GSC Biological and Pharmaceutical Sciences

eISSN: 2581-3250 CODEN (USA): GBPSC2

Cross Ref DOI: 10.30574/gscbps

Journal homepage: https://gsconlinepress.com/journals/gscbps/

(REVIEW ARTICLE)

Check for updates

# Nanoparticles: A promising approach for enhancing drug delivery and efficacy

Om N. Ajmire *, Pooja R. Hatwar, Ravindra L. Bakal and Ishar K. Thak

*Department of Pharmaceutics, Shri Swami Samarth Institute of Pharmacy, At Parsodi, Dhamangaon Rly, Dist Amravati (444709) Maharashtra, India.*

GSC Biological and Pharmaceutical Sciences, 2025, 30(02), 117-126

Publication history: Received on 23 December 2024; revised on 09 February 2025; accepted on 12 February 2025

Article DOI: https://doi.org/10.30574/gscbps.2025.30.2.0044

## Abstract

Nanoparticles (NPs) have emerged as a promising tool for enhancing drug delivery and efficacy with their unique properties, such as small size, high surface area, and biocompatibility, NPs can improve the solubility, permeability, and targeting of drugs. NPs can be synthesized from various materials, including natural or synthetic polymers, lipids, and metals. They offer several advantages, including improved bioavailability, targeted delivery, and reduced toxicity. This review article provides an overview of the types of NPs, their fabrication methods, and their applications in various drug delivery systems, including pulmonary, brain, topical, nasal, and ocular drug delivery. They can be used to treat respiratory diseases, neurological disorders, and cancers. However, there are challenges associated with NP-based drug delivery, including scalable and reproducible manufacturing, safety, and quality control.

**Keywords:** Nanoparticles; Pulmonary delivery; Brain delivery; Topical delivery; Nasal delivery; Ocular delivery

## 1. Introduction

Nanoparticles (NPs) are artificial particles that are smaller than 100 nanometers in diameter and are composed of metals such as gold, lipids, or polymers. Nanoparticles are particular advantageous in a diverse array of medicinal applications, including cancer treatment and diagnosis. Nanomaterials are used to produce more effective and regulated drug delivery techniques [1]. Recent developments in nanotechnology have generated a lot of interest in using nanoparticles as carrier for pulmonary drug delivery as an alternative to traditional inhalable formulations and dry powder inhalers based on nanoparticles [2]. Nanotechnology is widely used in almost every field of medicine, including imaging, biosensing, drug delivery, tissue engineering, implants, and microsurgery [3]. As any new pharmaceutical product, the launch of a PLGA-based nanomedicine formulation comprises a complex pathway from design, laboratory-scale development to scale-up manufacturing [4]. Advanced nanotechnology-based strategies aim to overcome the limitations of free drugs and promote passage through biological barriers that function as impediments to therapeutic agents [5]. Nanotechnology comprises the design, manufacture, and use of materials at the nanoscale to produce novel nanosized materials. maceomolecular, molecular, and atomic scales. Pharmaceutical nanoparticles are solid drug carriers that are submicron in size (less than 100 nm in diameter) and biodegradable or not [6]. Drug compounds that are difficult to dissolve and have low bioavailability when taken orally are commonly delivered using nanoparticles. Many medications have been shown to benefit from the use of nanoparticles in improving their pharmacokinetic profiles, lowering their toxicity, and increasing their oral bioavailability [7].

* Corresponding author: Om N. Ajmire

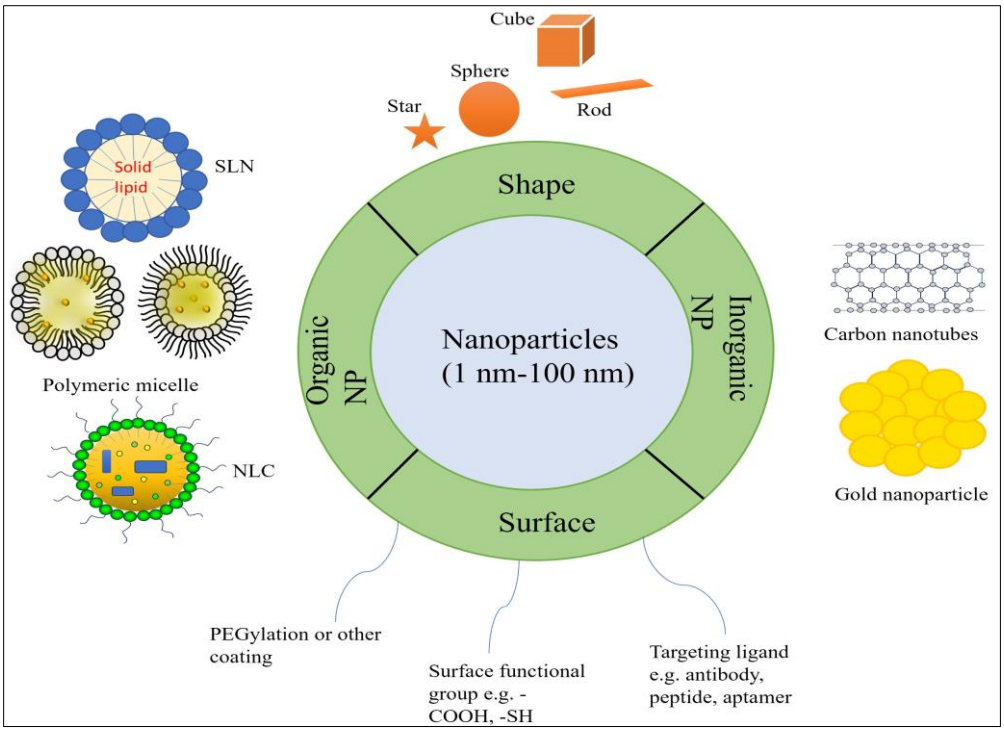


**Figure 1** Describing physicochemical characteristics of nanoparticle. SLN: Solid Lipid Nanoparticle; NLC: Nanostructured Lipid Carriers; NP: Nanoparticle [1]

### 1.1. Advantages of NPs

- Because nanoparticles are so small, they easily pass through tiny capillaries and are absorbed by cells, enabling effective drug accumulation at the body's target sites.
- Nanotechnology can make fabrics more durable because NPs have a high surface energy and a large surface area to volume ratio.
- Applications for nanoparticles include reproduction, water purification, disease control, and the reduction of toxicity and negative effects.
- Nanoparticles prepared using biodegradable materials enable sustained drug release at the target site over the course of days or even weeks [6].
- Nanostructures are substantially easier for cells to consume than large particles with sizes ranging from 1 to 10 μm [8].
- There are other ways to deliver the system, such as parenteral, nasal, and oral; they might improve the medications bioavailability [7].
- Standard emulsion production techniques are appropriate. Emulsions require the same basic components and are quite stable over time [9].
- Gold nanoparticles are used to identify several kinds of malignant cells, such as prostate, lung, and breast cancers [10].

### 1.2. Disadvantages of Nanoparticles

- In the pharmaceutical sciences, nanoparticles may be used to improve drug efficacy and decrease toxicity, but until recently they are not aware that the carrier systems may also associate risk to the patient.
- Nanotechnology is a highly cost consuming and laborious process.
- It requires highly qualified engineers and workers, causing additional concerns. The biotransformation of polymers results in toxic metabolites on repeated administration [11].
- In the biological environment, nanoparticles are extremely reactive due to their tiny size and large surface area.
- Non-biodegradable particles may build up at the medication delivery site when it is used, resulting in a chronic inflammatory reaction.
- Due of the restricted targeting capabilities of nanoparticles [6].
- They may include the use of strong, poisonous solvents during the preparation process, which might result in an allergic reaction and immunological response [7].

- Unexpected polymeric transition dynamics and an unpredictable propensity for gelation [9].

### 1.3. Types of Nanoparticles for Drug Delivery

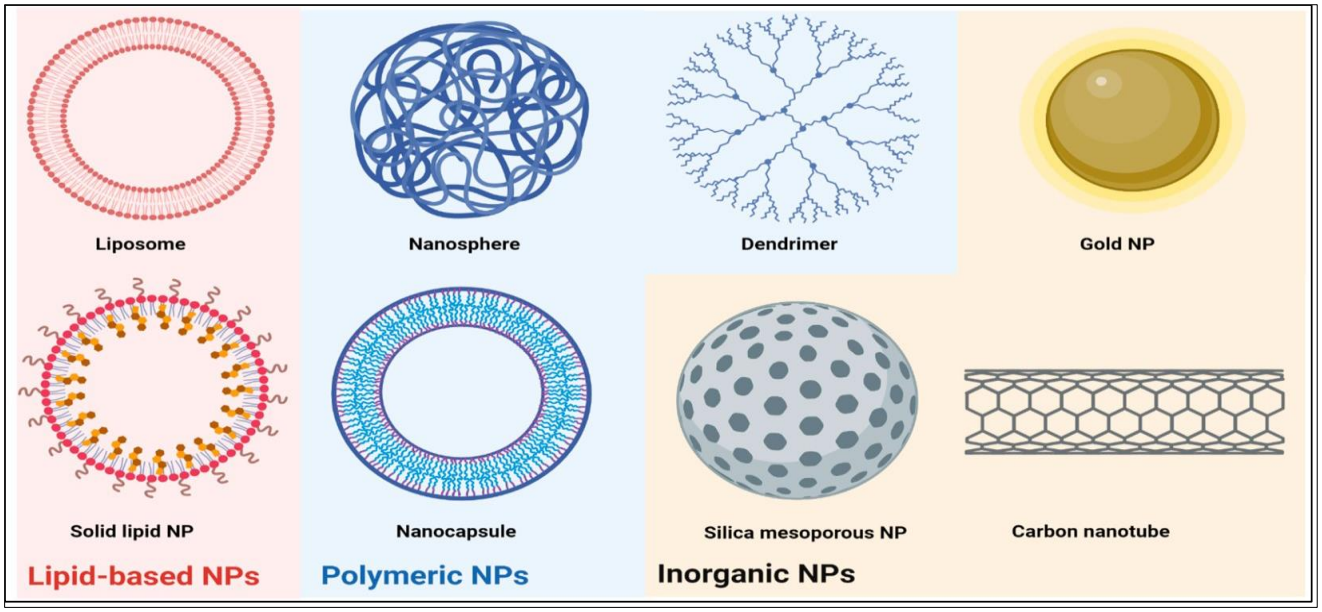


**Figure 2** General structure of the most common synthetic nanoparticles (NPs) used for drug delivery. [12]

*1.3.1. Polymeric nanoparticles*

Polymer NPs can be synthesized from natural or synthetic materials, as well as monomers or preformed Polymers allowing for a wide variety of possible Structures and characteristics. They can be for Mulated to enable precise control of multiple NP features and are generally good delivery vehicles because they are Biocompatible and have simple formulation parameters. Polymeric NPs are synthesized using various techniques such as emulsification (solvent displacement or diffusion), nanoprecipitation, ionic gelation and microfluidics, which all result in different final Products [13]. These polymeric nanoparticles also improved the bioavailability and reduced toxicity as of their biodegradable and biocompatible property [14]. Polymeric Nanoparticles can be separated into classes of hydrogels, Nanospheres, and nanocapsules, examples of the last being Polymeric micelles and polymersomes [15]. These can be obtained from natural or synthetic polymers, most of which are biodegradable and biocompatible [16]. While the latter moiety facilitates membrane penetration, the former moiety facilitates interaction with the negatively charged bacterial cell wall Bacteria [11].

*1.3.2. Lipid-based Nanoparticles*

Solid lipid nanoparticles are submicron sized nanocarriers made up of lipids. These consist of phosphor lipid Coating associated with a solid hydrophobic core of high Melting point with the material to be encapsulated. They are structurally different form other lipid based vesicular systems as they consist of a solid hydrophobic core having a monolayer of phospholipid coating. SLNs have acted as a potential carrier of therapeutic agents for systemic or localized delivery [17]. A variety of subset structures are present in lipid-based nanoparticles, but they are most commonly spherical platforms that contain at least one lipid bilayer that surrounds at least one internal aqueous compartment. As a delivery system, Lipid based NPs offer many advantages including for-mulation simplicity, self-assembly, biocompatibility, high Bioavailability, ability to carry large payloads and a range of physicochemical properties that can be controlled to Modulate their biological characteristic [13]. There are numerous benefits to using SLNs for drug delivery, including their ability to be manufactured without the use of organic solvents, their high physical stability, and the enhanced, controlled release of laden agents. The primary disadvantages of SLNs are the inflexibility of their shape, which results in limited drug loading efficiency (particularly for hydrophilic molecules), and undesired particle growth by agglomeration, which may result in the explosive release of the drug [18]. Nanostructured lipid carriers (NLCs) or oil-loaded solid lipid carriers are the second generation of Lipid carriers. The oil core of NLCs offers a variety of fascinating properties, including increased loading capacity, excellent biocompatibility, controlled release compared to the rapid release of liposomes, and feasibility of Large-scale production [16]. A broad range of therapeutics, including both lipophilic and hydrophilic drugs, can be encapsulated in the lipid bilayer or the aqueous core, expanding the use of liposomal drug carriers [12].

*1.3.3. Inorganic Nanoparticles*

Inorganic nanoparticles have largely been used as imaging contrast agents or photothermal therapy in cancer. Recent interest has been directed toward the development of inorganic nanoparticles as vaccines in preclinical settings. most inorganic materials have a smaller particle size, improved stability, controlled tunability, enhanced permeability, high drug loadings, and a Triggered release profile, which is ideal for antigen delivery as a vaccine [19]. Thrombi, comprised primarily of activated platelets and fibrin, can cause fatal vascular dysfunction by obstructing the blood supply to healthy organs. These systems can potentially target thrombi and improve treatment outcomes [20]. Inorganic materials such as gold, iron and silica have been used to synthesize nanostructured materials for various drug delivery and imaging applications. These inorganic NPs are precisely formulated and can be engineered to have a wide variety of sizes, structures and geometries. Gold NPs (AuNPs), which are the most well studied, are used in various forms such as nanospheres, nanorods, nanostars, nanoshells and nanocages. Additionally, inorganic NPs have unique physical, electrical, magnetic and optical properties, due to the properties of the base material itself. For example, AuNPs possess free electrons at their surface that continually oscillate at a frequency dependent on their size and shape, giving them photothermal properties [13]. The main mechanisms of inorganic nanomedicine to treat ALI Include inhibiting the inflammatory signal [21]. Because of their special physical characteristics, inorganic nanoparticles have found applications, most notably in biotechnology [22].

*1.3.4. Liposomes*

Liposomes are spherical, concentric vesicles that are formed by combining the greek terms "Lipos," which means fat, and "Soma," which means body. Liposomes are phospholipid molecules in a circular sac. In particular, it encloses a water droplet that is artificially formed to transport the medicine into the cellular barrier. Liposomes are 100 nm-sized nanoparticles [23]. Liposomes are classified according to their lamellar size as small unilamellar vesicles with compasses of 20 – 100 nm, large unilamellar vesicles with compasses exceeding 100 nm, giant unilamellar vesicles with compasses up to 1 μm, oligolamellar vesicles with compasses of 0.1-1 μm, and multilamellar vesicles with compasses up to 500 nm [24]. Liposomes are excellent for medication delivery since they can store both water-loving and water-hating drugs, as well as being biocompatible and biodegradable [25]. Liposomes have been employed as a nanocarrier in several N2B delivery experiments to treat various CNS conditions [18].

## 2. Targeting strategies of nanoparticles

The specificity and selectivity of nanoparticles for their intended targets can be improved by a variety of targeting strategies. One popular strategy is the surface modification of nanoparticles with ligands, such as antibodies, peptides, or small molecules, that can bind to specific receptors or markers expressed on the target cells or tissues. This receptor-mediated targeting can improve the cellular uptake and internalization of nanoparticles, leading to improved drug delivery and therapeutic outcomes. Another strategy is the use of stimuliresponsive nanoparticles, which can change their properties in response to specific environmental cues, such as pH, temperature, or enzymatic activity. Also, the incorporation of cell penetrating peptides or other membrane permeabilizing agents into the nanoparticle structure can facilitate the transport of nanoparticles across biological barriers, such as the blood brain barrier, increasing their ability to reach the desired target sites. The successful development of targeted nanoparticle-based drug delivery systems necessitates a thorough understanding of the biological and physiological characteristics of the target site, as well as the optimization of nanoparticle properties to achieve the desired targeting and delivery Profile [26]. Increasingly complex NPs are being developed to overcome many biological hurdles by combining different NP types, targeting techniques, and therapeutic modes [12].

### 2.1. Fabrication Methods

The drug's physicochemical qualities, the intended nanoparticle features, and the intended application all influence the production technique selection. To guarantee the reproducible production of nanoparticles with the required size, morphology, and drug loading, these fabrication techniques must be optimized. Drug delivery systems based on nanoparticles have been developed using a variety of manufacturing techniques [9]. Numerous recent research has looked at various techniques for fabricating polymeric nanoparticles as they relate to pulmonary medication formulations, in addition to chemical processing technologies. These methods often include emulsion polymerization, double emulsion/solvent evaporation, or polyelectrolyte complex creation [27].

### 2.2. Emulsion-based techniques

Drug loaded nanoparticles can be produced in emulsions using emulsion-based processes such sonication, micro fluidization, and high-pressure homogenization. These techniques make nanoscale emulsion droplets by spreading the drug and polymer in a volatile organic solvent, which is further emulsified under high shear conditions. Drug loaded

nanoparticles are created when the organic solvent is either evaporated or removed [26]. These methods often include emulsion polymerization, double emulsion/solvent evaporation, or polyelectrolyte complex creation. Drugs are entrapped in polymeric matrix nanoparticles by polyelectrolyte complexes using oppositely charged polymers. The drug gets released either by drug diffusion or polymer degradation [27].

### 2.3. Solvent evaporation/removal methods

Solvent evaporation or removal techniques, in which the medicine and polymer are first dissolved in a volatile organic solvent, can be used to create nanoparticles. To extract the final drug loaded nanoparticles, this solution is further put via solvent evaporation or removal procedures such rotary evaporation or lyophilization. To regulate the size, morphology, and drug loading of the resultant nanoparticles, the solvent selection and particular evaporation or removal process parameters can be tuned [26].

### 2.4. Precipitation techniques

Precipitation techniques, in which a drug containing solution is subjected to particular conditions to cause the drug to precipitate into nanoparticles, can be used to create nanoparticles. A nonsolvent that causes the medicine to precipitate out of the solution can be added to accomplish this. As an alternative, altering the solution's ph, temperature, or ionic strength may also cause the drugs to precipitate into nanoparticles. By adjusting the process parameter, these precipitation techniques enable the controlled synthesis of drug loaded nanoparticles with the required properties, including size and drug loading [26].

### 2.5. Self-assembly methods

When exposed to certain conditions, such as variations in pH, temperature, or solvent polarity, certain polymers and lipids have the ability to self assemble into nanoparticles. Thermodynamic interactions between lipid or polymer molecules drive this self-assembly process, which produces the spontaneous creation of nanostructures with certain sizes and forms. The ability to adjust key parameters, such as solvent selection, ionic strength, and concentration, to facilitate the self assembly of the desired nanoparticle morphologies, provides a simple and versatile technique for generating drug laden nanoparticles [26]. Ferritin, which is produced by most living things, is another appealing vaccination platform for infectious diseases based on self assembly nanoparticles [19].

### 2.6. Application of Nanoparticles

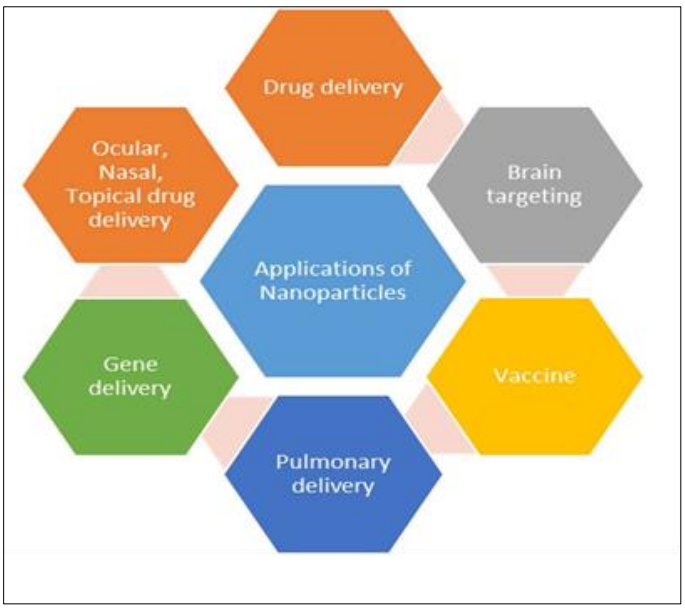


**Figure 3** Application of Nanoparticles [26].

*2.6.1. Application in Pulmonary Drug Delivery*

For many years, inhalation drug has been an option for treating respiratory conditions. For the first-line treatment of asthma and other chronic obstructive lung illnesses, inhalation has been found to be the most effective and non-invasive method of delivery. In addition, because the lungs have a vast surface area for absorption, high permeability, and an

excellent blood supply, they can absorb drugs for systemic distribution, such as drug delivery for disorders like diabetes mellitus [28]. The primary functions of the lungs are to enable gas exchange between the blood and the external Environment, and to maintain homeostatic systemic ph. The respiratory System is composed of the trachea, which bifurcates into the bronchi. The bronchi continue to branch into smaller bronchioles and ultimately in the terminal bronchi, which end with the alveolar sac. Nanoparticle pharmaceuticals offer several advantages over formulations containing larger Particles [27]. Solid lipid nanoparticles (SLN) have extensively been studied for a long time for potential pulmonary drug delivery. SLN are nanoscale aqueous suspensions prepared from physiological lipids, primarily triglycerides and phospholipids. As the formulations are based on using physiological components, they are less toxic and, As a result, more acceptable for pulmonary drug delivery [29].

*2.6.2. Application of Nanoparticles in Brain Drug Delivery*

To maintain its activities, the brain, an extremely sensitive and delicate mechanism, needs a consistent supply of nutrients and other essentials on a regular basis. A specific configuration of blood arteries for the central nervous system is known as the Blood Brain Barrier, or BBB. The majority of medications cannot reach the central nervous system due to the BBB. As a result, the BBB is regarded as an extremely powerful barrier. The BCECs, or brain capillary endothelial cells, are primarily responsible for the blood brain barrier. It is also made up of several kinds of cells, such as pericytes and neuronal cells. The brain capillary endothelial cells are connected by tight junctions. These continuous, tight junctions prevent or limit the movement of chemicals across the epithelium [28]. For a long time, the BBB has been acknowledged as a major obstacle in the delivery of drugs to the brain. Despite the fact that the BBB leakiness is recognized toevolve with some disease Conditions, detailed knowledge such as duration and Size of the BBB opening is not well understood. With advanced studies, new mechanisms have been discovered [30]. The BBB is an anatomical and biochemical barrier that works by tightly controlling the permeation of ions, macromolecules, and nutrients into the brain in order safeguard it from potentially harmful substances like toxins, pathogens, and drugs present in systemic circulation [12]. Protection of the CNS is provided by the BBB and CSF, Ensuring its most favorable Surroundings for proper functioning and homeostasis. There are selective biological barriers established by different cells at the following key interfaces.The BBB (cerebral vasculature),the blood-CSF barrier (choroid plexus), the brain-CSF Barrier (pia arachnoid) and the CSF—brain barrier (neuroependyma) [31].

*2.6.3. Application of Nanoparticles in Topical Drug Delivery*

Encapsulating active ingredients to alter a drug's release characteristics and transport is a popular pharmacological approach. The systems of nanoparticles have a lot of promise for DDS. A representative sampling of defined drug penetration evaluation techniques is often damaging. The primary determinant of PLGA's biodistribution and therapeutic effectiveness is its particle size [16]. Cosmetics employ almost 12% of all metallic nanoparticles. It is applied to provide enhanced stability and sensory qualities. To improve the spreadability and attractive qualities of cosmetics formulation for cosmetics, to provide enhanced protection from the sun and to possess the special ability to have a wider range of antimicrobial activity [32]. The outermost layer of the skin, or epidermis, gives the skin its protective qualities. Mostly composed of keratinocytes, this superficial layer is divided into four major principal strata. the stratum corneum, granular layer, spinous layer, and bottom layer. The topmost layer of the epidermis, the stratum corneum (SC), also referred to as the horny layer, has the primary barrier role and is 10–15 μm thick. The stratum corneum is made up of 10-15 layers of corneocytes flattened, hexagon-shaped, cornified dead cells encased in an intercellular matrix that is enriched in lipids [29]. The skin's vast surface area nearly 20 square feet makes it a potentially intriguing medication delivery route. The main goal of topical drug administration is to provide a local effect, which may (i) eliminate the need for systemically delivered pharmacological therapy, (ii) reduce the overall dosage needed to reach the targeted site (skin), and (iii) lessen harmful off-target consequences [33]. One technique for monitoring particles with diameters between about 30 and 1,000 nm is nanoparticle tracking analysis. This technique enables the viewing and recording of nanoparticles in a solution by combining laser light scattering microscopy and charge-coupled device microscopy [34]. Effective delivery of therapeutic drugs for the treatment of diseases is made possible by utilizing the skin's distinct physiological structure, which is rich in blood and lymphatic capillaries that are related to the body [35]. Compared to oral, intravascular, subcutaneous, and transmucosal routes, this drug delivery technique has several benefits [36]. The problem with topical drugs is that they penetrate the epidermal barrier [37].

*2.6.4. Application of Nanoparticles in Nasal Drug Delivery*

One of the more interesting methods for delivering pharmacologically active compounds systemically is nasal delivery, which is also a good substitute for more traditional oral and enteral administration. Actually, it bypasses first pass metabolism, makes administration simple and noninvasive, and may offer direct access to the central nervous system (CNS) by avoiding the blood brain barrier (BBB).The nasal cavity innervation, or the olfactory nerve, which connects the olfactory bulb with the olfactory region of the nasal cavity, as well as the trigeminal nerve, provide a special

opportunity for drug transport into the central nervous system (CNS) through nose to brain (N2B) administration. Actually, a significant amount of medication is transferred from the nose to the systemic circulation. Ranged between nearly 100% and less than 1% of the alleged amount that was given [38]. The more straightforward and straightforward method of brain targeting that stays out of the bloodstream is nose to brain administration. Clearance and expensive techniques. It functions becausee of the special link that the olfactory and trigeminal nerves create between the brain and the outside world. Drugs are exposed to the nasal mucosa, which is innervated by the trigeminal and olfactory nerves, after intranasal administration [39]. One potential application is in the treatment of respiratory diseases such asthma, chronic obstructive pulmonary disease (COPD), and cystic fibrosis. Nasal drug delivery systems (NDDS) have many potential applications [16].

*2.6.5. Application of Nanoparticles in Ocular drug delivery*

Because the human eye is a highly complex organ with unique physiology and anatomy, researchers have had a harder time developing the perfect drug carrier for the eye that targets a particular tissue. The anterior and posterior chambers, as well as the vitreous body, make up the inside of the eye. The anterior chamber is made up of tissues such as the cornea, iris, and lens. The choroid and sclera are among the tissues that make up the posterior chamber. The anterior chamber is at risk from a variety of vision related conditions, including glaucoma, diabetic retinopathy, cataract, and conjunctivitis and the back chamber. The Blood Retinal Barrier, or BRB, keeps the retina in the eye separate from the blood flow. Tight connections make up both the outer and interior BRB cells; the only difference is in their configuration. The flow of molecules or fluids between the retinal tissues and the ocular vasculature is regulated by these tight junctions. Additionally, it keeps the microenvironment in the retina intact and stops very big molecules and other harmful, foreign substances from entering the retina. Along with In addition to this barrier, there are numerous additional challenges that are specific to and inherent in the architecture of the eyes, both static and dynamic. The majority of these barriers typically protect the eye from harmful substances [28]. Less expensive and easier to make than other dosage designs [40].

## 3. Challenges and Future prospects in Nanoparticle-Based Drug Delivery

Any pharmaceutical product must show significant efficacy, safety, and quality in order to undergo successful clinical translation. A significant obstacle in the clinical translation of nanomedicines is their scalable and reproducible manufacturing, which is particularly difficult for dry powders based on inhalable nanoparticles. Therefore, these specifications apply to both the drying and nanosuspension fabrication processes. The majority of research on powders based on inhalable nanoparticles have primary nanoparticle sizes less than 300 nm [41]. Growing usage of nanotechnology NDDS can benefit from nanomaterials' several advantages, including as enhanced drug solubility, permeability, and targeting. These systems can be customized to meet each patient's unique requirements [42]. Because they can selectively target cancer cells while preserving healthy cells, natural chemicals have been thoroughly investigated as potential anticancer medicines [43]. In clinical practice, targeted treatments and immune therapies have been used extensively. Patients with a range of advanced cancers had better prognoses because to these medications. However, because of their poor solubility, low bioavailability, and serious adverse reactions, the majority of targeted drugs fail to produce the anticipated therapeutic effects. Analysis of the various NP administration methods, with a focus on the impact of inhaler NPs [15]. (i) Nanoparticle development and manufacturing; (ii) confirming the safety and tolerability of the NPs both when intact and when the body metabolizes them; (iii) NPs stability in bench and biological environments; (iv) NPs biocompatibility; (v) drug loading and release efficacy and pharmacokinetics; (vi) controlling their pathway requirements and completing the clinical trials within a reasonable timeframe; and, lastly, (vii) the viability of scaling up the produced materials [44]. Nanopharmaceuticals drug development and formulation strategies are constrained by the excipient selection for inhalation therapy, and the efficacy of inhalation therapy is further impacted by the stability of therapeutic substances [45]. The toxicity of both naturally occurring dust particles and ultrafine, poor solubility manufactured nanoparticles is a major problem in pulmonary medicine related to nanoparticle use [46]. To maintain the vaccine's biological purpose of eliciting a strong and accurate immune response, the cell membrane is coated. The phrase "ghost cancer cell membrane" has been used to preserve the cell membrane and collect intracellular cell material [47]. Significant progress has been made in improving cancer treatments thanks to the clinical success of immunotherapy and significant advancements in nanotechnology. Nanomaterials have considerable promise for providing solutions to overcome immune therapy's limitations, given the bottlenecks it encounters [48]. When drugs are administered to the mucosa, they may cause antigens to be diluted, inactivated, or blocked by enzymes, nasal secretions, or epithelial barriers [49]. As a result, the preferred method for treating local illnesses including COPD, asthma, and cystic fibrosis is now pulmonary drug administration. Furthermore, systemic diseases like diabetes have been treated via the pulmonary route [50].

## 4. Conclusion

Nanoparticles have shown great promise in enhancing drug delivery and efficacy. Their unique properties make them an attractive tool for improving the solubility, permeability, and targeting of drugs. However, there are still challenges to be addressed, such as scalability, biocompatibility, and toxicity. Further research is needed to fully explore the potential of NPs in drug delivery and to overcome the challenges associated with their use.

## Compliance with ethical standards

*Disclosure of conflict of interest*

No conflict of interest to be disclosed.

## References

[1] Waghmare PS, Chabukswar AR, Raut KG, Gaikwad-Pawar B, Jagdale SC. Nanoparticle-based targeted therapy through EGFR tyrosine kinase inhibitors and their recent advances in lung cancer therapy. Explor Med. 2024; 5:513–529.

[2] Chan HW, Chow S, Zhang X, Zhao Y, Tong HHY, Chow SF. Inhalable Nanoparticle-based Dry Powder Formulations for Respiratory Diseases: Challenges and Strategies for Translational Research. AAPS PharmSciTech. 2023 Apr 4;24(4):98. Doi: 10.1208/s12249-023-02559-y. PMID: 37016029; PMCID: PMC10072922.

[3] Saunders E, Chen LC, Gordon T, Lippmann M. Cardiopulmonary effects of nanomaterials, John Wiley & Sons, 2020,695-719

[4] Operti MC, Bernhardt A, Grimm S, Engel A, Figdor CG, Tagit O. PLGA-based nanomedicines manufacturing: Technologies overview and challenges in industrial scale-up. Int J Pharm. 2021 Aug 10;605:120807. Doi: 10.1016/j.ijpharm.2021.120807. Epub 2021 Jun 16. PMID: 34144133.

[5] Đorđević S, Gonzalez MM, Conejos-Sánchez I, Carreira B, Pozzi S, Acúrcio RC, Satchi-Fainaro R, Florindo HF, Vicent MJ. Current hurdles to the translation of nanomedicines from bench to the clinic. Drug Deliv Transl Res. 2022 Mar;12(3):500-525. Doi: 10.1007/s13346-021-01024-2. Epub 2021 Jul 23. PMID: 34302274; PMCID: PMC8300981.

[6] Jha S, Kori A, Patil MS. A Review on Nanoparticles. Int. J. of Pharm. Sci. 2024; 2(3):399-412.

[7] Lakshmi K MK, E Lavanya, Shaik N, Gadde VR,Formulation And Evaluation of Nanoparticles,A Review, Int. J. in Pharm. Sci. 2023; 1(7):196-204.

[8] Fernandez-Fernandez A, Manchanda R, Kumari M. Lipid-engineered nanotherapeutics for cancer management. Front Pharmacol. 2023 Mar 23;14:1125093. Doi: 10.3389/fphar.2023.1125093. PMID: 37033603; PMCID: PMC10076603.

[9] Ekambaram P, Sathali AH and priyanka k, solid lipid nanoparticles: a review, sci. revs. Chem. Commun, 2012;2(1): 80-102.

[10] Bagmar NA, Hatwar PR, and Dr. Bakal RL, a review on targeted drug delivery system,2023; (12)19:288-298.

[11] Sri Bala PSN, Khan PAR, Uddin SA, Muskan, Begum H, Nanoparticles for Drug Delivery Systems, International Journal of Pharmaceutical Sciences Review and Research. 2022; 74(1): 208-211.

[12] Vanbilloen WJF, Rechberger JS, Anderson JB, Nonnenbroich LF, Zhang L, Daniels DJ. Nanoparticle Strategies to Improve the Delivery of Anticancer Drugs across the Blood-Brain Barrier to Treat Brain Tumors. Pharmaceutics. 2023 Jun 23;15(7):1804. Doi: 10.3390/pharmaceutics15071804. PMID: 37513992; PMCID: PMC10383584.

[13] Mitchell MJ, Billingsley MM, Haley RM, Wechsler ME, Peppas NA, Langer R. Engineering precision nanoparticles for drug delivery. Nat Rev Drug Discov. 2021 Feb;20(2):101-124. Doi: 10.1038/s41573-020-0090-8. Epub 2020 Dec 4. PMID: 33277608; PMCID: PMC7717100.

[14] Farooq MA, Aquib M, Khan DH, Hussain Z, Ahsan A, Baig MMFA, Wande DP, Ahmad MM, Ahsan HM, Jiajie J, Wang B. Recent advances in the delivery of disulfiram: a critical analysis of promising approaches to improve its pharmacokinetic profile and anticancer efficacy. Daru. 2019 Dec;27(2):853-862. Doi: 10.1007/s40199-019-00308-w. Epub 2019 Nov 22. PMID: 31758497; PMCID: PMC6895293.

[15] Taghavizadeh Yazdi ME, Qayoomian M, Beigoli S, Boskabady MH. Recent advances in nanoparticle applications in respiratory disorders: a review. Front Pharmacol. 2023 Jul 19;14:1059343. Doi: 10.3389/fphar.2023.1059343. PMID: 37538179; PMCID: PMC10395100.

[16] Bian S, Cai H, Cui Y, Liu W, Xiao C. Nanomedicine-Based Therapeutics to Combat Acute Lung Injury. Int J Nanomedicine. 2021 Mar 18;16:2247-2269. Doi: 10.2147/IJN.S300594. PMID: 33776431; PMCID: PMC7987274.

[17] Kaur G, Narang RK, Rath G, Goyal AK. Advances in pulmonary delivery of nanoparticles. Artif Cells Blood Substit Immobil Biotechnol. 2012 Feb;40(1-2):75-96. Doi: 10.3109/10731199.2011.592494. Epub 2011 Aug 2. PMID: 21806501.

[18] Lee D, Minko T. Nanotherapeutics for Nose-to-Brain Drug Delivery: An Approach to Bypass the Blood Brain Barrier. Pharmaceutics. 2021 Nov 30;13(12):2049. Doi: 10.3390/pharmaceutics13122049. PMID: 34959331; PMCID: PMC8704573.

[19] Poon C, Patel AA. Organic and inorganic Nanoparticle vaccines for prevention of Infectious diseases. Christopher Poon et al 2020 Nano Ex. in press https://doi.org/10.1088/2632-959X/ab8075

[20] Dey RK, Jana B, Dastidar DG. Applications of nanotechnology in the treatment of pulmonary diseases. Vessel Plus 2023;7:17. https://dx.doi.org/10.20517/2574-1209.2023.06

[21] Chishti N, Dehghan MH, Nano-embedded microparticles based dry powder inhaler for lung cancer treatment. J Res Pharm. 2020; 24(3): 425-435.

[22] Falke P B, Shelke P G, Hatwar P R , Bakal R L and Kohale B N, A comprehensive review on Nanoparticle Characterization, classification, synthesis method, silver nanoparticles and its applications , GSC Biological and Pharmaceutical Sciences, 2024, 28(01), 171–184.

[23] Hamid M, Hatwar P R , Bakal R L and Kohale B N, A comprehensive review on Liposomes: As a novel drug delivery system, GSC Biological and Pharmaceutical Sciences, 2024, 27(01), 199–210.

[24] Mendake R A, Hatwar P R,Bakal R L, Hiwe K A and Barewar S S, Advance and opportunities in nanoparticle drug delivery for central nervous system disorders: A review of current advances, GSC Biological and Pharmaceutical Sciences, 2024, 27(03), 044–058

[25] Watmode DS, Kubde J A, Hatwar PR, Bakal RL and Kohale NB, A review on liposome as a drug delivery system for antibiotics, GSC Biological and Pharmaceutical Sciences, 2024, 28(01), 017–029.

[26] Daniel A, A review on Advancements in Nanoparticles Based Pulmonary Drug Delivery, 2024;(2)1:84-94.

[27] Bailey MM, Berkland CJ. Nanoparticle Formulations in Pulmonary Drug Delivery. Medicinal Research Reviews, 2009;(29)1:196-2009

[28] Unnikrishnan G, Joy A, Megha M, Kolanthai E, Senthilkumar M. Exploration of inorganic nanoparticles for revolutionary drug delivery applications: a critical review. Discov Nano. 2023 Dec 19;18(1):157. Doi: 10.1186/s11671-023-03943-0. PMID: 38112849; PMCID: PMC1PMC1073079

[29] Lai F, Caddeo C, Manca ML, Manconi M, Sinico C, Fadda AM. What's new in the field of phospholipid vesicular nanocarriers for skin drug delivery. Int J Pharm. 2020 Jun 15;583:119398. Doi: 10.1016/j.ijpharm.2020.119398. Epub 2020 May 4. PMID: 32376441.

[30] Dong X. Current strategies for brain drug Delivery. Theranostics , 2018; 8(6): 1481-1493.

[31] Ailioaie LM, Ailioaie C, Litscher G. Photobiomodulation in Alzheimer's Disease-A Complementary Method to State-of-the-Art Pharmaceutical Formulations and Nanomedicine? Pharmaceutics. 2023 Mar 11;15(3):916. Doi: 10.3390/pharmaceutics15030916. PMID: 36986776; PMCID: PMC10054386.

[32] Nagasa GD, Belete A. Review on Nanomaterials and Nano-Scaled Systems for Topical and Systemic Delivery of Antifungal Drugs. J Multidiscip Healthc. 2022 Aug 27;15:1819-1840. doi: 10.2147/JMDH.S359282. PMID: 36060421; PMCID: PMC9432385.

[33] Goyal R, Macri LK, Kaplan HM, Kohn J. Nanoparticles and nanofibers for topical drug delivery. J Control Release. 2016 Oct 28; 240:77-92. Doi: 10.1016/j.jconrel.2015.10.049. Epub 2015 Oct 28. PMID: 26518723; PMCID: PMC4896846.

[34] Mendake RA, Hatwar PR, Dr. Bakal RL, Amalkar SV. Review on Nanogel as a Novel Platform for Smart Drug Delivery System. Journal of Drug Delivery & Therapeutics. 2024; 14(8):161-174.

[35] Deulkar AD, Kubde AJ, Hatwar PR and Bakal RL. A review on transdermal drug delivery system, GSC Advanced Research and Reviews. 2024; 18(02): 347–361.

[36] Rotake BS, Hatwar PR, Bakal RL and Kohale BN, Transdermal drug delivery system recent advancements: A comprehensive review, GSC Biological and Pharmaceutical Sciences, 2024, 28(02), 059–072.

[37] Bagmar AN, Hatwar PR, Shelke GP and Bakal RL, A review on "Topical gels: an emerging drug delivery system, GSC Biological and Pharmaceutical Sciences, 2024, 28(02), 285–296.

[38] Clementino AR, Pellegrini G, Banella S, Colombo G, Cantù L,Onvico F, et al.Structure and fate of nanoparticles designed for The nasal delivery of poorly soluble drugs. Mol. Pharmaceutics 2021, 18, 3132−3146.

[39] Battaglia L, Panciani PP, Muntoni E, Capucchio MT, Biasibetti E, De Bonis P, et al. Lipid nanoparticles for intranasal Administration: application to nose-to-brain Delivery. EXPERT OPINION ON DRUG DELIVERY, 2018;(15)4:369–378.

[40] Watmode SD, Hatwar PR, Dr. Bakal RL and Rom VM, A REVIEW ON EYE DROP,2023;(12)21:1298-1306.

[41] Chan HW, Chow S, Zhang X, Zhao Y, Tong HHY, Chow SF. Inhalable Nanoparticle-based Dry Powder Formulations for Respiratory Diseases: Challenges and Strategies for Translational Research. AAPS PharmSciTech. 2023 Apr 4;24(4):98. doi: 10.1208/s12249-023-02559-y. PMID: 37016029; PMCID: PMC10072922.

[42] Pal R, Pandey P, Koli M, Srivastava K, Tiwari V, Gaur AK, Dutta P, The Comprehensive Review: Exploring Future Potential of Nasopulmonary Drug Delivery Systems for Nasal Route Drug Administration, Journal of Drug Delivery & Therapeutics. 2024; 14(3):126-136.

[43] Manzari-Tavakoli A, Babajani A, Tavakoli MM, Safaeinejad F, Jafari A. Integrating natural compounds and nanoparticle-based drug delivery systems: A novel strategy for enhanced efficacy and selectivity in cancer therapy. Cancer Med. 2024 Mar;13(5):e7010. doi: 10.1002/cam4.7010. PMID: 38491817; PMCID: PMC10943377.

[44] Mohamed NA, Marei I, Crovella S, Abou-Saleh H. Recent Developments in Nanomaterials-Based Drug Delivery and Upgrading Treatment of Cardiovascular Diseases. Int J Mol Sci. 2022 Jan 26;23(3):1404. Doi: 10.3390/ijms23031404. PMID: 35163328; PMCID: PMC8836006.

[45] Xie L, Xie D, Du Z, Xue S, Wang K, Yu X, Liu X, Peng Q, Fang C. A novel therapeutic outlook: Classification, applications and challenges of inhalable micron/nanoparticle drug delivery systems in lung cancer (Review). Int J Oncol. 2024 Apr;64(4):38. doi: 10.3892/ijo.2024.5626. Epub 2024 Feb 23. PMID: 38391039; PMCID: PMC10901537.

[46] Maurya S, Srivastava R, Arfin S, Hawthorne S, Jha NK, Agrawal K, Raj S, Rathi B, Kumar A, Raj R, Agrawal S, Paiva-Santos AC, Malik AA, Dua K, Rana R, Ojha S, Jha SK, Sharma A, Kumar D, El-Zahaby SA, Nagar A. Exploring state-of-the-art advances in targeted nanomedicines for managing acute and chronic inflammatory lung diseases. Nanomedicine (Lond). 2022 Dec;17(30):2245-2264. Doi: 10.2217/nnm-2021-0437. Epub 2023 Mar 28. PMID: 36975758.

[47] Nordin ML, Azemi AK, Nordin AH, Nabgan W, Ng PY, Yusoff K, Abu N, Lim KP, Zakaria ZA, Ismail N, Azmi F. Peptide-Based Vaccine against Breast Cancer: Recent Advances and Prospects. Pharmaceuticals (Basel). 2023 Jun 25;16(7):923. Doi: 10.3390/ph16070923. PMID: 37513835; PMCID: PMC10386531.

[48] Yu X, Fang C, Zhang K, Su C. Recent Advances in Nanoparticles-Based Platforms Targeting the PD-1/PD-L1 Pathway for Cancer Treatment. Pharmaceutics. 2022 Jul 29;14(8):1581. Doi: 10.3390/pharmaceutics14081581. PMID: 36015206; PMCID: PMC9414242.

[49] Zhang YB, Xu D, Bai L, Zhou YM, Zhang H, Cui YL. A Review of Non-Invasive Drug Delivery through Respiratory Routes. Pharmaceutics. 2022 Sep 19;14(9):1974. Doi: 10.3390/pharmaceutics14091974. PMID: 36145722; PMCID: PMC9506287.

[50] Zacaron TM, Silva MLSE, Costa MP, Silva DME, Silva AC, Apolônio ACM, Fabri RL, Pittella F, Rocha HVA, Tavares GD. Advancements in Chitosan-Based Nanoparticles for Pulmonary Drug Delivery. Polymers (Basel). 2023 Sep 21;15(18):3849. Doi: 10.3390/polym15183849. PMID: 37765701; PMCID: PMC10536410.