REVIEW ARTICLE

A Comprehensive Review on the Recent Applications and Development in Nanocarriers

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Abstract

Nanocarriers have shown promise as effective delivery vehicles. Controlled release, and enhanced efficacy of therapeutics, imaging agents, and functional payloads in various applications. An overview of the synthesis processes, characterization methodologies, and uses of nanocarriers in agriculture, environmental sustainability, and healthcare is given in this abstract. Common types of nanocarriers, including liposomes, polymeric nanoparticles, dendrimers, and metal-based nanoparticles, are discussed, along with their synthesis methods and key properties. Characterization techniques such as transmission electron microscopy, dynamic light scattering, Fourier-transform infrared, and cell viability assays are highlighted for evaluating the physicochemical properties, stability, and biocompatibility of nanocarriers. Applications of nanocarriers in drug delivery, diagnostics, gene therapy, agriculture, and environmental remediation are explored, showcasing their potential to address critical challenges and improve human health and environmental sustainability. Despite their promise, nanocarriers face challenges such as biocompatibility concerns, stability issues, and regulatory considerations, necessitating interdisciplinary collaboration and rigorous safety assessments for their successful translation into practical use. Looking ahead, nanocarriers hold tremendous promise for personalized medicine, combination therapies, smart and stimuli-responsive systems, theragnostic, and sustainable solutions, shaping a future where precision, efficiency, and tailored solutions transform healthcare, agriculture, and environmental management. To fully utilize nanocarrier technology and advance science, health, and technology for the good of society, more funding, cooperation, and research will be needed.

Key words: Application, biocompatibility, nanocarriers, stimuli-responsive system

INTRODUCTION TO NANOCARRIERS: REVOLUTIONIZING DELIVERY SYSTEMS

Recently, there have been significant developments in nanotechnology, which have accelerated the creation of creative solutions to problems in various industries, from agriculture to healthcare.[1] At the forefront of this transformation are nanocarriers, nanoscale vehicles engineered to efficiently and precisely transport and deliver a payload of therapeutic agents, imaging agents, nutrients, or other functional payloads to target areas. Nanostructured materials having exact control over size, shape, composition, and surface qualities are known as nanocarriers, also sometimes called nanoparticles or nanocontainers. Because of their small size—typically a few nanometres to several hundred nanometres—they can interact at the molecular and cellular levels with biological systems, creating novel prospects for specialized applications.[2]

IMPORTANCE AND APPLICATION

Nanocarriers are important because they can get past obstacles that conventional delivery systems can't, such as

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low solubility, low bioavailability, non-specific targeting, and quick bodily clearance.[3] Nanocarriers are transforming the delivery of medicines, imaging agents, and functional molecules by encapsulating or conjugating payloads within or onto their surfaces, improving stability, extending circulation duration, and enabling controlled release kinetics.

Medicine and drug delivery

In the realm of medicine, nanocarriers are extremely promising since they can address issues with drug delivery such as focused therapy, prolonged release, and improved therapeutic efficacy while reducing systemic side effects.[4] They make it possible for drugs to be precisely targeted to particular tissues or cells by passing through biological barriers, such as the blood-brain barrier and the tumor microenvironment.

Diagnostic imaging

Nanocarriers enable high-resolution imaging modalities such as positron emission tomography (PET), computed tomography (CT), and magnetic resonance imaging (MRI), which are adaptable platforms for the delivery of contrast agents in diagnostic imaging.[5] Early illness detection and precise therapy monitoring are made possible by their capacity to accumulate preferentially at target areas, which improves imaging sensitivity and specificity.

Agricultural applications

In addition to being used in healthcare, nanocarriers are also used in agriculture to deliver insecticides, fertilizers, and plant growth regulators precisely where they are needed. Sustainable agricultural methods are facilitated by nanocarriers, which improve efficacy, decrease environmental contamination, and stabilize agrochemicals by encasing them in nanostructures.[6]

Cosmetics and personal care

Nanocarriers are essential for the transport of active substances, such as vitamins, antioxidants, and moisturizers to the skin with improved penetration and bioavailability; they are also essential for cosmetics and personal care products.[7] They are more effective and satisfy customers because of their compact size, which also promotes longer release and better skin absorption.

TYPES OF NANOCARRIERS

Liposomes

Liposomes are phospholipid bilayers assembled into spherical vesicles that resemble biological membranes.

They can contain both hydrophilic and hydrophobic medications in their lipid bilayer aqueous cores and they are biocompatible.

When it comes to medication delivery, liposomes are flexible since they can be used for targeted distribution, continuous-release, or triggered release.[8]

Polymer based nanoparticles

Polyethylene glycol (PEG), chitosan, albumin, albumin, and various manmade or natural polymers, such as poly (lactic-co-glycolic acid) (PLGA) can make up polymeric nanoparticles can be produced with precise control over their size, shape, and surface characteristics.

One of the benefits of using polymeric nanoparticles is that they can target tissue or cells and provide prolonged drug release while shielding payloads from degradation.[9]

Dendrimers

With a well-defined structure made up of a core, branches, and surface functional groups, dendrimers are highly branched macromolecules.

They can precisely adjust surface chemistry, size, and form because of their unique design.

Because of its great loading capacity, multivalency, and capacity to cross biological barriers, dendrimers are used in medication administration, imaging, and diagnostics.[10]

Metal-organic oxide nanoparticle

Metal nanoparticles, such as gold and silver, or metal oxides, such as iron oxide and silica, have special optical magnetic, and catalytic capabilities as well [Table 1].

Biosensing, targeted medication delivery, imaging, and cancer therapy are just a few of the uses for them.[10]

Multifunctional platforms with both therapeutic and diagnostic capabilities can be created with metal-based nanoparticles [Figure 1].

Carbon-surface carrier system

Graphene, graphene oxide, and fullerenes are examples of carbon-based nanocarriers.

Due to their extraordinary mechanical, electrical, and thermal qualities, these nanoparticles are appealing for a wide range of uses.[11]

Table 1: Types of nanocarriers with their special characters

Nanocarrier types	Special characteristics	Examples
Liposomes	Encapsulation of hydrophilic and lipophilic drugs	Doxil
Polymeric nanoparticles	Controlled release kinetics	PLGA nanoparticles
Dendrimers	Highly branched structure for practice drug loading	Poly (amidoamine) PAMAM
Carbon nanotubes	High except for the ratio for targeted drug delivery	Single-walled carbon nanotubes
Micelles	Self-ascending structure for solubilizing hydrophobic drugs	SDS micelles
Nanocrystals	Enhanced the drug solubility and stability	Abraxane
Mesoporous silica nanoparticles	High surface area of drug loading and targeting	MCM-41

PLGA: Poly (lactic-co-glycolic acid)

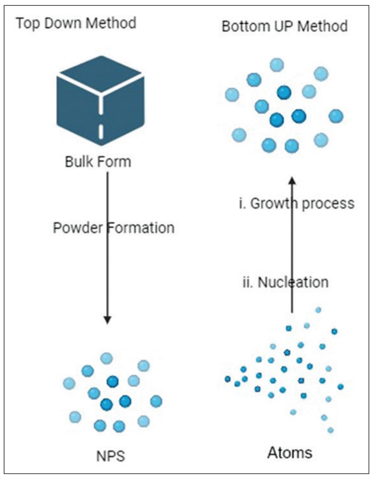

Figure 1: Top down-bottom-up method

The fields of mechanical delivery, biosensing, tissue engineering, and biocompatible implants are all investigating the use of carbon-based nanocarriers.[12]

Blended nanocarriers

To maximize synergistic effects and get beyond individual material restrictions, hybrid nanocarriers blend multiple types of materials.

Lipid polymer, dendrimer nanoparticles, and liposome polymer hybrids are a few examples.

For cutting edge, applications, hybrid nanocarriers provide specialized qualities, such as improved stability, controlled release, and multifunctionality.

SYNTHESIS METHOD

Different nanocarrier types and desired qualities require different synthesis techniques.

Bottom-up

Chemical precipitation is the process of creating nanoparticles by carefully removing precursor components from a solution. This process is frequently employed to create metal and metal oxide nanoparticles.[13]

The Sol-Gel method creates nanoparticles by hydrolyzing and condensing metal alkoxides or other precursors to create a sol that is later dried to create a gel. This technique is frequently applied in the synthesis of silica nanoparticles.

Emulsion to create polymer nanoparticles, polymerization entails the polymerization of monomers in the presence of initiators and surfactants. This technique is frequently applied in the synthesis of polymeric nanoparticles, including PEG and PLGA nanoparticles.

Top-down

Mechanical Milling: This method involves reducing bulk materials to nanoscale size by mechanically grinding or milling them. Metals, metal oxide, and other material nanoparticles are frequently created using this technique.

Lithography: This is the process of patterning substrates at the nanoscale using lithographic methods. This technique is frequently applied to the synthesis of nanocarriers with exact control over size and form, including silicon-based nanoparticles.

The method of electrospinning involves spinning polymer melts or solutions using an electric field to create nanofibers, which can subsequently be further treated to create nanoparticles or nanocomposites. This process is frequently employed in the synthesis of nanocarriers based on nanofibers.[14]

Methods of self-assembly

To generate micelles, which can enclose hydrophobic payloads in their core, amphiphilic molecules must first self-assemble in a solution. Liposomes and other lipids-based nanocarriers like micelles are frequently created using this technique.

Creating multilayered thin films or nanoparticles through the progressive adsorption of oppositely charged polymers or other materials onto a substrate or template is known as "layer-by-layer assembly.[15]" Polymer capsules, hybrid nanocarriers, and dendrimers are frequently synthesized using this technique.

Techniques for green synthesis

Utilizing biological entities, such as fungi, plants, bacteria, or enzymes to create nanoparticles from metal salts or other precursors is known as biological synthesis. This process is frequently employed to create environmentally friendly, biocompatible nanoparticles.

Using plant extracts or phytochemicals as reducing and stabilizing agents during the synthesis of nanoparticles is known as "plant-mediated synthesis.[16]" Metal and metal oxide nanoparticles are frequently synthesized using this technique.

Characterization techniques

When assessing the characteristics and functionality of nanocarriers, characterization methods are essential.

Examining morphology

Transmission electron microscopy (TEM)

This technique produces high-resolution images of nanocarriers that make it possible to see their morphology, size, and form at the nanoscale.

The comprehensive surface morphology and three-dimensional imaging of nanocarriers that scanning electron microscopy (SEM) provides sheds light on their structural characteristics.

Atomic force microscopy (AFM)

Enables surface topography and high-resolution imaging of nanocarriers in a variety of settings, including liquid.[17]

Dimensions and distribution of size

Dynamic light scattering (DLC) measures the hydrodynamic size and size distribution of nanocarriers in solution to yield data on polydispersity and particle size distribution. Static light scattering (SLS) is based on the light scattering intensity, this technique provides absolute measurements of particle size and is a useful addition to DLS for accurate size determination. Nanoparticles tracking analysis (NTA) tracks the Brownian motion of individual nanoparticles in a solution to determine their size distribution and concentration.[18]

Constituent chemistry

Assists in material identification and surface chemistry characterization, Fourier transform infrared spectroscopy (FTIR) detects functional groups and chemical bonds present in nanocarriers. Surface chemistry and functionalization can be better understood by using X-ray photoelectron spectroscopy (XPS), which provides data on the elemental composition and chemical states of nanocarrier surface energy dispersive X-ray spectroscopy (EDS/EDX). This technique, which complements TEM and SEM for elemental napping, uses X-ray fluorescence to analyze the elemental composition of nanocarriers.

Surface tension

Zeta Potential Analysis: Indicates surface charge and stability by measuring the electrophoretic mobility of nanocarriers in solution. Analysis of zeta potentials provides light on possible connections between colloidal systems and their stability.[19]

Studies on stability

Centrifugation

Evaluate the stability of sedimentation and the tendency of nanocarriers to aggregate when subjected to centrifugal force, offering insights on the stability of colloidal matter.

Storage stability

Assesses how nanocarriers change over time in terms of size, shape, and physicochemical characteristics under varied storage circumstances (e.g., temperature, humidity).

Loading and releasing drugs

Drug delivery applications rely on High-Performance Liquid Chromatography (HPLC) to quantify drug loading in nanocarriers and track drug release kinetics from nanocarrier formulations.

Biocompatibility and harmfulness

Tests for cell viability

Utilize cell-based tests, such as MTT, Alamar Blue, or LDH release assays to evaluate the cytotoxicity and biocompatibility of nanocarriers.

The biodistribution, pharmacokinetics, and *in vivo* behavior of nanocarriers can be assessed using imaging techniques, such as fluorescence imaging, MRI, and PET.

APPLICATION OF NANOCARRIERS

The distinct characteristics of nanocarriers have transformed numerous domains by permitting focused distribution, regulated discharge, and improved medicinal effectiveness.

Medicine delivery framework

Targeted drug delivery reduces side effects and enhances therapeutic results by using nanocarriers to deliver medications just to stick areas or cells. Sustained Release: By allowing for the regulated and prolonged release of medications over time, nanocarriers can lower the frequency of dosage and increase patient compliance. Improved Bioavailability: By encasing weakly soluble medications, nanocarriers can increase the solubility and bioavailability of certain medications, thereby boosting their therapeutic efficiency.

Imaging substances in diagnosis

Contrast agents

In imaging modalities including CT, MRI, and ultrasound, the contract is improved by using nanocarriers loaded with imaging agents, such as gadolinium, iron oxide, or gold nanoparticles. Fluorescent Probes: To diagnose and track diseases, high-resolution fluorescence imaging is made possible by nanocarriers functionalized with fluorescent dyes or quantum dots.

Gene delivery and gene therapy

To treat genetic abnormalities, cancer, and infectious diseases, therapeutic nucleic acids, such as DNA, RNA, or small interfering RNA (siRNA) can be delivered to target cells using nanocarriers. This allows for gene editing, silencing, or expression notification.

Application in agriculture

Delivery of pesticides

By preventing pesticides from degrading, increasing their stability, and enabling regulated release. Nanocarriers help to reduce pollution in the environment and increase the effectiveness of pest control measures. Delivery of Nutrients: By delivering nutrients, fertilizers, or plant growth regulators to crops, nanocarriers increase crop output, nutrient uptake efficiency, and resilience to environmental stressors.

Personal care items and cosmetics

Cosmetics, anti-aging creams, and sunscreen formulas benefit from the enhanced penetration, bioavailability, and efficacy of active compounds including vitamins, antioxidants, peptides, and moisturizers that are delivered to the skin through nanocarriers. Hair Care Products: By providing better absorption and retention of nourishing agents and hair treatments, nanocarriers increase the delivery of these products, improving the appearance and health of hair.

Delivery of vaccinations

Enhancing immune responses and vaccine efficacy, nanocarriers enable the transfer of adjuvants and antigens to immune cells. Personalized treatment, cancer immunotherapy, and the development of innovative vaccine formulations are made possible by them.

Therosclerotic

Theranostic applications—where diagnosis, therapy, and longitudinal illness monitoring take place concurrently—are made possible by nanocarriers that combine therapeutic and diagnostic capabilities. With this method, many conditions can be treated with precise and customized strategies.

CHALLENGES AND LIMITATION

Nanocarriers have a lot of potential for usage in many different applications, but before they can be successfully used in real-world applications, they must overcome several obstacles and restrictions.

Biocompatibility and toxicological issues

Biological systems may experience negative reactions because of immunological responses or cytotoxic effects caused by nanocarriers. Biocompatibility and toxicity profiles can be influenced by material selection, surface changes, and degradation of products.

Issues with stability

The stability and performance of nanocarriers can be impacted over time by aggregation, degradation, or physiochemical property changes. It is necessary to address issues related to stability preservation throughout transportation, storage, and biological interactions.

Off-target consequences

Unintentional adverse effects and reduced treatment efficacy can result from non-specific interactions between biological components and nanocarriers. Improving the safety and effectiveness of nanocarriers requires strategies that maximize on-target effects while reducing targeting specificity.

Barriers related to biology

Biological barriers that impede the ability of nanocarriers to reach target areas include mucosal barriers, the blood-brain barrier, and cellular absorption processes. To increase the effectiveness of nanocarrier delivery, methods for getting beyond biological barriers such as surface altercations, targeted ligands, and stimuli-responsive formulations are required.

Manufacturers challenges with scalability

Complex procedures, specialized tools, and experience are frequently needed for the production and scaling up of nanocarriers. Commercialization and large-scale manufacturing are hindered by issues with quality control, reproducibility, and regulatory compliance.

Methods of clearence

The reticuloendothelial system or renal clearance can quickly remove nanocarriers from the bloodstream, which can effectively shorten their duration in circulation.

Surface alterations and stealth coatings are two tactics that need to be refined to avoid clearance processes and extend circulation time.

Regulatory elements to consider

Concerns of salary evaluation, characterization, and standardization are presented in the changing regulatory environment for nanocarriers. A thorough pre-clinical and clinical study is necessary to prove the safety, efficacy, and quality and regulatory approval procedures can differ between jurisdictions.

Prices and availability

In resource-constrained environments, the high costs associated with the development and manufacturing of nanocarriers may restrict their affordability and accessibility.

For broad acceptance and maximum impact, strategies for economical synthesis, scalable production, and reasonable cost are crucial.

FUTURE PERSPECTIVE

Future multidisciplinary cooperation, continuous research, and technical developments could lead to revolutionary breakthroughs in a variety of sectors with nanocarriers.

Individualized medical care

To create individualized treatment plans with higher efficacy and fewer adverse effects, nanocarriers allow for the precise and targeted administration of therapies depending on the unique traits, genetic makeup, and illness profiles of each patient.

Therapeutic combination

To overcome medication resistance, promote treatment results in complicated diseases, such as cancer, and enable synergistic effects, nanocarriers make it easier to co-deliver numerous therapeutic agents, including medicines, nucleic acid, and imaging agents.

Sensible and stimulus-adaptive nanocarriers systems

The use of sophisticated stimuli-responsive materials and mechanisms in future nanocarriers would enable precise spatiotemporal control over therapy by enabling on-demand drug release in response to various stimuli including pH, temperature, light, magnetic fields, or biochemical signals.

Nanocarriers for therapeutics

By enabling simultaneous disease diagnosis, treatment monitoring, and targeted therapy, theragnostic nanocarriers with integrated diagnostic and therapeutic functions will transform precision medicine and patient care for a wide range of illnesses and disorders.

Nanotechnology in immunization

To improve vaccination efficacy, stability, and immunogenicity against infectious diseases, emerging pathogens, and malignancies, nanocarriers will be essential to the development of next-generation vaccines. They will facilitate the transport of antigens, immune modulation, and adjuvants.

Using biosensing and imaging

With applications in diagnostics, treatments, and biomedical research, nanocarriers will continue to progress in bioimaging and biosensing technologies, allowing high-resolution imaging, early illness detection, and real-time monitoring of biological processes.

Regeneration medicine

To meet vital demands in the treatment of degenerative diseases and injuries, nanocarriers will help create regenerative therapies by delivering growth factors, stem cells, and biomaterials to enable tissue repair, regeneration, and organ transplantation.

Application in the environment and agriculture

With the use of nanocarriers, tailored distribution of agrochemicals, soil amendments, and nanosensors for precision farming, pollution control, and food preservation will be possible for sustainable agriculture, environment remediation, and food safety.

3D Manufacturing with nanotechnology

For applications in tissue engineering, drug delivery, and regenerative medicine, nanocarriers will work with additive manufacturing processes, such as 3D printing to produce functionalized scaffolds, implants, and constructions.

International Health Solutions: Because they provide accessible, scalable, and reasonably priced solutions that are customized to meet local needs, nanocarriers have the potential to address global health concerns such as infectious illnesses, maternity and child health, and healthcare access in underprivileged populations.

CASE STUDIES AND EXAMPLE

Utilizing liposomal doxorubicin for cancer therapy

Liposomal doxorubicin is a well-known nanocarrier-based chemotherapy used to treat malignancies such as ovarian and breast cancer. Brands that contain this drug include Doxil® and Myocet®.

Compared to traditional doxorubicin, these liposomal formulations increase therapeutic efficacy, decrease systemic toxicity, and improve drug distribution to tumor locations.

The clinical benefits of liposomal doxorubicin in enhancing patient outcomes and quality of life are demonstrated by real-world data and clinical trials.

Utilizing gadolinium nanoparticles in MRI contrast agents

Brain tumors and cardiovascular issues are among the conditions that can be diagnosed with MRI using gadolinium-based nanoparticles, such as Gadovist®.

Better imaging sensitivity and specificity made possible by these nanoparticles facilitate early disease identification, precise diagnosis, and therapy panning. Gadolinium nanoparticles' safety profile and diagnostic value in improving the quality of MRI are emphasized in clinical studies and case reports.

Lipid nanoparticles (LNPs) for gene delivery

Patients suffering from hereditary transthyretin-mediated amyloidosis (hatter amyloidosis) can receive small interfering RNA (siRNA) delivered to target liver cells through lipid nanoparticles, such as the FDA-approved medication onpattro (patisiran)

LNPs offer a promising therapeutic method for treating genetic disorders and other diseases at the molecular level by encasing and delivering siRNA to mute the expression of disease-causing genes.

Clinical trials show how effective LNP-based gene treatments are in slowing the course of disease, achieving better clinical results, and raising patients' standard of living. Using Polymeric

Nanoparticles for targeted drug delivery

Paclitaxel is delivered to tumor cells in patients with metastatic breast cancer, non-small cell lung cancer, and pancreatic cancer using polymeric nanoparticles in Abraxane, a nanoparticle albumin-bound (nab) formulation of the medicine.

Through their increased permeability and retention (EPR) action, polymeric nanoparticles improve tumor targeting, increase drug solubility, and lengthen the duration of circulation.

When compared to traditional chemotherapy regimens, Abraxane® is safer and more effective in improving survival outcomes and minimizing side effects. This has been supported by real-world evidence and clinical trials.

The use of nanoparticles in agriculture

To increase crop efficacy, decrease environmental pollution, and minimize off-target impacts, pesticides, herbicides, and fungicides are delivered to crops using nanocarriers.

Pesticides can be made more soluble, and stable, and adhere to plant surfaces by using nanoformulations, such as Emulsifiable Concentrates and water-dispersible granules, which improves crop yields and insect control. Nano pesticides are useful for managing pesticide resistance, managing pests, and advancing sustainable agriculture methods, as shown by field experiments and agricultural studies.

CONCLUSION

To summarize, nanocarriers are a game-changing technology that has the potential to completely change a range of industries, including agriculture, environmental sustainability, healthcare, and diagnostics. Nanocarriers can precisely manage various functional payloads, such as medications, imaging agents, nutrients, and others by precise control over their size, shape, composition, and surface qualities. This results in targeted distribution, controlled releases, and better therapeutic efficiency. Notwithstanding their potential, nanocarriers are not without difficulties and constraints. These include issues with stability, off-target effects, biocompatibility, and regulatory concerns. The safe and efficient translation of nanocarriers into useful applications necessitates interdisciplinary cooperation, technological innovation, and thorough safety evaluations. In terms of applications, personalized medicine, combination therapies, stimuli-responsive and intelligent systems, theragnostic, environmentally friendly, and sustainable agricultural and environmental remediation are all possible using nanocarriers. Nanocarriers hold the key to unlocking new frontiers in science, medicine, and technology, offering creative solutions to global challenges and enhancing the quality of life for individuals and communities worldwide. As nanoscience and nanotechnology continue to innovate, they will play a crucial role in shaping a future where precision, efficiency, and tailored solutions transform health-care delivery, improve agricultural productivity, and mitigate environmental challenges. To fully utilize nanocarriers and realize their promise for a more promising, healthier, and sustainable future, additional research, funding, and cooperation will be needed.

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