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# Cutting-Edge Developments in Nanoparticle Systems for Managing Respiratory Ailments

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**ABSTRACT:**

Recent advancements in nanotechnology have revolutionized respiratory therapeutics by enabling targeted, controlled, and efficient pulmonary drug delivery. Nanoparticle systems such as lipid, polymeric, and solid lipid nanoparticles, dendrimers, and biomimetic carriers enhance solubility, sustain release, and minimize systemic toxicity. Engineered for inhalation routes, these nano systems ensure deep lung deposition and rapid onset. Innovative fabrication methods—like spray drying, microfluidic synthesis, and surface modification—improve aerodynamic performance and drug stability. Emerging inhalable mRNA vaccines, bio-responsive nanoparticles, and smart inhalers highlight the move toward precision respiratory medicine. However, challenges in scalability, long-term safety, and regulation must be overcome to fully realize the potential of inhalable nanomedicine.

## Introduction

Respiratory diseases such as asthma, COPD, pulmonary infections, and lung cancer remain major global health burdens due to high morbidity and mortality. Conventional therapies often face challenges like poor bioavailability, limited target specificity, and systemic side effects. Physiological barriers of the respiratory tract, including mucociliary clearance and enzymatic degradation, further limit effective drug delivery. Nanotechnology offers innovative solutions through nanoparticle-based systems—such as liposomes, polymeric and solid lipid nanoparticles, and metallic carriers—that enhance solubility, stability, and targeted delivery. Recent advances in smart, stimuli-responsive, and inhalable nanocarriers enable controlled release and localized drug action, improving efficacy while reducing systemic toxicity.

## Challenges of Conventional Respiratory Therapies

Conventional treatments for respiratory diseases, including oral, parenteral, and inhalation routes, face major limitations. Oral and systemic administration often leads to poor bioavailability due to first-pass metabolism, causing systemic side effects and reduced efficacy. Although inhalation therapy targets the lungs directly, traditional inhalers and nebulizers suffer from inefficient drug deposition and instability of sensitive agents like peptides and nucleic acids. Moreover, conventional formulations lack targeted delivery, resulting in non-specific distribution and poor localization at diseased sites. Physiological barriers such as mucociliary clearance, enzymatic degradation, and macrophage uptake further restrict drug retention and absorption, compromising therapeutic outcomes.

**Nanoparticle Systems: A New Frontier in Pulmonary Drug Delivery**

Nanoparticle systems have transformed pharmaceutical research by addressing the challenges of conventional drug delivery. In respiratory therapy, they enable precise, localized, and sustained drug delivery to the lungs, enhancing efficacy and minimizing systemic toxicity. Their nanoscale size allows deep lung penetration and efficient interaction with pulmonary tissues. Nanoparticles, derived from lipids, polymers, proteins, or metals, protect drugs from degradation, improve solubility, and allow controlled or stimuli-responsive release. Surface functionalization with ligands ensures targeted delivery to diseased lung regions. Inhalable formulations, such as dry powders and nebulized nanosuspensions, offer improved drug deposition, patient compliance, and therapeutic outcomes in conditions like asthma, COPD, tuberculosis, and lung cancer.

**Types of Nanoparticles Used in Respiratory Therapy**

Nanoparticle-mediated drug delivery systems hold significant potential in treating respiratory disorders by enhancing drug solubility, bioavailability, and targeted deposition within pulmonary tissues. Various nanoparticle platforms have been designed, each exhibiting distinct physicochemical characteristics, mechanisms, and therapeutic benefits. The principal categories of nanoparticles explored for pulmonary drug delivery are summarized below.

**1. Liposomes**

Liposomes are spherical nanocarriers consisting of phospholipid bilayers enclosing an aqueous interior. They exhibit excellent biocompatibility and biodegradability, enabling the encapsulation of both hydrophilic and lipophilic therapeutic agents. Liposomal formulations enhance drug stability, provide controlled release, and support targeted delivery within the lungs. In respiratory medicine, liposomes have been effectively utilized for the administration of corticosteroids, antibiotics, and anticancer agents. Notably, liposomal amikacin has demonstrated efficacy in treating nontuberculous mycobacterial pulmonary infections.

**2. Polymeric Nanoparticles**

Polymeric nanoparticles are synthesized from biodegradable natural or synthetic polymers such as PLGA (poly-lactic-co-glycolic acid), chitosan, and alginate. Drugs can be either encapsulated within their polymeric matrix or adsorbed onto the particle surface, allowing for sustained and controlled release. Their adjustable particle size and surface charge enhance suitability for targeted pulmonary drug delivery. These systems are especially beneficial in managing chronic respiratory disorders such as asthma and COPD, where extended therapeutic action is desirable.

**3. Solid Lipid Nanoparticles (SLNs)**

Solid lipid nanoparticles (SLNs) feature a solid lipid core stabilized by surfactants, offering high physical stability and controlled drug release. Combining the benefits of polymeric nanoparticles and liposomes, SLNs enhance the delivery of poorly soluble drugs with improved pulmonary deposition and retention. Additionally, they exhibit greater resistance to oxidative degradation than liquid lipid carriers.

**4. Nanostructured Lipid Carriers (NLCs)**

Nanostructured lipid carriers (NLCs) represent a next-generation lipid-based system combining solid and liquid lipids to enhance drug loading and stability. In respiratory therapy, NLCs offer superior mucosal adhesion and deep alveolar penetration, proving effective for the delivery of anti-inflammatory and anticancer drugs.

**5. Metallic Nanoparticles**

Metallic nanoparticles, such as gold, silver, and iron oxide nanoparticles, have gained attention for their diagnostic and therapeutic (theranostic) applications in respiratory diseases. Owing to their unique optical and magnetic properties, they can be used for imaging, biosensing, and targeted drug delivery. For instance, gold nanoparticles have been utilized in photothermal therapy for lung cancer, while silver nanoparticles exhibit antimicrobial activity against respiratory pathogens.

**6. Dendrimers**

Dendrimers are highly branched, tree-like macromolecules with a well-defined architecture that allows precise control over size, shape, and surface

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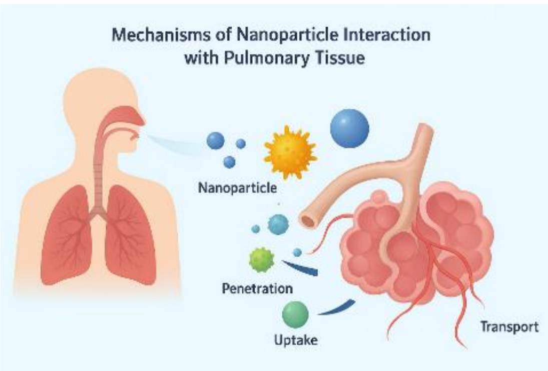
functionality. They can encapsulate drugs within internal cavities or conjugate them to surface groups, offering high loading efficiency and targeted delivery. Their ability to cross biological membranes makes them promising carriers for gene and peptide-based therapies for pulmonary disorders.

**7. Nanomicelles**

Nanomicelles are self-assembled amphiphilic structures with a hydrophobic core and hydrophilic shell. They are particularly suitable for solubilizing hydrophobic drugs and protecting them from degradation. In respiratory drug delivery, nanomicelles have been investigated for transporting anti-inflammatory and anticancer agents via inhalation, achieving enhanced deposition in the deep lungs.

**Mechanisms of Nanoparticle Interaction with Pulmonary Tissue**

The therapeutic success of nanoparticle-based drug delivery systems in respiratory diseases largely depends on their ability to effectively interact with and penetrate pulmonary tissues. Once administered through the inhalation route, nanoparticles encounter various biological barriers within the respiratory tract that influence their deposition, retention, cellular uptake, and overall therapeutic outcome. Understanding these interactions is crucial for optimizing nanoparticle design and ensuring efficient drug delivery to target sites within the lungs.




**1. Deposition and Distribution in the Respiratory Tract**

The initial step in nanoparticle-based pulmonary delivery involves particle deposition, which is governed by particle size, shape, density, and aerodynamic behavior.

- **Particles larger than 5 µm** are typically deposited in the upper airways (trachea and bronchi) through inertial impaction.
- **Particles between 1–5 µm** settle in the bronchioles via gravitational sedimentation.
- **Nanoparticles smaller than 1 µm** can reach the alveolar region through diffusion, allowing them to target deep lung tissues where gas exchange occurs.

The high surface area of nanoparticles enhances their interaction with the alveolar epithelium, facilitating improved drug absorption and retention at the site of action.

**2. Interaction with Pulmonary Barriers**

Upon deposition, nanoparticles encounter several biological barriers such as the **mucus layer, alveolar surfactant, epithelial cells, and immune defenses**.

- The **mucus layer** acts as a physical and chemical barrier, trapping foreign particles. Surface modification of nanoparticles with hydrophilic polymers like PEG (polyethylene glycol) can help them evade mucociliary clearance.
- The **alveolar surfactant**, composed mainly of phospholipids and proteins, can alter nanoparticle surface properties and influence uptake by epithelial cells.
- **Epithelial tight junctions** restrict paracellular transport; hence, nanoparticles are often designed to exploit endocytic pathways for intracellular delivery.

**3. Cellular Uptake Mechanisms**

Nanoparticles enter pulmonary cells primarily through **endocytosis**, which includes mechanisms such as clathrin-mediated, caveolae-mediated, macropinocytosis, and phagocytosis.

- **Epithelial cells** mainly internalize nanoparticles through receptor-mediated endocytosis, which can be enhanced by ligand functionalization.
- **Alveolar macrophages**, part of the lung's immune defense, can engulf nanoparticles,

leading to either therapeutic benefit (in the case of intracellular infections) or clearance (reducing drug efficacy). Designing nanoparticles with surface modifications that minimize macrophage recognition helps prolong their residence time in the lungs.

**4. Drug Release and Intracellular Fate**

Once internalized, nanoparticles release their therapeutic payload either passively through diffusion or actively in response to specific stimuli such as **pH, enzymes, or redox gradients**. Stimuli-responsive nanoparticles ensure controlled and localized drug release within diseased tissues, minimizing damage to healthy lung cells. Intracellular trafficking pathways determine whether nanoparticles are degraded in lysosomes or escape into the cytoplasm to exert their therapeutic action.

**5. Clearance and Biocompatibility**

Nanoparticles are cleared from the lungs through mucociliary transport in the conducting airways and phagocytosis in the alveolar regions. Their **size, surface charge, and composition** play a critical role in determining clearance rates. Biocompatible and biodegradable materials such as phospholipids, chitosan, and PLGA are preferred to minimize toxicity and ensure safe degradation after therapeutic action.

**Targeted and Controlled Drug Delivery in the Respiratory Tract**

The primary goal of nanoparticle-based respiratory drug delivery is to achieve **precise, site-specific, and sustained release** of therapeutic agents within the lungs. Targeted and controlled drug delivery systems aim to maximize drug concentration at diseased sites while minimizing systemic exposure and adverse effects. In the context of respiratory diseases, where inflammation, infection, or tumor growth is localized in specific lung regions, such precision in drug delivery offers significant therapeutic advantages over conventional methods.

**1. Principles of Targeted Drug Delivery**

Targeted delivery in the respiratory tract can be achieved through **passive** or **active targeting** mechanisms.

- **Passive targeting** exploits the physiological characteristics of the diseased tissue, such as enhanced vascular permeability and impaired lymphatic drainage, allowing nanoparticles to accumulate at the site of inflammation or tumor through the *enhanced permeability and retention (EPR)* effect.
- **Active targeting** involves surface functionalization of nanoparticles with specific ligands, such as antibodies, peptides, aptamers, or sugars, which bind to overexpressed receptors on diseased cells. For example, nanoparticles conjugated with transferrin or folic acid ligands can specifically target cancerous or inflamed lung tissues, improving therapeutic precision.

**2. Controlled Drug Release Mechanisms**

Controlled release from nanoparticles ensures sustained therapeutic action and reduces dosing frequency. Several strategies are employed to achieve controlled release:

- **Diffusion-controlled systems**, where the drug diffuses gradually from the nanoparticle matrix.
- **Degradation-controlled systems**, in which biodegradable polymers like PLGA or chitosan degrade over time, releasing the drug in a predictable manner.
- **Stimuli-responsive systems**, where drug release is triggered by changes in pH, temperature, enzyme levels, or redox conditions specific to the diseased lung microenvironment.

For instance, nanoparticles that degrade in response to acidic pH can selectively release drugs in inflamed or infected lung regions where local acidity is elevated.

**3. Inhalable Nanocarriers for Localized Delivery**

Inhalation remains the most efficient and non-invasive route for delivering nanoparticles to the lungs. Inhalable formulations such as **dry powder inhalers (DPIs)**, **pressurized metered-dose inhalers (pMDIs)**, and **nebulized nanosuspensions** are designed to ensure optimal aerodynamic behavior for deep lung deposition. These systems enable rapid drug onset, localized action, and reduced systemic side effects. Moreover, nanocarriers can be engineered to adhere to the mucosal surface or penetrate mucus barriers, ensuring prolonged

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retention and improved bioavailability in pulmonary tissues.

**4. Dual and Co-Delivery Systems**

Recent research has explored **dual-drug** or **co-delivery nanoparticle systems** to simultaneously deliver multiple therapeutic agents, such as an anti-inflammatory and an antibiotic, or a chemotherapeutic and a gene therapy agent. This synergistic approach enhances therapeutic efficacy, combats drug resistance, and allows combination therapy in a single formulation, which is particularly beneficial in complex respiratory conditions like cystic fibrosis and lung cancer.

**5. Advantages and Therapeutic Outcomes**

Targeted and controlled nanoparticle systems significantly enhance **therapeutic index**, **reduce systemic toxicity**, and **improve patient compliance**. They ensure prolonged drug residence time, reduced dosing frequency, and better management of chronic diseases such as asthma, COPD, pulmonary fibrosis, and lung carcinoma. These systems also hold promise for personalized medicine, where therapy can be tailored based on the disease's molecular profile.

**Nanoparticle-Based Strategies for Specific Respiratory Disorders**

Nanoparticle-mediated drug delivery has opened new horizons in the management of various respiratory diseases by improving drug targeting, enhancing bioavailability, and reducing systemic toxicity. The unique ability of nanoparticles to localize drugs at specific lung sites and cross biological barriers has made them highly effective for treating chronic, infectious, and malignant respiratory disorders. The following section outlines the role of nanoparticle-based strategies in major respiratory ailments.

**1. Asthma**

Asthma is a chronic inflammatory disorder characterized by airway hyperresponsiveness, mucus overproduction, and bronchoconstriction. Conventional inhalation therapies using corticosteroids and bronchodilators often suffer from poor deposition and short duration of action. Nanoparticle systems offer improved drug retention and controlled release within the inflamed airways.

- **Polymeric nanoparticles** (e.g., PLGA, chitosan) have been developed to deliver corticosteroids like budesonide or fluticasone with sustained anti-inflammatory effects.
- **Lipid-based nanocarriers** enhance pulmonary absorption of poorly soluble drugs and improve mucosal penetration.
- **Ligand-targeted nanoparticles** can specifically bind to receptors overexpressed on inflammatory cells, such as eosinophils and mast cells, achieving precise drug localization.

**2. Chronic Obstructive Pulmonary Disease (COPD)**

COPD involves progressive airflow limitation caused by chronic inflammation and oxidative stress in the lungs. Traditional therapies show limited efficacy due to poor drug retention and systemic side effects. Nanotechnology-based interventions focus on targeted antioxidant and anti-inflammatory delivery.

- **Solid lipid nanoparticles (SLNs)** and **nanostructured lipid carriers (NLCs)** have been formulated to deliver corticosteroids and $\beta_2$-agonists with enhanced stability and prolonged release.
- **Nanoparticles encapsulating antioxidants** such as curcumin or N-acetylcysteine help mitigate oxidative damage to alveolar tissues.
- Smart nanocarriers capable of responding to oxidative stimuli can release therapeutic agents specifically in inflamed COPD-affected regions.

**3. Pulmonary Tuberculosis (TB)**

Pulmonary tuberculosis remains one of the deadliest infectious respiratory diseases worldwide. The long duration of conventional oral therapy and the emergence of multidrug-resistant TB (MDR-TB) have emphasized the need for novel drug delivery systems. Nanoparticle-based formulations improve drug solubility, enhance macrophage targeting, and reduce dosing frequency.

- **Polymeric nanoparticles** encapsulating first-line drugs such as rifampicin, isoniazid, and pyrazinamide allow sustained release and effective intracellular delivery.

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- **Liposomal and solid lipid nanoparticles** facilitate drug accumulation within alveolar macrophages, the primary site of *Mycobacterium tuberculosis* infection.
- Inhalable nanocarriers provide localized drug deposition in the lungs, reducing systemic toxicity and improving patient compliance.

**4. Lung Cancer**

Lung cancer is one of the most fatal malignancies globally, with conventional chemotherapy limited by systemic toxicity and multidrug resistance. Nanoparticles enable targeted and combination-based approaches for improved treatment outcomes.

- **Gold nanoparticles (AuNPs)** and **polymeric micelles** are being explored for site-specific delivery of anticancer drugs such as paclitaxel and cisplatin.
- **Ligand-functionalized nanoparticles** carrying tumor-targeting moieties (e.g., folate, transferrin, EGFR antibodies) selectively accumulate in cancer cells, enhancing efficacy while minimizing off-target effects.
- **Theranostic nanoparticles** combine therapy and imaging capabilities, allowing simultaneous cancer dete
- ction and treatment monitoring.

**5. Pulmonary Infections and Pneumonia**

Bacterial and viral infections of the lungs often pose treatment challenges due to antibiotic resistance and limited penetration of drugs into infected tissues.

- **Silver and zinc oxide nanoparticles** exhibit strong antimicrobial properties and are being investigated as adjuncts to traditional antibiotics.
- **Liposomal antibiotic formulations** enhance intracellular uptake and reduce dosing frequency in bacterial pneumonia.
- During the COVID-19 pandemic, **nanocarrier-based systems** were explored for mRNA vaccine delivery and antiviral drug encapsulation, demonstrating the clinical potential of nanomedicine in respiratory viral infections.

**6. Pulmonary Fibrosis and Cystic Fibrosis**

In fibrotic and mucus-associated disorders, drug diffusion is significantly hindered due to dense mucus barriers and scarred tissue.

- **Mucus-penetrating nanoparticles**, often coated with PEG, can bypass these barriers to deliver antifibrotic agents like pirfenidone directly to affected regions.
- **Gene-loaded nanoparticles** are under investigation for cystic fibrosis to deliver CFTR-correcting genes and improve epithelial function.

**Conclusion**

Nanoparticle-based inhalation systems offer targeted and efficient pulmonary drug delivery, significantly enhancing therapeutic outcomes in respiratory diseases such as asthma, COPD, pulmonary infections, and lung cancer. Innovations including stimuli-responsive nanoparticles, biomimetic coatings, and inhalable nucleic acid formulations are advancing precision respiratory therapy. Nonetheless, successful clinical translation requires overcoming challenges in large-scale manufacturing, aerosol reproducibility, biocompatibility, and regulatory approval. Overall, these emerging nanotechnologies hold great potential to transform the future of pulmonary drug delivery.

**Reference**

1. Sarode A, Patel P, Vargas-Montoya N, et al. Inhalable dry powder product (DPP) of mRNA lipid nanoparticles (LNPs) for pulmonary delivery. *Drug Deliv Transl Res*. 2024.
2. Ahmed R, et al. Formulation and clinical translation of inhalable nanomedicines for the treatment and prevention of pulmonary infectious diseases. *Drug Deliv Transl Res*. 2025.
3. Liu S, et al. Charge-assisted stabilization of lipid nanoparticles enables nebulization/inhalation of mRNA LNPs. *Nat Commun*. 2024.
4. Zimmermann CM, et al. Spray-drying siRNA-lipid nanoparticles for dry powder inhalation. *J*


*Control Release*. 2022. Gordon A, et al. Inhalable dry powders for lung mRNA delivery. *Adv Healthc Mater*. 2024.

5. Elella MHA, et al. Spray-dried nanolipid powders for pulmonary drug delivery. *Pharmaceutics*. 2024.

6. Costabile G, et al. State-of-the-art review on inhalable lipid and polymer nanoparticles. *Pharmaceutics*. 2024.

7. Cojocaru E, et al. Nanoparticle-based drug delivery systems in inhaled therapy. *Pharmaceuticals (Basel)*. 2024.

8. Chan HW, et al. Inhalable nanoparticle-based dry powder formulations: formulation and particle engineering strategies. *Pharmaceutics*. 2023.

9. Huang Z, et al. Nanoparticle-mediated pulmonary drug delivery: biological barriers and strategies. *Drug Deliv Transl Res*. 2021.

10. Peng S, et al. Nano-formulations for pulmonary delivery: past, present and future. *Pharmaceutics*. 2024.

11. Mahmoud DE, et al. Inhalable nanotechnology-based drug delivery systems for inflammatory lung diseases. *Pharmaceutics*. 2025.

12. Shafi H, et al. Advanced spray-dried inhalable microparticles/nanoparticles. *Pharmaceutics*. 2024.

13. Elella MHA, et al. Spray-dried proliposomes and inhalable lipid nanocarriers for antifungal pulmonary delivery. *Pulm Pharmacol Ther*. 2024.

14. Ogawa K, et al. Stable and inhalable powder formulation of mRNA-LNPs: drying techniques and stabilization. *Int J Pharm*. 2024.

15. Elella MHA, Mansour HM. Design and aerosol performance models for co-spray dried antibiotic/nanoparticle powders for DPI delivery. *J Pharm Sci*. 2024.

16. Costabile G, et al. Pulmonary LNP and polymeric nanoparticle technologies: comparative analysis. *Int J Pharm*. 2024.

17. Dhege CT, et al. Pulmonary drug delivery devices and nanosystems: barriers, strategies and clinical perspectives. *Eur J Pharm Biopharm*. 2024.

18. Pardi N, Hogan MJ, Porter FW, Weissman D. mRNA vaccines: a new era for vaccinology. *Nat Rev Drug Discov*. 2018.

19. Garaizar A, et al. Mechanistic studies on LNP behaviour in acidic endosomes: implications for pulmonary delivery. *Proc Natl Acad Sci U S A*. 2024.

20. Friis C, et al. Spray-dried LNP formulations enabling intratracheal mRNA delivery. *J Control Release*. 2024.

21. Munir M, et al. Formulation and delivery methods for lung imaging—nanoparticle contrast agents and aerosol methods. *EJNMMI Radiopharm Chem*. 2023.

22. Acosta MF, Mansour HM. Inhalable nanoparticles and microparticles for targeted pulmonary delivery. *AAPS J*. 2021.

23. Yu C, Fan CQ, Chen YX, et al. Global research trends and hotspots in nano-drug delivery systems for lung cancer: bibliometric analysis (1998–2024). *Discov Oncol*. 2025.

24. George M, et al. Treatment of lung diseases via nanoparticles and nanorobots. *Adv Drug Deliv Rev*. 2025.

25. Qi Y, et al. Advanced nanotherapies for precision treatment of acute pulmonary inflammation. *Nanomedicine (Lond)*. 2025.

26. Shaibie NA, et al. Inhaled biologics for respiratory diseases: clinical potential and formulation challenges. *Drug Deliv Transl Res*. 2025.

27. Jessamine V, et al. Application of nanoparticles as advanced drug delivery tools for COPD. *Heliyon*. 2024.

28. Arte KS, et al. Recent advances in drying and development of solid lipid nanoparticle powders for inhalation. *J Pharm Sci*. 2024.

29. Chan JW, Mansour HM. Advanced excipient strategies (leucine, sugars) for stabilizing

nanoparticle dry powders for DPI. *Int J Pharm*. 2023.

30. Shapiro J, et al. Biomimetic membrane-coated nanoparticles for pulmonary targeting and immune evasion. *ACS Nano*. 2024.

31. Wang W, Zhong Z, Huang Z, et al. Nanomedicines for targeted pulmonary delivery: receptor-mediated strategies and alternatives. *Nanoscale*. 2024.

32. Peng S, et al. Machine learning and in silico design of ionizable lipids for LNPs. *Chem Eng J*. 2024.

33. Srisuma P, Braatz RD, et al. Control and optimization of lyophilization for continuous manufacturing of inhalable biologic powders. *AIChE J*. 2025.