA, or siRNA) and the surface, as well as simple encapsulation inside dendrimers that improves the solubility of lipophilic drugs in water. Covalent associations can be formed by cleavable bonds that should only be broken when they reach the target, which is frequently malignant cells, or by stable bonds, especially for dendrimers that are thought to be active in and of themselves. Dendrimers are three-dimensional macromolecules and these structures show multivalence, narrow molecular weight dispersion, customizable size and shape features, and a high degree of molecular homogeneity. Together, these physicochemical properties and improvements in biodegradable backbone design have given dendrimers a wide range of uses in formulation science and nano pharmaceutical advancements[18].

Nanogels/Hydrogels

By enhancing the stability of pharmaceuticals and enabling their regulated release, nanomaterials can open up new avenues for the treatment of illness. Hydrogels that range in size from 1 to 1000 nm are called nanogels. By modifying the gel's volume, water content, colloidal stability, mechanical strength, and other physical and chemical properties, they may sense and respond to environmental signals. Additionally, they may transport and protect the active ingredients that are contained within. Due to their outstanding stability and tunability, nanogels have been extensively employed in medication delivery. The Crosslinked polymeric particles, known as micro gels or nanogels, can be categorized as hydrogels if they are made of chains of water-soluble or swellable polymers. They have favorable mechanical qualities, biocompatibility, and a high-water content. The capacity of stimulus-responsive nanogels to encapsulate bioactive medicines, their high

stability for prolonged blood circulation, and the controlled release and site-specific targeting of loaded drugs, which is regulated by environmental stimuli[19].

Polymeric nanocarriers

Nanoparticles with a size ranges from 1 to 1000 nanometer are known as polymeric nanoparticles, and can have active substances adsorbing on their surfaces or trapped within their walls. Colloidal systems composed of synthetic or natural polymers are known as polymer-based nanoparticles. Compared to other nanocarriers like liposomes, micelles, and inorganic Nano systems, they provide a number of advantages, including the ability to scale up and the use of Good Manufacturing Practices (GMP) in the production process. Emulsification, which involves dripping an organic solution containing the monomer and cargo into an aqueous solution, is one of the most straightforward techniques for creating polymeric nanoparticles with encapsulated cargo. The cargo is simultaneously trapped inside the polymeric nanoparticle as spherical droplets of organic fluid stay suspended, enabling the hydrophilic end of the monomer to self-assemble towards the watery exterior in a manner akin to lipids[20].

Polymersomes

Similar to conventional liposomes, polymerosomes are self-assembled nanoscale structures made of amphiphilic block copolymers that have special benefits since they are polymeric. Both hydrophilic and hydrophobic molecules can be encapsulated in these vesicles because they have an aqueous core encircled by a membrane made of hydrophilic and hydrophobic blocks. They are appealing for a number of uses, such as medication administration, gene therapy, and bio sensing, due to their adjustable size, shape, and mechanical characteristics. Because their polymeric membranes are less likely to fuse and leak, Polymersomes are more stable than liposomes and can circulate for longer periods of time in biological systems. Additionally, Polymersomes can be functionalized to easily change their surface characteristics, which enables targeted delivery to specific tissues or cells. This flexibility is especially beneficial in cancer treatment since targeted drug delivery can lower adverse effects and enhance therapeutic effectiveness[21].

Biodegradable polymeric implants

Medical implants made of biodegradable polymers are intended to offer therapeutic advantages obviating the need for surgical removal as it gradually decomposes naturally in the body. Polymers like polylactic acid (PLA) and polyglycolic acid (PGA), which are biocompatible and encourage tissue regeneration, are commonly used to make these implants. They are appropriate for use in tissue engineering, medication administration, and bone fixing because their rates of degradation can be adjusted to correspond with healing processes. These implants' regulated release of therapeutic substances improves treatment outcomes and reduces adverse effects. For improved performance, ongoing research aims to improve their mechanical characteristics and degradation profiles.

Polymeric prodrugs

Polymeric prodrugs are novel drug delivery systems aim to increase the bioavailability and therapeutic effectiveness of pharmacologically active compounds. These prodrugs can enhance solubility and stability while enabling regulated release by conjugating medications to biocompatible polymers. Because the medicine is only released in the targeted area, the polymeric structure enables site-specific targeting and lowers systemic toxicity. A variety of polymers, including PLA and PEG, are used to improve the drug's pharmacokinetics and customize the release profile. The potential of polymeric prodrugs in advanced treatments is demonstrated by ongoing research into their application in cancer treatment and chronic illnesses.

Stimuli – responsive polymers

Stimuli-responsive polymers are increasingly employed in drug-delivery systems due to their ability to control the release of medicinal compounds in response to triggers like temperature, pH, or light. The smart polymers are modifying their permeability, swelling behavior, or solubility through structural changes, which enables the medication release at target site, including tumors or inflammatory tissues. For example, while thermos responsive polymers can react to changes in body temperature, pH-sensitive polymers can release medications in the acidic conditions seen in many malignancies. Stimuli-responsive polymers are a viable option for sophisticated drug delivery applications because of their focused strategy, which maximizes therapeutic efficacy while reducing side effects[22].

Nano sponges

Usually composed of biocompatible polymers, Nano sponge drug carrier systems are novel delivery systems distinguished by their porous, sponge-like architectures. Numerous therapeutic substances, including hydrophobic medications, can be encapsulated in these nanosized carriers and released in a regulated manner. Due to the porous structure of Nano sponges, they are able to hold a lot of drugs and release them over a long period of time. They can also be functionalized to improve targeting capabilities, ensuring that drugs reach certain tissues or cells, including malignancies. Recent studies suggest that Nano sponges may improve the pharmacokinetics and decrease the adverse effects of anticancer medications and other therapies[23].

PROTEIN-BASED DRUG CARRIERS

Albumin nanoparticles are a potential drug delivery system because they are biocompatible, biodegradable, and enhances the solubility and stability of drugs. These nanoparticles, which are composed of human or bovine serum albumin, are able to efficiently encapsulate a variety of drugs, including proteins and chemotherapeutics (BSA or HSA). To improve accumulation in particular tissues or tumors, their surface can be readily altered for targeted administration. Albumin's special qualities, like its capacity to bind fatty acids and other ligands, help to enhance pharmacokinetics and enable the controlled release of medications. All things considered, albumin nanoparticles

offer a flexible way to improve medication administration and therapeutic effectiveness.

Antibody drug conjugates (ADCs)

A number of factors, including mAb specificity, drug potency, linker technology, and stoichiometry and location of conjugated medicines, have been meticulously optimized in recent years, leading to significant advancements in antibody-drug conjugates. An innovative treatment format with the potential to revolutionize antibody-drug conjugate (ADC), which links a humanized or human monoclonal antibody with highly cytotoxic small molecules (payloads) through chemical linkers, is the treatment for cancer chemotherapy[24].

Protein micelles and protein-based hydrogels

Advanced drug carrier technologies that make use of proteins' natural characteristics to improve drug delivery effectiveness include protein micelles and protein-based hydrogels. Hydrophobic medications can be encapsulated in protein micelles, which are created when amphiphilic proteins self-assemble, increasing the drugs' solubility and bioavailability. Because of their ability to react to physiological cues, these micelles can be released in specific locations under control. Protein-based hydrogels, on the other hand, provide a sustained release profile and a three-dimensional network that can hold a lot of water and medications. Their biocompatibility and adjustable mechanical characteristics ensure that they are suitable for a variety of applications, including tissue engineering and localized medication delivery. Both systems have the potential to be functionalized to enhance targeting and lessen adverse effects, providing promising answers in contemporary medicine. Hydrogels and protein micelles can be functionalized to enhance targeting, reduce off-target effects, and increase therapeutic index when administered. They are potential platforms in the fields of drug delivery and nanomedicine because of their special qualities[25].

Silk fibroin nanoparticles and elastin-like polypeptides (ELPs)

ELPs are sophisticated drug carrier systems with special qualities for regulated drug delivery. ELPs can experience reversible phase shifts in response to temperature variations because they mirror the natural elastin protein. This property improves the bioavailability and therapeutic effectiveness of hydrophobic medications by enabling their encapsulation and regulated release. Derived from silk proteins, silk fibroin nanoparticles have remarkable mechanical strength, biocompatibility, and biodegradability. They can offer prolonged release patterns and encapsulate a range of medicinal ingredients. Silk fibroin nanoparticles and ELPs are both intriguing prospects for use in regenerative medicine and cancer treatment because they can be altered to improve their targeting properties[26].

Protein nanotubes and ferritin Nanocages

There are two promising drug delivery methods that take benefit of their distinct structural characteristics. Various medicinal substances, including biomolecules and chemotherapeutics, can be contained within a spherical Nanocages constructed of ferritin, a naturally occurring iron storage protein. In addition to their biocompatibility, ferritin Nanocages can release drugs in response to specific stimuli, making them an excellent option for targeted therapy and imaging. Proteins, on the other hand, self-assemble to form tubular structures called protein nanotubes. By facilitating the regulated release of medications and being specifically tailored for targeting, these nanotubes can increase the therapeutic index while reducing adverse effects. Both technologies provide flexible drug delivery platforms that may find use in regenerative medicine and cancer treatment.

Transferrin conjugates and protein – lipid hybrid nanoparticles

Advanced drug delivery methods that take advantage of both proteins and lipids for targeted therapy include transferrin conjugates and protein-lipid hybrid nanoparticles. Protein-lipid hybrid nanoparticles provide a flexible drug delivery platform by fusing the stability of lipids with the biocompatibility of proteins. Both hydrophilic and hydrophobic medications can be encapsulated by these nanoparticles, enhancing pharmacokinetics and enabling controlled release. Because of its hybrid nature, the surface can be modified to improve targeting and decrease immune recognition, which increases the effectiveness of treatment. Together, transferrin conjugates and protein-lipid hybrid nanoparticles offer intriguing strategies for improving drug delivery and therapeutic outcomes for a variety of diseases[27].

INORGANIC DRUG CARRIERS

Inorganic drug carriers, such as silica and gold nanoparticles, promote drug delivery by enhancing stability, facilitating tailored release, and accommodating different therapeutic agents, optimizing efficacy and minimizing side effects. Inorganic nanoparticles Because of their exceptional benefits in nanomedicine, inorganic nanoparticles are becoming more and more popular as adaptable drug delivery systems., which include enhanced stability, size adjustability, and the potential to carry a range of medicinal compounds. Among the commonly used materials are calcium phosphate nanoparticles, silica, gold, silver, iron oxide, and zinc oxide. By increasing the solubility and bioavailability of hydrophobic medications, these carriers can make it easier for the body to distribute them to the right places. The ability of inorganic nanoparticles to modify their surfaces, which enables the attachment of targeting ligands and improves the selectivity of drug delivery to particular cells, including cancer cells, is a key benefit. In order to maximize effectiveness and minimize adverse effects, they can also offer regulated release profiles, which guarantee that therapeutic chemicals are given at ideal rates[28].

Quantum Dots (QDs)

QDs are having gained interest as drug delivery systems in nanomedicine due to their unique optical and electrical properties. Because these nanoparticles may be engineered to emit certain light wavelengths, they are helpful for imaging and tracking medication administration in vivo. Anticancer medications and biomolecules are among the

therapeutic substances that QDs can encapsulate, improving their stability and solubility. The surface modifiability of quantum dots is one of their primary advantages since it allows targeting ligands to adhere and allows for targeted distribution to diseased and malignant cells. Additionally, QDs can improve treatment outcomes by enabling regulated drug release through stimuli-responsive mechanisms. Despite its potential, more research is required due to worries about QDs' toxicity and biocompatibility. All things considered, quantum dots offer a promising platform for cutting-edge medication delivery systems.

Carbon nanotubes (CNTs)

In nanomedicine, CNTs have unique structural features, high surface area, and extraordinary mechanical strength. These cylindrical nanostructures, with their improved stability and solubility, are capable of encapsulating a diverse range of therapeutic molecules, including proteins, nucleic acids, and small drugs. Targeting ligands will connect to functionalized carbon nanotubes (CNTs), enabling targeted delivery to sick cells, including cancer cells. This targeted approach increases medicinal efficacy while decreasing adverse effects. Furthermore, CNTs can improve treatment results by enabling regulated drug release through temperature-responsive or pH-responsive mechanisms. Additionally, studies have demonstrated CNTs' potential for multimodal therapy, which combines imaging, therapy, and medication delivery. However, before clinical application, careful research is required due to probable toxicity and biocompatibility issues. All things considered, in the emerging field of nanomedicine, carbon nanotubes have great promise as adaptable drug delivery methods[29].

Hybrid Carriers

Hybrid carriers mix characteristics of various materials, such polymers and nanoparticles, in order to increase the effectiveness, targeting, and regulated release of medication delivery systems, which ultimately results in better therapeutic results[30].

Hybrid nanoparticles

By integrating the advantageous properties of different materials—such as polymers and inorganic compounds hybrid nanoparticles have significantly enhanced the efficiency of drug delivery systems. The use of multiple integrated components significantly improves the stability, bioavailability, and targeted delivery of drugs. These nanoparticles can be engineered to respond to specific stimuli, including variations in temperature or pH, enabling site-specific drug release at tumors or other diseased areas. Additionally, targeting ligands may be conjugated to their surfaces to enhance selectivity toward diseased tissues and reduce off-target effects. Recent studies have also emphasized the potential of hybrid nanoparticles in advanced therapeutic applications such as gene delivery and immunotherapy, showcasing their versatility and promise in next-generation drug delivery technologies. All things considered, hybrid nanoparticles offer a flexible foundation for improving medication delivery methods in customized medicine.

Polymeric nano capsules with inorganic cores

Advanced drug delivery technologies that combine the advantages of inorganic and organic materials are polymeric nano capsules with inorganic cores. To improve stability and biocompatibility, these nano capsules have a polymeric shell encasing an inorganic core, like metal nanoparticles or silica. The inorganic core enhances imaging capabilities and facilitates photo thermal therapy, while the polymeric shell designed to respond to specific conditions, such as changes in pH or temperature. All things considered, this hybrid approach has a lot of potential to increase therapeutic efficacy[31,32.33].

Bio nanocomposite drug carriers

Bio-nanocomposite drug carriers are novel delivery methods that improve drug targeting and efficacy by combining natural polymers with inorganic or organic nanoparticles. The components work in concert to provide targeted delivery, reduce adverse effects, and improve therapeutic results. Drug release profiles can be further optimized by customizing bio nanocomposites to react to certain stimuli, such as pH or temperature. They can be applied to tissue engineering, cancer treatment, and vaccine delivery due to their versatility[34].

FUTURE PROSPECTS AND CHALLENGES

The future of biocompatible drug carriers is incredibly promising, with significant potential to revolutionize the pharmaceutical landscape. As the understanding of nanotechnology, materials science, and drug delivery mechanisms advances, the design of more sophisticated, efficient, and targeted drug carriers will emerge. A promising approach involves designing multifunctional carriers capable of delivering multiple drugs or therapeutic agents simultaneously, thereby enabling effective combination therapies for complex conditions such as cancer, neurodegenerative, and autoimmune diseases. Furthermore, progress in biomaterials including smart polymers and stimuli-responsive materials—has made it possible to design carriers that release drugs in response to specific environmental cues such as pH, temperature, or enzyme activity, thereby improving the precision and control of therapeutic delivery.

Personalized medicine is another key area where biocompatible drug carriers are expected to have a major impact. The ability to tailor drug delivery systems to the individual patient’s genetic and molecular profile could optimize treatment efficacy while minimizing adverse effects. Moreover, the continued development of non-invasive delivery methods could further improve patient compliance and the overall treatment experience.

Despite the enormous potential, several challenges persist in the development and clinical translation of biocompatible drug carriers. One of the primary obstacles is ensuring the safety and long-term stability of these carriers. While biocompatibility suggests that the materials do not provoke adverse immune responses, their degradation products, long-term accumulation in the body, and potential toxicity still require thorough evaluation. The risk of unforeseen side effects, such as off-target effects or immune reactions,

remains a concern for both new materials and existing carriers.

The scalability of the production of biocompatible drug carriers is another significant challenge. Many of the synthesis methods for nanoparticles, liposomes, or polymers are highly specialized and often difficult to scale up for large-scale commercial production. Standardization and reproducibility of drug carriers are crucial to ensuring consistent quality and performance across batches, which can be particularly challenging when dealing with complex, multifunctional carriers. Additionally, the regulatory approval process for drug carriers can be complex and time-consuming, requiring extensive preclinical and clinical testing to meet stringent safety and efficacy standards. Regulatory bodies must establish clear guidelines for the evaluation of novel drug carriers, particularly as new materials and delivery mechanisms emerge. This regulatory uncertainty can slow down the development of promising drug delivery systems. Lastly, the economic and logistical aspects of manufacturing biocompatible carriers pose another challenge. The cost of producing these advanced drug delivery systems may limit their accessibility, especially in low-resource settings. Ensuring cost-effectiveness without compromising the quality and efficacy of the carriers will be crucial for their widespread adoption.

CONCLUSION

Biocompatible drug carriers mark a major advancement in drug delivery by improving stability, targeted action, and minimizing side effects. Despite their potential, challenges such as safety, degradation, regulatory issues, and large-scale production remain. Continued research in materials science and pharmacology is essential to refine carrier design, enhance drug compatibility, and establish clinical standards. Their evolution promises more personalized, effective, and safer therapies in modern healthcare.

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