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Pharmaceutical Delivery Methods Using Nanotechnology: Current Trends and Prospects

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ABSTRACT

With many benefits over traditional synthetic nanocarriers, including biocompatibility, biodegradability, and decreased toxicity, bio-based nanomaterials have become a game-changing platform in drug delivery systems. This study thoroughly examines the current state of biobased nanomaterial synthesis, functionalization, and application. This study examines lipid-based carriers, dendrimers, proteins, and metallic nanoparticles that are synthesized using green chemistry to enhance regulated and targeted medication delivery. Combination treatments that make use of biobased nanocarriers tackle problems like multidrug resistance, and advances in surface modification techniques and stimuli-responsive designs have increased the efficacy and site-specific release of drugs. Pulmonary and personalized medicine applications exemplify their adaptability in accomplishing localized delivery and customizing treatments to unique patient profiles. Despite challenges in large-scale production, stability, and regulatory approval, biobased nanomaterials have the potential to revolutionize medicine delivery. Advancements in green synthesis, multifunctionality, and nanocarrier optimization are driving this revolution. Better clinical outcomes and a long-term strategy for precision medicine are possible with their incorporation into next-gene medicines. To address the pressing demand for safer and more sustainable drug delivery platforms in modern medicine, this review highlights the eco-friendly, biocompatible, and biodegradable nature of bio-based nanomaterials.

KEYWORDS: Biobased Nanomaterials, Drug Delivery System, Biopolymers, Dendrimers, Biocompatibility.

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INTRODUCTION

Oral and parenteral administration are the mainstays of traditional medication delivery strategies. Patients are more likely to take their medication as prescribed when it is given orally in the form of tablets, capsules, or solutions because of the ease and convenience of this method of administration. But it has drawbacks, such as digestive tract breakdown resulting in low bioavailability, hepatic first-pass metabolism, and the possibility of gastrointestinal discomfort. Oral and parenteral administration, two of the most common traditional medication delivery techniques, have their advantages and disadvantages. Although oral administration is popular because of its low barrier to entry and high rate of patient compliance, the bioavailability of the drug is low because of its breakdown in the intestines and the liver's first-pass metabolism, which limits the quantity of active medicine that reaches the bloodstream [1-3]. Oral medications also have the potential to irritate the gastrointestinal tract, have low drug loading capacity, and have stability problems. While parenteral routes offer rapid medication action by avoiding the GI tract, they are intrusive, painful, and infection-prone, and they usually necessitate the employment of skilled medical personnel for administration [4]. Furthermore, traditional methods don't always have the best control over drug release, so the levels of the medicine can fluctuate, which can make the treatment less effective and more likely to cause side effects [5]. They also have a problem with non-specific distribution, which means they can harm healthy tissues in addition to their intended targets. Such effects can lead to systemic toxicity. The inability to direct medications to certain tissues or cells, particularly across biological barriers such as the blood-brain barrier, instability in response to environmental changes, and low drug solubility and permeability are further obstacles [6]. Because of these drawbacks, new drug delivery systems have been developed to increase bioavailability, target specificity, controlled release, and patient compliance [2]. One cutting-edge method is the use of

nanomaterials in drug delivery systems (NDDS), which make use of nanoparticles, which are man-made substances with sizes ranging from 1 to 100 nanometres to enhance the transportation and effectiveness of medicinal substances [7]. **Table 1 and Table-2** Comparing and contrasting different synthesis approaches of Biodegradable Nanoparticles and their applications. Improved medication loading, stability, and controlled release are all made possible by the distinctive physicochemical characteristics of these nanomaterials, which include a large surface area relative to their volume as well as customizable geometric and chemical characteristics **[Figure-1]** [8]. NDDS can increase bioavailability, a major benefit, by preventing medication breakdown and easing its uptake across cellular membranes [9].

Furthermore, nanoparticles can be functionalized with antibodies or ligands that bind to specific receptors on sick cells; such functionality allows for targeted distribution, which concentrates the medicine where it will do the best while sparing healthy tissues from it [10, 11]. By zeroing in on certain areas, we can lessen the likelihood of harmful side effects while simultaneously increasing the effectiveness of our treatments. In addition, NDDS can overcome the drawbacks of conventional drug delivery systems by increasing the amount of time a medication spends in circulation and enabling controlled and sustained release [1]. In general, drug delivery systems based on nanomaterials provide hope for improving safety and therapeutic outcomes in a range of diseases by addressing issues such as nonspecific distribution, fast elimination, and low solubility [12, 13].

Materials on the nanoscale that are derived from living organisms include lipids, proteins (such as albumin and silk fibroin), and polysaccharides (like cellulose and chitosan). together with various biomolecules [14, 15]. Using these materials for medication delivery reduces the risk of toxicity and adverse immune responses because they are biocompatible and generally biodegradable, as they are engineered to interact with biological systems [14]. Their structural resemblance to biological components and their natural origin makes them biocompatible, meaning the body can handle them well and they won't cause major immune reactions [14]. Controlling drug release kinetics, improving drug stability, and enabling targeted distribution to specific tissues or cells are all possible with biobased nanomaterials, which can be fine-tuned to reduce systemic side effects and increase therapeutic efficacy [8]. Reducing long-term buildup and toxicity hazards, their biodegradability further guarantees that they break down into non-toxic byproducts [16]. For the most part, biobased nanomaterials provide a safer and more effective platform for drug administration. This is because they are biocompatible and can be targeted and released with outstanding precision, which improves patient outcomes while minimizing toxicity [17–19]. The purpose of this review is to present a synopsis of biobased nanomaterials, with an emphasis on their biocompatibility, biodegradability, and ability to deliver drugs to specific locations, to improve drug delivery systems.

TYPES OF BIOBASED NANOMATERIALS:

A Variety the biocompatibility, biodegradability, and ability to be generated from natural sources of biobased nanomaterials have made them attractive options for medication delivery systems, as they minimize toxicity and environmental effect [8].A wide range of biobased nanomaterials, including dendrimers, lipid-based structures, protein-based nanomaterials, biodegradable polymers, polysaccharide-based nanomaterials, and green-synthesized metallic nanoparticles, have been the subject of substantial research and are now being used for controlled and targeted drug delivery [15, 20].

PROTEIN BASED NANOMATERIALS

The majority of protein-based nanomaterials used for drug delivery fall into one of three broad classes: chemical, physical, or self-assembly [21]. Chemical methods, like emulsion and complex coacervation procedures, allow control over nanoparticle size and shape and achieve great encapsulation efficiency [22], but they may produce somewhat larger particles and require surfactants and stabilizers. Although electrospray can degrade macromolecules due to operational stresses, nano spray drying is more cost-effective and can produce stable nanoparticles in a gentle environment. However, it is only suitable for small-scale production and isn't ideal for hydrophobic drugs [23]. The self-assembly approach, which involves desolvation, allows proteins that are tolerant of the process conditions to spontaneously produce nanoparticles in response to changes in solvent conditions. In the end, the particles are ti Biocompatibility, biodegradability, and the capacity to shield encapsulated medications from enzymatic breakdown and kidney toxicity are essential features exhibited by these protein nanoparticles. Increasing clearance enhances the drug's half-life, activity, and stability [24]. They provide for controlled and prolonged drug release by allowing synthesis parameters to be fine-tuned for size, surface properties, and shape. In addition, very stable, and loaded with drugs very well [21]. Modifying the surface of nanoparticles enables tailored delivery, which improves the efficacy of treatments while reducing unwanted side effects. There have been successful applications of protein-based nanoparticles in delivery of nucleic acids, proteins, peptides, and anticancer medications [25]. Vaccines, tailored treatments for cancer and lung illnesses, and cellular uptake via endocytosis all make use of them. By improving bioavailability, targeting delivery, and reducing toxicity, protein-based nanoparticles provide a safe, effective, and adaptable platform for medication delivery, surpassing many of the shortcomings of conventional approaches [26].

Table 1. Comparing and contrasting different synthesis approaches of Biodegradable Nanoparticles

Synthesis Approach	Principle	Advantages	Disadvantages	Applications
Emulsification Method	Mixing two immiscible phases with a stabilizer	Simple and scalable	High energy input	Drug delivery, Cosmetics, Food Industry
Nanoprecipitation Method	Rapid mixing of organic and	High encapsulation	Use of organic solvents	Gene therapy, Drug delivery, Tissue

	aqueous phases	efficiency		engineering
Solvent Evaporation Method	Dissolving polymer and drug in solvent, followed by solvent evaporation	Controllable particle size	Residual solvent traces	Imaging, Encapsulation, Agriculture
Self-Assembly Method	Spontaneous organization of molecules into ordered structures	Biocompatible materials	Limited control over morphology	Tissue engineering, Drug delivery, Diagnostics
Electrospray Method	Applying high voltage to a polymer solution to generate droplets	Narrow size distribution	Need for specialized equipment	Controlled release, Drug delivery, Inhalation Therapy

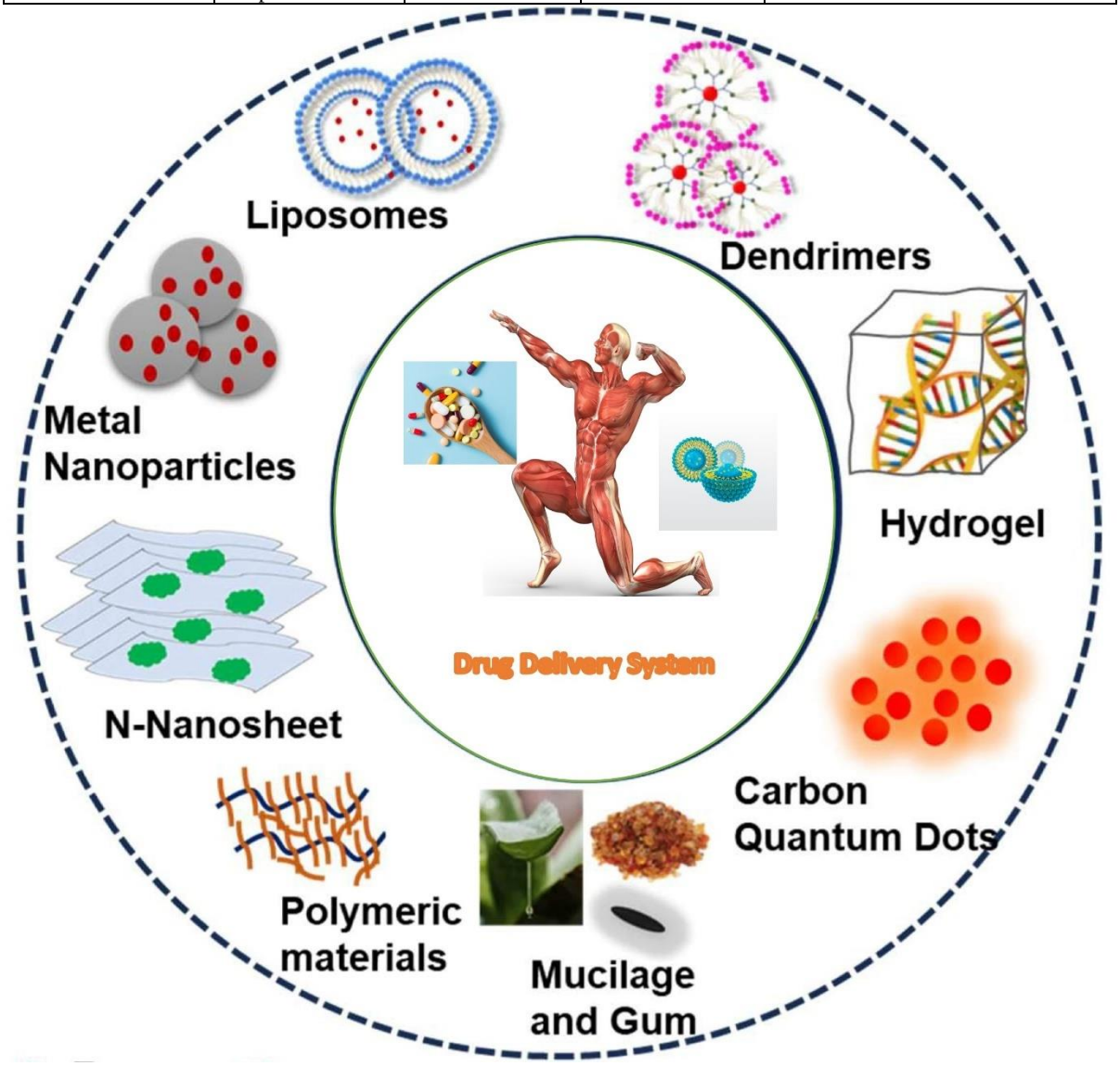

Figure 1. Depiction of the different shapes and structural NMs toward drug delivery systems

BIODEGRADABLE POLYMER

Drug delivery systems employ biodegradable polymers, which can be precisely controlled through a variety of ways of synthesis to accomplish controlled, targeted, and long-lasting medication delivery via their characteristics [27]. Nanoparticles, microparticles, hydrogels, and implantable devices customized to individual therapeutic needs can be fabricated using common synthesis techniques such as emulsion-based procedures (both single and double emulsion), polymerization, solvent evaporation, and nanoprecipitation [28]. The use of synthetic polymers (polylactic acid [PLA] and polyglycolic acid [PGA]) and natural

polymers (chitosan, alginate, collagen) that biodegrade into harmless byproducts like carbon dioxide and water makes surgical removal unnecessary [29]. Controlled and predictable drug release profiles are achieved by fine-tuning their degradation rate by altering their chemical composition, crystallinity, and hydrophilicity [30].

Biodegradable polymers have several useful characteristics, such as being biocompatible, biodegradable, mechanically strong, and able to prevent the premature degradation of encapsulated pharmaceuticals, which improves their stability and bioavailability [31]. Because of their ability to allow extended drug release and targeted administration, they decrease systemic adverse effects and increase patient compliance by lowering dosage frequency [32]. Their surfaces can also be altered to enhance muco-adhesion or to target particular tissues for better therapeutic results. Biodegradable polymers have many uses in the drug delivery industry, including ocular drug delivery (which uses them to get around anatomical obstacles and give sustained release for eye diseases like glaucoma and retinal disorders), colon-specific delivery, cancer treatment, and vaccine administration [33]. They are an essential component of cutting-edge, risk-free, and efficacious medication delivery systems due to their adaptability, which is shown by their usage in implantable devices, microspheres, hydrogels, and nanoparticles [34].

POLYSACCHARIDE BASED NANOMATERIALS

Nanomaterials derived from polysaccharides are abundant in nature, biodegradable, and biocompatible, making them ideal for use in drug delivery systems [35]. They Such methods that enable fine control of particle size, shape, and drug loading capacity include emulsification, nanoprecipitation, complicated coacervation, and sophisticated techniques like microfluidics. To create stable nanoparticles that can effectively encapsulate a range of medications, these techniques take advantage of the chemical activity of polysaccharides, particularly their free carboxyl and hydroxyl groups [36]. Among the many desirable characteristics displayed by polysaccharide nanoparticles are their low toxicity in physiological settings, excellent targeting ability, rapid and regulated drug release rates, and high drug loading efficiency. You may chemically alter their surfaces to make them more stable, particular in their targeting, and interact with biological systems better [37].

Nanoparticles derived from polysaccharides have many potential uses in medication delivery, including anticancer treatment and targeted distribution to the intestines and mouth [38]. Some examples of such materials include functionalized nanoparticles, which have demonstrated successful delivery of medications that are poorly soluble in water, and polysaccharide-gold nanocomplexes, which have been designed to enable regulated release of drugs. Improved drug bioavailability, reduced side effects, and precise distribution to target tissues can be achieved by the use of polysaccharide-based nanoparticles, which provide a durable, adaptable, and effective platform [39].

Two basic approaches are the divergent and convergent methods for synthesizing dendrimers, which are nanoscale polymers that are radially symmetrical, highly branching, and monodisperse [40]. Starting with a multifunctional core molecule, Tomalia's divergent synthesis expands outward by adding monomer units successively, producing dendrimers with increasing generations and surface functional groups. This process was established in the 1980s. While this method's rapid growth and large payload capacity make it ideal for imaging and drug delivery applications, it also requires an excess of monomer to limit by-products and might cause structural flaws as a result of side reactions [41, 42]. Hawker and Fréchet introduced the convergent technique in 1990, offering better control over structure, fewer contaminants, and accurate surface functionalization. The process involves synthesizing dendritic branches (dendrons) and attaching them to a core. However, this method is not optimal for mass production, necessitates increased human effort, and imposes size restrictions on dendrimers due to steric hindrance.

DENDRIMERS

Dendrimers have several desirable characteristics, such as a highly ordered structure, a high branching degree, surface chemistry that may be adjusted, drug-encapsulating cavities, and excellent solubility in water [43]. Increased bioavailability, regulated and targeted drug release, greater cellular penetration, and high drug loading capacity through covalent or non-covalent interactions are all made possible by these properties [40]. To help with targeted distribution and decrease systemic toxicity, dendrimers are utilized as carriers for anticancer medications, imaging agents, and gene delivery vectors in drug delivery. Dendrimers have the capacity to either encapsulate or conjugate pharmaceuticals makes it possible for the drug to be released in response to stimuli and extends its half-life [44]. Dendrimers are still a wonderful platform to work with, even though they have certain drawbacks, including possible toxicity and complicated production to ensure the distribution of drugs in a safe, effective, and multipurpose manner [45].

LIPID-BASED NANOSTRUCTURES

Many different approaches are used to create lipid-based nanostructures, such as solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs), which allow for efficient regulated release of drugs and their encapsulation [46]. Microemulsion, ultrasonic homogenization, thin-film hydration, nanoprecipitation, and high-pressure homogenization (HPH) are among the most common synthesis methods [12]. The top-down method of high-pressure homogenization creates nanoparticles by driving emulsions of melted lipids and surfactants through small holes in a material at high pressure. Particles with controlled size and stability can be produced on a wide scale using this technology. While the microemulsion method does produce lipid nanoparticles, it is laborious and requires high surfactant concentrations and dilution steps [47]. The process involves dispersing a warm lipid phase into an aqueous surfactant solution, followed by rapid cooling. Although ultrasonic homogenization can break down lipid particles using cavitation energy, it has the potential to degrade lipids and have low encapsulation efficiency [48]. When lipids are dissolved in organic solvents, thin films are formed. These films, when hydrated, self-assemble into nanoparticles, and this process is known as bottom-up hydration. However, size control and batch variability are common issues associated with this approach [49, 50]. This method is preferred in advanced formulations like mRNA vaccines because of its excellent size

control and high encapsulation efficiency. Nanoprecipitation is a solvent-based self-assembly technique that combines aqueous phases with organic solvents that contain lipids. It triggers the formation of nanoparticles through rapid solvent diffusion [51]. Encapsulating hydrophilic and hydrophobic molecules, being biodegradable, having a high drug loading capacity, protecting labile medicines, and being biocompatible are all important attributes of lipid-based nanostructures [52]. Because of their amphiphilic character, they can release drugs selectively, increase their bioavailability, and decrease their systemic toxicity [48]. Facilitating the bridging of biological barriers and enhancing cellular uptake, they are in use in a variety of therapeutic domains, including cancer treatment, gene therapy, vaccine administration, and neurological disorders [53]. Thanks to their scalable manufacturing methods and excellent physicochemical and biological features, lipid-based nanostructures provide a versatile and useful platform for current drug delivery systems [54].

Table 2. Biodegradable Polymers for Nanoparticle Applications

Polymer	Biocompatibility	Tunable Properties	Controlled Degradation Kinetics
PLGA (Poly(lactic-co-glycolic acid))	Well-established, Generally non-toxic	Lactid to glycolic acid ratio controls degradation rate, hydrophobicity, and mechanical strength	Faster degradation with higher glycolic acid content
PLA (Polylactic acid)	Good biocompatibility	Molecular weight, crystallinity, and processing methods influence mechanical properties, drug release, and degradation rate	Slower degradation compared to PLGA
PCL (Polycaprolactone)	Excellent biocompatibility, Low inflammatory response	Crystallinity and molecular weight affect hydrophobicity, mechanical properties, and degradation rate	Slowest degradation rate among these polymers
Chitosan (Natural polysaccharide)	Biocompatible, Biodegradable, Mucoadhesive properties	Molecular weight, degree of deacetylation (%), and processing methods influence encapsulation efficiency, drug release, and gelation Properties	Degradation rate depends on factors like pH and enzymatic activity

Table 3. Toxicity and Compatibility of Biodegradable Nanoparticles

Method/Approach	Focus	Advantages	Disadvantages
In vitro studies	Cellular and molecular level effects	Controlled environment. High throughput screening possible. Less ethical concerns than in vivo studies.	Limited representation of complex biological systems. Potential artifacts due to isolated cell cultures
Cell viability assays	Measure cell death or proliferation	Simple and reliable. Provides information on cytotoxicity	May not reflect in vivo effects
Reactive Oxygen Species (ROS) assays	Detect oxidative stress caused by NPs	Indicates potential for cellular Damage	Not specific to NP exposure
Gene expression analysis	Identify changes in gene expression due to NP exposure	Offers insights into cellular response mechanisms	Requires specialized techniques and interpretation
In vivo studies	Whole-organism response to NPs	More realistic assessment of toxicity. Allows for investigation of biodistribution and excretion	Ethical considerations. Higher cost and time compared to in vitro studies
Histopathology	Examination of tissue structure for signs of damage	Provides detailed information on organ and tissue effects	Requires sacrificing animals
Blood tests	Analyze changes in blood cell counts and markers of inflammation	Indicates potential for systemic effects	May not be specific to NP exposure
Physicochemical characterization	Analysis of NP size, shape, surface charge, and degradation rate	Crucial for understanding NP behavior and potential interactions with biological Systems	Requires specialized equipment and expertise

Computational modeling	Simulation of NP-cell interactions	Can predict potential risks and guide further testing	Relies on accurate input data and may not fully capture biological complexity

METALLIC NANOPARTICLES MADE IN AN ECO-FRIENDLY MANNER

Sustainable, low-cost, and environmentally friendly methods are used to create metallic nanoparticles (MNPs) approaches that make use of naturally occurring substances as a source of reduction and stabilization, including but not limited to plants, bacteria, fungi, and algae [55]. To reduce metal ions to their zero-valent nanoparticle form under mild circumstances, green synthesis uses natural biomolecules, such as phytochemicals in plant extracts, rather than traditional physical and chemical synthesis methods, which often use harmful chemicals and consume a lot of energy [56]. The size and form of nanoparticles can be controlled by using extracts from plants, such as leaves, bark, fruits, and roots. These extracts typically contain chemicals like polyphenols, flavonoids, and proteins that serve as both reducing and capping agents [57]. Stable nanoparticles with adjustable physicochemical characteristics are produced throughout the synthesis process by combining the biological extract with metal salt solutions. This mixture undergoes nucleation, growth, and stabilization phases [58]. Nanoparticle production and morphology are confirmed by characterization techniques such as XRD, TEM, and UV-Vis spectroscopy [59]. Metal nanoparticles (MNPs) made from environmentally friendly materials have several advantages over their chemically produced equivalents, such as better biocompatibility, stronger antibacterial and anticancer properties, and fewer adverse effects [60]. Because of their one-of-a-kind optical, electrical, and surface characteristics, they are excellent drug delivery carriers that allow for targeted therapy, controlled drug release, and enhanced bioavailability [57]. While addressing sustainability challenges in nanotechnology, green MNPs show significant promise for applications in nanomedicine, such as cancer treatment, antimicrobial treatments, and diagnostic imaging, thanks to their biocompatibility and ecologically benign synthesis [61].

CURRENT TRENDS IN BIOBASED

Nanomaterials for Drug Delivery

To overcome the limits of current drug delivery methods, recent developments in biobased nanomaterials have focused on integrating sustainability, biocompatibility, and enhanced targeting capabilities. conventional medical treatments [62]. New developments aim to create multipurpose nanocarriers made of biomolecules and natural polymers with enhanced bioavailability, regulated release, and decreased systemic toxicity [63]. Surface modifications and ligand attachments are being used to construct biobased nanomaterials, including proteins, polysaccharides, and biodegradable polymers. Such work is done to improve targeted delivery and cellular uptake [57]. Lipid nanoparticles (LNPs), most notably used in mRNA COVID-19 vaccines, show how biobased carriers can safeguard biologics and allow for targeted distribution to cells, leading to an upsurge in RNA-based treatments and vaccinations [64]. Furthermore, there is growing interest in metallic nanoparticles that have been manufactured utilizing plant extracts and microbial processes. These nanoparticles have the potential to provide smart and localized therapy, which might be especially useful in the fields of oncology and chronic diseases [65, 66]. Biobased nanomaterials provide biocompatible platforms for these advancements in nanobiotechnology, materials engineering, and micro-robotics, which are leading to new possibilities for individualized and highly regulated drug administration [67]. The development of biobased nanomaterials is progressing from the lab to the clinic because of improvements in scalable and repeatable synthesis processes. To improve the therapeutic efficacy and safety, there is a general trend toward patient-centric, ecologically sustainable drug delivery systems that integrate state-of-the-art nanotechnology with the inherent benefits of biobased materials [68]. This technology also offers improved safety characteristics and utilizes environmentally friendly manufacturing processes [1]. One example of a new technology is a nanocarrier that can sense changes in environmental factors like pH and temperature and release a medicine accordingly.

Targeted Drug Delivery

Biobased nanomaterials are commonly used for targeted medication delivery, which typically entails attaching targeting ligands like antibodies, peptides, and aptamers to the surface of nanoparticles identification of tumors [69, 70]. To improve cellular absorption and minimize off-target effects, these ligands bind preferentially to receptors that are overexpressed on cancer cells. Furthermore, stimuli-responsive nanoparticles are engineered to discharge their medicinal cargo in reaction to particular environmental triggers present in sick tissues, such as the acidic pH, increased enzyme levels, redox states, or temperature fluctuations typical of tumor microenvironments [62]. To illustrate the point, redox-responsive systems make use of the increased intracellular glutathione concentrations in cancer cells to break disulfide bonds and release medications intracellularly, whereas pH-responsive nanoparticles use the slightly acidic tumor milieu to initiate drug release. The use of pH, redox, and enzyme triggers in multi-stimuli responsive systems allows for the exact and on-demand release of drugs, which improves therapeutic efficacy and reduces systemic toxicity [71, 65]. When it comes to targeted delivery, biobased nanomaterials like ligand-functionalized polysaccharide nanoparticles for cancer treatment, protein-based nanocarriers designed for receptor-mediated uptake, and lipid-based nanostructures like liposomes modified with targeting moieties for infectious diseases and cardiovascular disorders are just a few examples [72, 73]. When it comes to cancer, infections, and cardiovascular disorders, stimuli-sensitive biobased nanocarriers have proven to be an effective tool for regulated medication release, leading to better treatment outcomes [74]. As an example, nanoparticles made of keratin have been designed to distribute anticancer medications in a way that is responsive to three stimuli: pH, glutathione, and enzymes. These nanoparticles have been shown to have superior targeting and release profiles [71]. An effective, safe, and precise method for targeted medication administration across a wide range of disorders is to combine surface ligand alteration with stimuli-sensitive mechanisms in bio-based nanomaterials [75].

Treatments Used in Combination

To combat drug resistance and increase therapeutic effectiveness, combination therapies utilizing nanodrug delivery systems (NDDS) have emerged as a crucial tactic, especially in disease management [76, 77]. The use of biobased nanocarriers allows for the simultaneous intracellular uptake by target cells and the co-delivery of several medications with various physicochemical qualities inside a single nanoparticle, all while preserving ideal synergistic drug ratios [58]. Problems with monotherapies, such as systemic toxicity, limited therapeutic windows, and multidrug resistance (MDR) [78, 79], are addressed by this method. The use of biobased nanomaterials in combination with immunotherapy, chemotherapy, and targeted therapies has improved pharmacokinetics, decreased side effects, and improved tumor targeting [80]. These nanomaterials include polymeric nanoparticles, liposomes, dendrimers, and hybrid nanocarriers. An example of a polymeric nanoparticle that successfully overcomes multidrug resistance is one that combines paclitaxel with the P-glycoprotein modulator tariquidar. These nanoparticles are surface-functionalized with biotin to target tumors, and they show much higher cytotoxicity and tumor growth inhibition than single-drug formulations [49]. Just as free curcumin had no effect on cervical cancer cells, chitosan nanoparticles coated with curcumin increased cellular absorption and cytotoxicity. Despite the antagonistic effects of the free drugs on breast cancer cells, a biodegradable triple block nanocarrier containing doxorubicin and cisplatin was able to co-deliver the two drugs in a synergistic fashion [81]. The carrier also included polycaprolactone (PCL) and a carboxyl-functionalized core. In preclinical settings, micellar nanoparticles functionalized with phage proteins selectively delivered paclitaxel to breast cancer cells, resulting in significant tumor shrinkage and necrosis [77]. Amphiphilic deblock copolymers in dual-drug co-delivery systems have also improved therapeutic effects by enabling the simultaneous delivery of doxorubicin and platinum-based medicines to cells [82]. To improve effectiveness, decrease drug resistance, and minimize side effects in cancer and other diseases, biobased nanomaterial-mediated combination treatments provide a potential platform for regulated delivery of various medications in a synergistic manner [83]. Table-3 showing the advantage and disadvantages of biodegradable nanoparticles.

Pulmonary Drug Delivery

The use of inhalable nanodrug delivery systems (NDDS) for pulmonary drug delivery is an exciting new approach to targeting lung cancers directly with treatments, which could significantly reduce side effects symptoms that manifest across the body as a result of traditional chemotherapy [84, 85]. To improve localized drug delivery, biodegradable polymeric nanoparticles, lipid-based carriers, and ligand-functionalized nanocomplexes are utilized. These nanomaterials overcome physiological barriers, such as the mucus layer and mucociliary clearance, and increase drug retention and permeability within lung tissues [86]. Methods for enhancing medication retention include the development of nanoparticles topical particles that cling to mucous membranes, enhancing drug release using stimuli-responsive materials, and optimizing particle size and surface charge to maximize mucus penetration reacting to acidity or alkalinity in the lung's microenvironment [87, 88]. Metastatic lung cancer models have shown improved therapeutic efficacy and localized drug concentration when administered nanoparticles conjugated with epidermal growth factor ligands, and inhalable doxorubicin nanoparticles decorated with tumor necrosis factor-related apoptosis-inducing ligand (TRAIL) demonstrated synergistic tumor targeting and apoptosis induction [89, 85].

Despite these advancements, there are still obstacles to overcome in pulmonary drug delivery. These include patient-specific variations in lung function that impact drug deposition, issues in accurately measuring drug release at tumor locations, and the possibility of local toxicity due to high drug concentrations [44]. Further refining aerosolization technology can enhance dosage control, repeatability, and patient compliance [90]. To improve anti-tumor immunity, future initiatives aim to create multifunctional biobased nanocarriers that can precisely target tumors, release their contents in a regulated and sustained manner, and modulate the immune system. One example of this is nano-based vaccines that can be administered via the pulmonary route [91]. Biobased nanomaterials with the ability to enhance local medication efficacy, decrease systemic toxicity, and improve patient quality of life have the potential to completely transform the way lung cancer is treated [92].

Breakthroughs in Nanocarriers

The development of more biocompatible nanocarriers has centred on improving their form, size, and surface characteristics. This development aims to increase the effectiveness of targeting and extend the duration of circulation [93]. You can fine-tune these properties using techniques like adjusting synthesis settings and using surface modification tactics [94]. For example, as compared to older lipid-based systems like SLNs, NLCs made of a combination of solid and liquid lipids had better drug loading capacity, improved physical stability, and biocompatibility [95, 96]. Their occlusive properties and diminutive size make them perfect for delivering medications through difficult routes with minimal negative effects [97]. Hybrid lipid-polymer nanoparticles combine the benefits of both improving encapsulation efficiency and stability [73, 98], whereas polymer-based nanoparticles also help with drug solubility and controlled release, although they may encounter obstacles such as immune response. Nanoparticle stability, immune system recognition and clearance, cellular uptake, and targeting specificity can all be improved by surface modification techniques like PEGylation, ligand conjugation, and charge modulation [62, 99, 100]. While ligand conjugation allows receptor-mediated endocytosis for selective administration, PEGylation extends circulation duration by supplying a hydrophilic stealth coating [101, 102]. Depending on the therapeutic situation, charge modulation can enhance contact with cell membranes or mucus barriers. The creation of tailored drug delivery systems that are safe, efficacious, and facilitated by breakthroughs in nanocarrier design and surface engineering has wide-ranging implications for the treatment of cancer, infections, neurological illnesses, and other conditions [103–105].

Use in Individualized Health Care

Biobased nanoparticles are vital in personalized medicine because they enable the customization of medical treatments for each individual patient. This approach takes into account the particular illness characteristics of each individual patient [106-108]. Improved bioavailability and absorption rates of medications can be achieved through the engineering of nanodrug delivery systems (NDDS), which also allows for improved solubility of drugs that are poorly water-soluble and more precise control over

the timing of drug release [109]. With this level of personalization, therapeutic drugs are administered at the most effective concentrations possible, which in turn improves treatment outcomes while decreasing adverse effects [110, 111]. To provide more effective and personalized treatment regimens, NDDS can modify the composition, size, and surface properties of nanoparticles to address patient-specific parameters such as genetic variants, disease stage, and tissue environment [112, 113]. Targeted distribution and regulated release are crucial for optimizing therapeutic efficacy while avoiding systemic toxicity, which is especially important in complicated disorders such as infections and cancer [72, 106, 114].

Difficulties and Looking Ahead

Because of their biodegradability, biocompatibility, and other desirable properties, biobased nanomaterials show enormous potential for use in drug delivery systems. This potential could enable the controlled and targeted delivery of drugs [14, 115]. However, several obstacles still stand in the way of their widespread clinical translation. Some nanomaterials may cause unwanted immune responses or build up in organs, leading to harmful effects [116–119]. Assuring consistent biocompatibility and limiting toxicity are key challenges. Because breakdown or aggregation might reduce the efficacy of medication delivery, another worry is the stability of biobased nanoparticles in physiological settings and during storage [1, 120, 121]. Because of biological hurdles that limit the penetration and accumulation of nanoparticles at disease locations, such as the blood-brain barrier, tumor microenvironment heterogeneity, and mucus layers, achieving high targeting efficiency is still difficult [122-124]. Furthermore, it is still difficult to mass-produce biobased nanomaterials with exact control over size, shape, and surface characteristics in a cost-effective and repeatable manner [125]. Regulatory constraints and the need for thorough safety evaluation methodologies further slowdown clinical adoption [125, 126]. To improve site-specific medication release and decrease adverse effects, novel nanoparticle signs with stimuli-responsive and multifunctional properties are the focus of future prospects [127, 128]. Various methods for altering surfaces, including Enhancements are being made to ligand conjugation, charge modulation, PEGylation, and circulation time in order to make them more specific and accurate targets [126]. Concerns about the environment and the economy have spurred developments in green synthesis and methods of scalable production. Personalized medicine methods that incorporate biobased nanomaterials hold the potential for safer, more effective, and individually tailored treatments [126, 129]. Another new development is the use of theragnostic, which combine medicine delivery with diagnostic capabilities. Ongoing interdisciplinary research and collaboration among material scientists, biologists, and doctors may overcome the existing constraints of biobased nanomaterials in next-generation drug delivery systems.

CONCLUSION

Improved bioavailability, targeted administration, controlled release, and decreased toxicity are just a few ways in which biobased nanomaterials have revolutionized medication delivery standard (conventional) methods. Their biodegradability and compatibility with living organisms are guaranteed by their natural origin, and their targeted specificity and therapeutic effectiveness are enhanced through surface functionalization with ligands. By reducing systemic adverse effects and increasing patient outcomes, these nanomaterials allow for targeted medicine delivery to sick areas. New developments, including polymer-lipid hybrid nanoparticles, improve therapeutic efficacy by combining the advantages of different materials to provide a stable, sustained-release, and efficiently encapsulated product. To further adapt treatments to each patient's profile and disease features, biobased nanocarriers enable the integration of combination therapies with personalized medicine. Biobased nanomaterials, due to their adaptability, hold great promise as transformative medical tools that can enhance therapeutic outcomes for a diverse range of diseases and usher in a new era of personalized therapy. Unlocking the full potential of biobased nanomaterials will require interdisciplinary collaboration to address challenges in achieving scalable manufacturing, demonstrating long-term biosafety, and meeting regulatory standards for clinical adoption. This will pave the way for safer, more efficient therapeutic interventions across diverse medical applications.

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