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Evaluation of the Potential of Nanotechnology in Enhancing Drug Bioavailability

Mufakkir Aziz[1], Muhammad Shahab Ud Din[2], Irfan Gul[2], Zia Ur Rehman[3], Syed Aman Ullah Shah Bukhari[4]

[1] Department of Medical Laboratory Technology, Faculty of Allied Health Sciences, The University of Agriculture Dera Ismail Khan, Pakistan.
[2] Faculty of Pharmacy, Gomal University Dera Ismail Khan, Pakistan.
[3] Department of Bioscience, Islamic International University Islamabad, Pakistan.
[4] Department of Chemical Engineering, University of Engineering and Technology Lahore, Pakistan.

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A B S T R A C T

Background: Poor bioavailability is a significant constraint for many therapeutic medicines, limiting their efficacy and clinical significance. Conventional drug delivery techniques frequently fail to address issues such poor solubility, enzymatic degradation, and non-specific dispersion. Nanotechnology offers novel approaches to overcoming these limitations and increasing medication absorption. **Objective:** This article examines how nanotechnology-based drug delivery systems can improve pharmaceutical bioavailability by highlighting several nanocarrier platforms and their modes of action. **Methods:** A complete literature review was undertaken from 2020 to 2025, utilizing recent publications. The study focuses on the mechanisms by which nanotechnology enhances bioavailability and the clinical applications of various nanocarriers such as liposomes, polymeric nanoparticles, solid lipid nanoparticles, dendrimers, nanoemulsions, and micelles. **Results:** Nanocarriers improve drug bioavailability through various mechanisms, including improved solubility and dissolution, protection against gastrointestinal degradation, targeted delivery via ligand modification, and leveraging the enhanced permeability and retention (EPR) effect. Several FDA-approved formulations, like Doxil, indicate the successful application of nanotechnology in clinical contexts. **Conclusion:** Nanotechnology has great potential for improving drug delivery and treatment results. While problems such as safety, cost, and regulatory approval persist, ongoing research and development are projected to result in smarter, more efficient drug delivery systems capable of revolutionizing modern pharmacotherapy.

Keywords: Nanotechnology, drug bioavailability, Nanocarriers, targeted drug delivery, Liposomes, Polymeric nanoparticles, Solid lipid nanoparticles.

Corresponding Author: *Mufakkir Aziz*
Email: mufakkiraziz125@gmail.com
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INTRODUCTION

Bioavailability is an important pharmacokinetic characteristic that relates to the proportion of a drug that enters the systemic circulation in its active form and thus becomes available for therapeutic action. It is an important factor in determining a drug's efficacy and safety profile, since low bioavailability can lead to inferior therapeutic outcomes or greater toxicity if higher dosages are employed to compensate (1). Bioavailability is influenced by the drug's physicochemical qualities, the formulation matrix, and physiological circumstances such enzymatic degradation, pH, and gastrointestinal motility (2).

Traditional medication delivery methods, such as tablets, capsules, and solutions, provide limited control over drug release and site-specific effect. Many promising medications fail in development because they are unable to overcome

physiological barriers such as the acidic pH of the gastrointestinal tract, digestive enzymes, and hepatic first-pass metabolism (3). These constraints highlight the critical need for novel drug delivery methods that improve drug solubility, protect therapeutic molecules from degradation, and assure efficient absorption and targeted distribution.

Nanotechnology has emerged as a game-changing tool for addressing these difficulties, allowing the development of nanoscale drug delivery devices with improved physicochemical and pharmacokinetic features. Nanocarriers such as liposomes, polymeric nanoparticles, solid lipid nanoparticles, dendrimers, and nanoemulsions have various benefits, including increased surface area for dissolution, hydrophobic drug encapsulation, and surface functionalization for targeted administration (4). Furthermore, nanocarriers can cross biological barriers, modulate drug release kinetics, and use the increased permeability and retention (EPR) effect for tumor targeting (5).

Recent advances in nanomedicine have resulted in the successful development and clinical approval of nanotechnology-based formulations, such as Doxil (liposomal doxorubicin) and Abraxane (albumin-bound paclitaxel), which have shown superior pharmacokinetics and therapeutic outcomes when compared to conventional formulations (6). These accomplishments underscore nanotechnology's enormous potential to change drug delivery and therapy techniques, particularly for medicines with low bioavailability.

Challenges in Conventional Drug Delivery Systems

Poor Solubility and Dissolution Rate

The majority of newly produced medications fall into Biopharmaceutics Classification System (BCS) Classes II and IV, which are distinguished by low water solubility and/or permeability (7). This reduces their capacity to dissolve in gastrointestinal fluids, which delays or prevents absorption.

First-pass Metabolism

Oral medications undergo substantial first-pass metabolism in the liver and intestinal walls, lowering the active drug concentration that reaches the bloodstream. This is especially problematic for hormones and chemotherapeutic agents (8).

Enzymatic and pH Degradation

The gastrointestinal (GI) tract is a hostile environment with varying pH and a large number of digesting enzymes. Many peptides, proteins, and nucleic acid-based therapies disintegrate before they are absorbed (9).

Non-specific Distribution

Conventional formulations frequently fail to target specific tissues or cells, resulting in systemic exposure and increased risk of adverse effects. This is especially concerning for hazardous medications such as chemotherapeutic agents (10).

Low Permeability Across Biological Barriers

Large molecular weight medicines and hydrophilic substances frequently have low permeability across epithelial and endothelial barriers, thus limiting bioavailability (11).

Mechanisms by which nanocarriers enhance bioavailability

Increased Solubility

Nanoparticles greatly increase the surface area-to-volume ratio of poorly soluble medicines, accelerating dissolution and absorption (12).

Protection against Degradation

Nanocarriers protect medications against acidic pH and enzymatic breakdown in the GI tract. This is critical for delivering sensitive biologics and peptides (13).

Enhanced Permeability

Nanocarriers improve paracellular and transcellular transport, allowing therapeutic molecules to pass tight epithelial junctions (14).

Controlled and sustained release

Many nanocarriers are designed to have longer drug release patterns, which keep therapeutic levels stable over time and reduce dose frequency (15).

Targeted Delivery

Surface modification with ligands such as antibodies, peptides, or aptamers enables nanoparticles to bind specifically to over expressed receptors on sick cells, increasing site-specific drug accumulation while decreasing off-target effects (16).

The Need for Continued Research

Despite the obvious benefits, nanomedicine development, scaling, and regulatory approval face significant difficulties. Manufacturing complexity, reproducibility, cost-effectiveness, and long-term safety are all issues that require interdisciplinary collaboration and innovation (17).

This review thoroughly examines the mechanisms by which nanotechnology improves medication bioavailability, investigates several nanocarrier systems, and considers current obstacles and future possibilities in this rapidly growing subject.

Mechanisms for Enhanced Bioavailability through Nanotechnology

Nanotechnology has transformed medication delivery by overcoming traditional systems' shortcomings, particularly

in terms of therapeutic agent bioavailability (18). Bioavailability, or the fraction of a given dose that enters systemic circulation in an active state, is critical to a drug's efficacy (19). Nanocarriers have been designed to overcome obstacles such as poor solubility, enzymatic degradation, and ineffective absorption, resulting in improved therapeutic effects (20). The following mechanisms explain how nanotechnology improves drug bioavailability.

Improved Solubility and Dissolution

A large number of pharmacologically active chemicals have poor water solubility, resulting in low oral bioavailability. Nanotechnology solves this by shrinking medication particles to the nanoscale, increasing their surface area-to-volume ratio, and improving dissolving rates in the gastrointestinal (GI) tract (21).

The conversion of pharmaceuticals into nanocrystals or nanoparticles enhances their wettability and dissolution rate, allowing for improved absorption. For example, nanocrystals have been demonstrated to improve the solubility and bioavailability of poorly soluble medicines, making them more effective when administered orally (22).

Magnetic nanoparticles (MNPs) have also been used to increase drug solubility. Their small size and wide surface area enable improved interaction with hydrophobic medicines, resulting in increased dispersion and solubility in aquatic settings (23).

Protection against enzymatic and pH degradation

Many therapeutic compounds, particularly peptides and proteins, are vulnerable to breakdown by enzymes and the acidic environment of the stomach (24). Nanocarriers can encapsulate these medications, protecting them from the severe environment and keeping them stable until they reach the absorption site (25). For example, chitosan-based nanoparticles have showed the potential to shield encapsulated pharmaceuticals against enzymatic degradation, hence increasing their stability and bioavailability (25).

Improved Permeability and Retention (EPR) Effect

Pathological disorders such as cancer cause the vasculature of affected tissues to become more permeable, resulting in decreased lymphatic outflow. The Enhanced Permeability and Retention (EPR) effect causes nanoparticles to collect preferentially in tumor tissues (26).

Nanoparticles with sizes ranging from 100 to 200 nm can take use of the EPR effect, allowing for passive tumor targeting and increased medication concentration at the desired spot. However, the efficiency of the EPR effect varies depending on the tumor type and is regulated by factors such as tumor heterogeneity and vascular architecture (27).

Targeted and Controlled Drug Release

Nanotechnology provides both passive and active targeting tactics, which improve medication accumulation at specific areas while decreasing off-target effects. Surface functionalization of nanoparticles with targeting ligands such as antibodies or peptides enables receptor-mediated endocytosis, resulting in site-specific delivery (28).

Smart nanovectors have been designed to offer regulated and prolonged medication release in response to certain physiological cues such as pH or temperature changes. These devices not only increase patient compliance by reducing dose frequency, but they also ensure consistent plasma drug concentrations, which is critical for treating chronic illnesses (29).

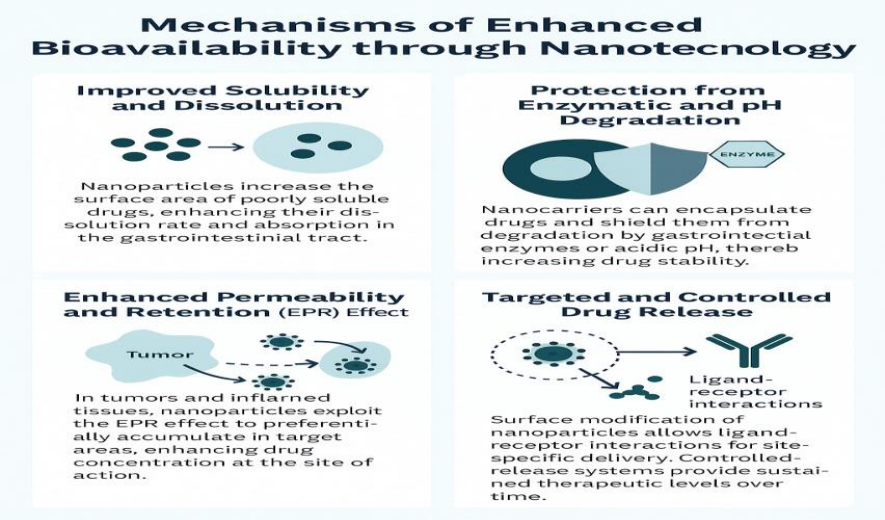

Figure 1: This series of graphs demonstrates nanotechnology's varied impact in increasing drug bioavailability.

Nanocarriers improve pharmacokinetic profiles by increasing the solubility and dissolution rates of poorly water-soluble drugs, protecting against enzymatic and pH-mediated degradation in the gastrointestinal tract, leveraging the Enhanced Permeability and Retention (EPR) effect for targeted accumulation in tumor or inflamed tissues, and enabling site-specific and controlled drug release through surface modification. The infographic also discusses numerous nanocarrier systems, including liposomes, polymeric nanoparticles, solid lipid nanoparticles (SLNs), dendrimers, nanoemulsions, and micelles, each of which has distinct structural and functional advantages for successful drug administration. These systems have shown significant promise in overcoming the limits of conventional drug formulations by enhancing therapeutic efficacy, stability, and patient compliance across multiple routes.

Nanocarrier Systems in Drug Delivery

Nanocarrier technologies have transformed medication delivery by increasing bioavailability, stability, and targeted administration of therapeutics (30). The following subsections describe numerous nanocarriers, including their architecture, benefits, and clinical applications.

Liposomes

Structure and advantages

Liposomes are spherical vesicles made up of one or more phospholipid bilayers with an aqueous core. Thier structure enables them to encapsulate hydrophilic and lipophilic medicines. Benefits include biocompatibility, the capacity to protect pharmaceuticals from deterioration, and the possibility of tailored administration (31).

Clinical Applications

Liposomes have been used to treat a variety of conditions, including cancer and infections. For example, Doxil®, a PEGylated liposomal version of doxorubicin, is approved to treat AIDS-related Kaposi's sarcoma, ovarian cancer, and multiple myeloma. Encapsulation in liposomes enhances pharmacokinetics and decreases cardiotoxicity (32).

Polymeric nanoparticles

Biodegradable Polymers

Polymeric nanoparticles are often composed of biodegradable polymers such as poly (lactic-co-glycolic acid) (PLGA) and chitosan. These materials are biocompatible, allowing for regulated drug release (33).

Controlled Release and Surface Modification

Surface modification, such as coating PLGA nanoparticles with chitosan, can improve mucoadhesion, cellular uptake, and drug release profiles. This method has been useful in increasing the bioavailability of a variety of medicinal drugs (34).

Solid lipid nanoparticles (SLNs)

Stability and Biocompatibility

SLNs are made up of solid lipids stabilized with surfactants, which provide benefits such as regulated drug release, protection of labile medicines, and increased stability. They are made of biocompatible lipids, making them ideal for a variety of administration methods (35).

Enhanced Absorption

Studies have indicated that SLNs increase the oral bioavailability of poorly soluble medicines by enhancing drug penetration across the gastrointestinal system and improving transcellular uptake. They are also being investigated for topical delivery because of their capacity to produce occlusive films, which improve skin penetration (36).

Dendrimers

Branching Structure and Functional Versatility

Dendrimers are highly branching, monodisperse macromolecules having a central core, internal layers (generations), and multiple surface functional groups. This design supports high drug loading and surface customization for targeted delivery (37).

Applications

Dendrimers can bind to nucleic acids, making them useful for gene transfer. They can also improve the solubility of poorly soluble medicines by enclosing them in internal cavities or creating complexes on their surfaces (38).

Nanoemulsions and Micelles

Enhanced Solubilization of Hydrophobic Drugs

Nanoemulsions and Micelles improve the solubility of hydrophobic drugs. Nanoemulsions are fine oil-in-water or water-in-oil dispersions stabilized with surfactants, whereas micelles are colloidal dispersions generated by amphiphilic molecules. Both techniques can solubilize hydrophobic medicines and increase their bioavailability (39).

Applications

Nanoemulsions and micelles have been studied for a variety of delivery routes, including oral, parenteral, and ocular. Their compact size and capacity to increase drug solubility make them ideal for administering a wide range of medicinal agents (40).

Applications of Nanotechnology in Drug Bioavailability Enhancement

Cancer Treatment

Nanotechnology has transformed cancer treatment by increasing the bioavailability of chemotherapeutic drugs. Liposomes, polymeric nanoparticles, and dendrimers can

carry chemotherapy medications directly to the tumor, reducing systemic side effects (41). Nanocarriers, such as Doxil® (liposomal doxorubicin), have been proven to boost chemotherapeutic drugs' bioavailability, hence improving therapeutic efficacy (42). Furthermore, the controlled release capabilities of these nanocarriers assure sustained drug levels at the target site, increasing the drug's overall effectiveness and lowering toxicity to healthy tissues (43).

Table 1: Overview of the various nanocarriers, their structures, advantages, and clinical applications.

Nanocarrier Type	Structure	Advantages	Applications
Liposomes	Spherical vesicles with phospholipid bilayers	Biocompatible, versatile, drug protection, enhanced stability	Doxil® (liposomal doxorubicin) for cancer therapy
Polymeric Nanoparticles	Made from biodegradable polymers like PLGA and chitosan	Biodegradable, controlled release, surface modification	Targeted drug delivery for cancer, gene therapy
Solid Lipid Nanoparticles	Solid lipid core with surfactant coating	Improved stability, biocompatibility, controlled drug release	Oral and topical drug delivery, especially lipophilic drugs
Dendrimers	Highly branched, monodisperse macromolecules	High drug-loading capacity, surface functionalization	Gene delivery, poorly soluble drugs
Nanoemulsions and Micelles	Small oil-in-water or water-in-oil dispersions, amphiphilic molecules	Enhanced solubilization of hydrophobic drugs, good drug penetration	Oral, parenteral, ocular drug delivery

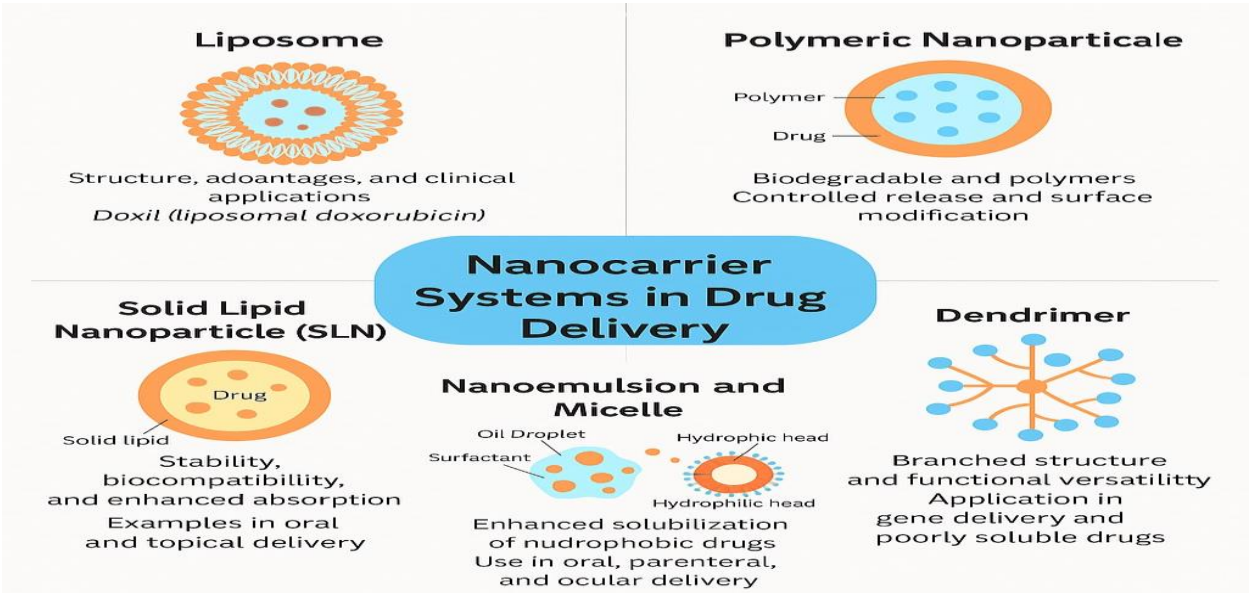

Figure 2: This picture depicts the therapeutic areas in which nanocarrier-based systems considerably improve drug bioavailability, such as cancer therapy, brain-targeted delivery, oral administration, infectious disease treatment, gene therapy, and ophthalmic applications. It emphasizes the different types of nanocarriers used and the distinct pharmacokinetic or therapeutic benefits obtained by nanotechnological treatments.

Drug Delivery to the Brain

The blood-brain barrier (BBB) poses a substantial difficulty to medicine delivery for CNS illnesses (44). Nanocarriers, particularly nanoparticles, have showed promise in crossing the BBB and delivering therapeutic medicines for diseases such as Alzheimer's and Parkinson's (45). Surface modification of nanoparticles with particular ligands or antibodies can improve transport across the BBB, increasing the bioavailability of CNS-targeted medicines (46). Nanoemulsions and micelles have also been utilized to transport medications with low water solubility to the brain (47).

Oral Drug Delivery

Oral medication delivery techniques confront difficulties such as poor solubility, gastrointestinal instability, and inadequate bioavailability (48). Nanotechnology has solved these difficulties by creating nanoparticle-based systems that increase medication solubility and stability. Solid lipid nanoparticles (SLNs) and polymeric nanoparticles, for example, have been utilized to increase therapeutic oral bioavailability by preventing enzymatic degradation and enhancing dispersion in the gastrointestinal system (49).

Targeted Drug Delivery for Infectious Diseases

Nanotechnology has also been used in the treatment of infectious disorders. Nanoparticles can be engineered to preferentially target pathogens or infected cells, increasing the bioavailability of antimicrobial drugs at the point of infection (50). Nanocarriers, such as liposomes, can encapsulate antibiotics, increasing their stability and delaying their release. This targeted method lowers the likelihood of antibiotic resistance by ensuring that the medicine reaches the infection site at therapeutic levels (51).

Gene therapy

Nanocarriers have significant potential in gene therapy, as they may carry genetic material to targeted cells or organs (52). Polymeric nanoparticles and dendrimers are widely employed for gene transfer because of their ability to encapsulate and protect nucleic acids (53). These nanocarriers increase the bioavailability of therapeutic genes by allowing them to enter target cells and preventing nuclease destruction. This method is being investigated for the treatment of hereditary illnesses such cystic fibrosis and muscular dystrophy (54).

Ocular Drug Delivery

The eye provides a particular obstacle for drug administration due to its anatomical barriers, such as the corneal epithelium, blood-retinal barrier, and limited bioavailability of many medications (55). Nanotechnology has enabled the creation of sophisticated ocular drug delivery systems that improve medication bioavailability and therapeutic efficacy in conditions such as glaucoma, macular degeneration, and diabetic retinopathy (56).

Nanoemulsions and micelles have been extensively investigated for ocular medication delivery (57). These nanocarriers increase the solubility of hydrophobic medicines, allowing them to pass through the corneal barrier and reach therapeutic levels in the eye (58). Recent investigations suggest that nanoemulsions containing cyclosporine A for dry eye disease or corticosteroids for macular edema produce prolonged release and boost medication absorption in the ocular tissues (59).

Table 2: Summarizing the applications of nanotechnology in drug bioavailability enhancement along with the relevant citations.

Application	Nanocarrier Type	Advantages	References
Cancer Treatment	Liposomes (e.g., Doxil), Polymeric Nanoparticles, Dendrimers	Targeted delivery, reduced systemic toxicity, bypasses drug resistance	41-43
Drug Delivery to the Brain	Lipid Nanoparticles, Polymeric Nanoparticles, Nanoemulsions	Overcome blood-brain barrier, improved bioavailability and brain-targeted delivery	44-47
Oral Drug Delivery	Solid Lipid Nanoparticles (SLNs), Polymeric Nanoparticles, Nanosuspensions	Enhanced solubility, sustained release, improved absorption	48,49
Targeted Drug Delivery in Infectious Diseases	Liposomes, Polymeric Nanoparticles, Nanogels	Localized delivery, reduced side effects, enhanced stability and activity	50,51
Gene Therapy	Dendrimers, Lipid Nanoparticles, Polymeric Nanoparticles	Efficient gene encapsulation and release, controlled and sustained delivery	52-54
Ocular Drug Delivery	Nanoemulsions, Micelles, Liposomes	Enhanced drug solubilization, prolonged retention in ocular tissues	55-59

Challenges and Future Directions in Nanotechnology for Drug Bioavailability Enhancement

Stability and Shelf-life of Nanocarriers

Nanocarrier stability is a critical challenge in clinical translation. Nanoparticles are prone to aggregation, disintegration, and changes in physicochemical properties over time, which can result in diminished efficacy and bioavailability. The shelf life of these carriers is crucial for commercial use because any structural changes can impact drug loading, release patterns, and overall therapeutic effectiveness (60).

Solution Directions

To address these challenges, researchers are aiming to improve nanoparticle surface modification, which can increase colloidal stability (61). The creation of more stable polymers, lipids, and other materials for nanocarrier production is also essential. Furthermore, lyophilization strategies are being investigated to improve nanocarrier stability during storage (62).

Toxicology and Biocompatibility

The potential toxicity of nanomaterials remains a major issue, as nanoparticles can collect in numerous organs and cause negative effects. Nanoparticles' interaction with biological systems can cause inflammation, immunological reactions, and cytotoxicity. Nanoparticles' biocompatibility is influenced by their size, surface charge, and substance, and must be extensively studied before clinical application (63).

Solution

Extensive preclinical toxicity studies are required to assess the safety of nanocarriers. Furthermore, the development of biodegradable nanoparticles and those that imitate the features of naturally occurring biomolecules may aid in mitigating negative impacts. Also, creating nanocarriers that are cleared from the body without causing toxicity is an ongoing area of research (64).

Regulatory hurdles and standardization

The lack of defined regulatory frameworks for nanomedicines prevents their extensive clinical implementation (65). Regulatory organizations, such as the US Food and medication Administration and the European Medicines Agency, have yet to set clear rules for approving nanotechnology-based medication delivery systems. This uncertainty may postpone the commercialization of promising nanocarrier systems (66).

Solution Directions

Comprehensive regulatory guidelines for nanomedicines are critical. International collaboration between regulatory bodies and scientific communities is required to set these standards, which ensure the safety and efficacy of nanocarriers (67). Furthermore, developing characterisation methodologies to assess nanoparticle properties is critical for regulatory approval (68).

Large-Scale Manufacturing

The move from lab-scale nanocarrier synthesis to large-scale manufacturing presents considerable hurdles (69). Nanoparticle production frequently necessitates specialized equipment, precise control of conditions, and high-quality raw ingredients, making it costly and difficult to scale up. Furthermore, maintaining the quality and consistency of nanocarriers in mass production is a continuous challenge (60).

Solution Directions

To address manufacturing issues, create scalable production technologies such as solvent evaporation, high-pressure homogenization, and microfluidics (61). The use of automated technologies and artificial intelligence for quality control can improve the production process (62).

Drug Release and Targeting Precision

While nanocarriers have the potential to improve targeted medicine delivery, precise control over drug release is still a difficulty (63). Drug release kinetics must be carefully planned to guarantee long-termtherapeutic benefits without premature release or insufficient drug concentration at the target site. Furthermore, accurate targeting of specific tissues or cells (e.g., cancer cells) while reducing off-target effects remains an important study area (64).

Solution Directions

Advances in smart nanocarriers that respond to environmental cues (such as pH, temperature, or enzyme activity) provide the possibility of controlled drug release (65). Another technique for improving drug delivery precision is surface modification with particular ligands or antibodies that target receptor-expressing cells (66).

Personalized Medicine and Nanotechnology

Personalized medicine, which tailors pharmacological therapy to individual patients, is a growing field in which nanotechnology can play an important role (67). Nanocarriers can be programmed to deliver medications based on individual genetic profiles, disease condition, and other criteria. However, more research and clinical validation are needed to integrate nanotechnology and personalized medicine (68).

Solution Directions

Personalized nanomedicine will benefit from advancements in genomes, biomarker identification, and diagnostic procedures (69). Integrating nanocarriers with diagnostic instruments like nanoparticles for biomarker detection

allows for real-time monitoring of treatment efficacy and patient response (70).

Future Directions

The future of nanotechnology in drug bioavailability enhancement holds promise for overcoming current hurdles. Nanomaterial design innovations, such as biocompatible polymers and stimuli-responsive systems, will make drug delivery safer and more efficient. Furthermore, combining nanocarriers with other therapeutic techniques, such as gene therapy and immunotherapy, has the potential to open up new treatment options for complicated diseases including cancer and neurological disorders (71).

Solution Directions

Nanocarriers that can overcome biological barriers (e.g., the blood-brain barrier) and those that can be tailored to specific disorders are being studied extensively (72). The integration of nanotechnology, AI, machine learning, and data analytics will speed up the development of next-generation medication delivery systems (73).

Future Perspectives

Key Achievements and Progress

Recent breakthroughs in the production of nanocarriers, including liposomes, polymeric nanoparticles, solid lipid nanoparticles (SLNs), dendrimers, nanoemulsions, and micelles, have opened the way for more effective drug delivery (74). These carriers have been developed to increase drug solubility, stability, and controlled release (75). Furthermore, utilizing the Enhanced Permeability and Retention (EPR) effect in tumors, as well as the ability for targeted and site-specific drug administration, has resulted in major advancements in cancer treatment and other diseases (76).

Nanotechnology-based systems have also shown encouraging results in breaking biological barriers such as the blood-brain barrier, which has traditionally been one of the most difficult obstacles in medication delivery. Furthermore, integrating nanotechnology with personalized medicine would enable more individualized therapeutic techniques, improving treatment effectiveness and safety (77).

Challenges to Overcome

Despite progress, clinical translation of nanocarriers remains a difficult task (68). Toxicity, long-term stability, regulatory problems, and large-scale production must all be addressed to assure the safety and viability of nanotechnology-based drug delivery systems (79). More thorough preclinical and clinical research is needed to determine the long-term safety and effectiveness of these systems, as well as to better understand their pharmacokinetic and pharmacodynamic profiles (80).

Future Prospects

Looking ahead, the future of nanotechnology in medicine delivery is bright. Ongoing research focuses on creating intelligent nanocarriers that can release medications in response to specific inputs like pH, temperature, or enzyme activity (81). The combination of nanocarriers with diagnostic tools such as imaging agents and biomarkers will allow for real-time monitoring of medication distribution, resulting in a more tailored approach to therapy (82).

Nanomedicine is positioned to play a critical role in treating diseases that now have few treatment choices (83). Artificial intelligence (AI) and machine learning innovations are expected to drive the next generation of advances in nanocarrier design and optimization, allowing for more accurate and efficient drug delivery systems (84).

CONCLUSION

Nanotechnology has emerged as a disruptive approach to drug delivery, providing novel solutions to long-standing issues such as poor solubility, instability, enzymatic degradation, and the lack of tailored delivery associated with traditional drug formulations. Nanocarriers such as liposomes, polymeric nanoparticles, solid lipid nanoparticles, dendrimers, nanoemulsions, and micelles have shown great promise in a variety of therapeutic areas by increasing drug bioavailability through mechanisms such as improved solubility, degradation protection, and targeted release. Despite significant advances, various problems have to be addressed, including toxicity issues, regulatory hurdles, high production costs, and scalability, in order to assure safe and effective clinical translation. Future research is planned to focus on the creation of smart, responsive nanocarriers, as well as the incorporation of artificial intelligence and precision medicine approaches to improve medication delivery strategies. With continuous improvements and interdisciplinary collaboration, nanotechnology has the potential to reshape the future of pharmacology, making therapies more efficient, patient-specific, and available.

REFERENCES

1. Olsman, M., Sereti, V., Andreassen, K., Snipstad, S., van Wamel, A., Eliasen, R., ... & de Lange Davies, C. (2020). Ultrasound-mediated delivery enhances therapeutic efficacy of MMP sensitive liposomes. *Journal of controlled release*, *325*, 121-134.
2. Xia, W., Singh, N., Goel, S., & Shi, S. (2023). Molecular imaging of innate immunity and

immunotherapy. *Advanced drug delivery reviews*, *198*, 114865.
3. Mansouri, S., Alharbi, Y., & Alqahtani, A. (2024). Current status and prospects for improved targeted delivery approaches for cancer. *Pathology-Research and Practice*, *253*, 154993.
4. Sengar, A. (2025). The Role of Liposomal Drug Delivery in Modern Medicine and the Expanding Potential of Nanocarriers.
5. SANAP, D., & GHUGE, P. (2024). Microemulsions as a potential carrier for improved drug delivery. *Journal of Research in Pharmacy*, *28*(6).
6. Yang, D., Xu, G., Ding, H., Zhong, L., Zhu, J., Mi, X., ... & Fang, L. (2024). Population pharmacokinetic and exposure-toxicity analyses of nab-paclitaxel after pegylated recombinant human granulocyte colony-stimulating factor administration in patients with metastatic breast cancer. *Cancer Chemotherapy and Pharmacology*, *94*(4), 523-534.
7. Baral, K. C., & Choi, K. Y. (2025). Barriers and Strategies for Oral Peptide and Protein Therapeutics Delivery: Update on Clinical Advances. *Pharmaceutics*, *17*(4), 397.
8. Liu, Y., Liang, Y., Yuhong, J., Xin, P., Han, J. L., Du, Y., ... & Ma, Y. (2024). Advances in nanotechnology for enhancing the solubility and bioavailability of poorly soluble drugs. *Drug Design, Development and Therapy*, 1469-1495.
9. Singh, K., Jain, D., Sethi, P., Gupta, J. K., Tripathi, A. K., Kumar, S., ... & Guru, A. (2024). Emerging pharmacological approaches for Huntington's disease. *European Journal of Pharmacology*, 176873.
10. Rashidi, N., Davidson, M., Apostolopoulos, V., & Nurgali, K. (2024). Nanoparticles in cancer diagnosis and treatment: Progress, challenges, and opportunities. *Journal of Drug Delivery Science and Technology*, 105599.
11. Zheng, G., Zhang, B., Yu, H., Song, Z., Xu, X., Zheng, Z., ... & Zhao, Y. (2025). Therapeutic applications and potential biological barriers of nano-delivery systems in common gastrointestinal disorders: a comprehensive review. *Advanced Composites and Hybrid Materials*, *8*(2), 1-22.
12. Zhuo, Y., Zhao, Y. G., & Zhang, Y. (2024). Enhancing drug solubility, bioavailability, and targeted therapeutic applications through magnetic nanoparticles. *Molecules*, *29*(20), 4854.
13. Liu, Y., Liang, Y., Yuhong, J., Xin, P., Han, J. L., Du, Y., ... & Ma, Y. (2024). Advances in nanotechnology for enhancing the solubility and bioavailability of poorly soluble drugs. *Drug Design, Development and Therapy*, 1469-1495.
14. Munir, M., Zaman, M., Waqar, M. A., Khan, M. A., & Alvi, M. N. (2024). Solid lipid nanoparticles: a versatile approach for controlled release and targeted drug delivery. *Journal of liposome research*, *34*(2), 335-348.
15. Tang, Y., Wu, Z., Hu, H., Yu, D., Liu, C., Jiang, H., ... & Hu, Y. (2024). Indocyanine green-mediated fabrication of urchin-like hydroxyethyl starch nanocarriers for enhanced drug tumor EPR and deep penetration effects. *International Journal of Biological Macromolecules*, *271*, 132616.
16. Sengar, A. (2025). The Role of Liposomal Drug Delivery in Modern Medicine and the Expanding Potential of Nanocarriers.
17. Kattimani, V., Bhukya, N. K. N., Panga, G. S. K., Chakrabarty, A., & Lingamaneni, P. (2024). Nano-Drug Carriers for Targeted Therapeutic Approaches in Oral Cancer: A Systematic Review. *Journal of Maxillofacial and Oral Surgery*, *23*(4), 763-771.
18. Munaweera, I., & Yapa, P. (2024). *Principles and applications of nanotherapeutics*. CRC Press.
19. Amponsah, S. K., & Pathak, Y. V. (2025). Pharmacokinetic Principles and Concepts: An Overview. *Basics and Clinical Applications of Drug Disposition in Special Populations*, 1-9.
20. Arya, A., & Yashan, N. The Nanorevolution in Medicine: Advancing Drug Delivery Systems with Nanomaterials and Nanodevices.
21. Gaikwad, S. S., Morales, J. O., Lande, N. B., Catalán-Figueroa, J., Laddha, U. D., & Kshirsagar, S. J. (2024). Exploring paediatric oral suspension development: Challenges, requirements, and formulation advancements. *International journal of pharmaceutics*, 124169.
22. Tian, Z., Mai, Y., Meng, T., Ma, S., Gou, G., & Yang, J. (2021). Nanocrystals for Improving Oral Bioavailability of Drugs: Intestinal Transport Mechanisms and Influencing Factors. *AAPS PharmSciTech*, *22*(5), 179. https://doi.org/10.1208/s12249-021-02041-7
23. Tian, Z., Mai, Y., Meng, T., Ma, S., Gou, G., & Yang, J. (2021). Nanocrystals for Improving Oral Bioavailability of Drugs: Intestinal Transport Mechanisms and Influencing Factors. *AAPS PharmSciTech*, *22*(5), 179. https://doi.org/10.1208/s12249-021-02041-7
24. Shinde, V. R., Revi, N., Murugappan, S., Singh, S. P.,

& Rengan, A. K. (2022). Enhanced permeability and retention effect: A key facilitator for solid tumor targeting by nanoparticles. *Photodiagnosis and photodynamic therapy*, *39*, 102915. https://doi.org/10.1016/j.pdpdt.2022.102915

25. Al-Edresi, S., Hamrah, K. A., & Al-Shaibani, A. (2024). Formulation and validation of Candesartan cilexetil-loaded nanosuspension to enhance solubility. *Pharmacia*, *71*, 1-13.
26. Wu, J. (2021). The Enhanced Permeability and Retention (EPR) Effect: The Significance of the Concept and Methods to Enhance Its Application. *Journal of Personalized Medicine*, *11*(8), 771. https://doi.org/10.3390/jpm11080771
27. Khan, J., & Yadav, S. (2024). Nanotechnology-based Nose-to-brain Delivery in Epilepsy: A Novel Approach to Diagnosis and Treatment. *Pharmaceutical Nanotechnology*, *12*(4), 314-328.
28. Emeihe, E. V., Nwankwo, E. I., Ajegbile, M. D., Olaboye, J. A., & Maha, C. C. (2024). Revolutionizing drug delivery systems: Nanotechnology-based approaches for targeted therapy. *International Journal of Life Science Research Archive*, *7*(1), 040-058.
29. Jadhav, V., Roy, A., Kaur, K., Rai, A. K., & Rustagi, S. (2024). Recent advances in nanomaterial-based drug delivery systems. *Nano-Structures & Nano-Objects*, *37*, 101103.
30. Cao, Z., Liu, J., & Yang, X. (2024, October). Deformable nanocarriers for enhanced drug delivery and cancer therapy. In *Exploration* (Vol. 4, No. 5, p. 20230037)
31. Liu, P., Chen, G., & Zhang, J. (2022). A Review of Liposomes as a Drug Delivery System: Current Status of Approved Products, Regulatory Environments, and Future Perspectives. *Molecules (Basel, Switzerland)*, *27*(4), 1372. https://doi.org/10.3390/molecules27041372
32. Chen, J., Hu, S., Sun, M., Shi, J., Zhang, H., Yu, H., & Yang, Z. (2024). Recent advances and clinical translation of liposomal delivery systems in cancer therapy. *European Journal of Pharmaceutical Sciences*, *193*, 106688.
33. Sengar, A. (2025). *Liposomal drug delivery systems: An intro as a primer for advanced therapeutics. Preprints*.
34. Beach, M. A., Nayanathara, U., Gao, Y., Zhang, C., Xiong, Y., Wang, Y., & Such, G. K. (2024). Polymeric nanoparticles for drug delivery. *Chemical Reviews*, *124*(9), 5505-5616.
35. Wang, Y., Li, H., Rasool, A., Wang, H., Manzoor, R., & Zhang, G. (2024). Polymeric nanoparticles (PNPs) for oral delivery of insulin. *Journal of Nanobiotechnology*, *22*(1), 1.
36. Li, M., Fang, G., Zahid, F., Saleem, R., Ishrat, G., Ali, Z., ... & ud Din, F. (2024). Co-delivery of paclitaxel and curcumin loaded solid lipid nanoparticles for improved targeting of lung cancer: In vitro and in vivo investigation. *Heliyon*, *10*(9).
37. Mangle, A. P., Ravindra, L., Hatwar, P. R., & Kubde, J. A. (2025). Lipid-Based Nanocarriers for Enhanced Oral Bioavailability: A Review of Recent Advances and Applications. *Asian Journal of Pharmaceutical Research and Development*, *13*(1), 71-80.
38. Choudhary, S., Gupta, L., Rani, S., Dave, K., & Gupta, U. (2017). Impact of Dendrimers on Solubility of Hydrophobic Drug Molecules. *Frontiers in pharmacology*, *8*, 261. https://doi.org/10.3389/fphar.2017.00261
39. Yoo, H. J., & Yang, S. G. (2025). Enhanced oral bioavailability of megestrol acetate via polymer-hybridized solid lipid nanoparticles using ultrasonic nebulization method. *Journal of Pharmaceutical Investigation*, *55*(1), 105-112.
40. Bose, A., Roy Burman, D., Sikdar, B., & Patra, P. (2021). Nanomicelles: Types, properties and applications in drug delivery. *IET nanobiotechnology*, *15*(1), 19–27. https://doi.org/10.1049/nbt2.12018
41. Nicolaescu, O. E., Belu, I., Mocanu, A. G., Manda, V. C., Rău, G., Pîrvu, A. S., ... & Ciocîlteu, M. V. (2025). Cyclodextrins: Enhancing Drug Delivery, Solubility and Bioavailability for Modern Therapeutics. *Pharmaceutics*, *17*(3), 288.
42. Tenchov, R., Hughes, K. J., Ganesan, M., Iyer, K. A., Ralhan, K., Lotti Diaz, L. M., ... & Zhou, Q. A. (2025). Transforming Medicine: Cutting-Edge Applications of Nanoscale Materials in Drug Delivery. *ACS nano*.
43. Ur Rahman, M., Hussain, H. R., Akram, H., Sarfraz, M., Nouman, M., Khan, J. A., & Ishtiaq, M. (2025). Niosomes as a targeted drug delivery system in the treatment of breast cancer: preparation, classification and mechanisms of cellular uptake. *Journal of Drug Targeting*, 1-17.
44. El-Tanani, M., Satyam, S. M., Rabbani, S. A., El-Tanani, Y., Aljabali, A. A., Al Faouri, I., & Rehman, A. (2025). Revolutionizing Drug Delivery: The Impact of Advanced Materials Science and Technology on Precision Medicine. *Pharmaceutics*, *17*(3), 375.
45. Mohammed, P. N., Hussen, N. H., Hasan, A. H., Salh,

H. J. H., Jamalis, J., Ahmed, S., ... & Kamal, M. A. (2025). A review on the role of nanoparticles for targeted brain drug delivery: synthesis, characterization, and applications. *EXCLI journal*, *24*, 34.

46. Jin, L., Nie, L., Deng, Y., Khana, G. J., & He, N. (2025). The Application of Polymeric Nanoparticles as Drug Delivery Carriers to Cells in Neurodegenerative Diseases. *Cell Proliferation*, e13804.
47. Chauhan, A., Mori, D., Soniwala, M., Prajapati, B., & Shah, S. (2025). Neuro-Nanocarriers: Redefining Treatment Pathways for Brain Disorders. *BioNanoScience*, *15*(1), 1-26.
48. Mitrović, D., Zaklan, D., Đanić, M., Stanimirov, B., Stankov, K., Al-Salami, H., & Pavlović, N. (2025). The Pharmaceutical and Pharmacological Potential Applications of Bilosomes as Nanocarriers for Drug Delivery. *Molecules*, *30*(5), 1181.
49. Mangle, A. P., Ravindra, L., Hatwar, P. R., & Kubde, J. A. (2025). Lipid-Based Nanocarriers for Enhanced Oral Bioavailability: A Review of Recent Advances and Applications. *Asian Journal of Pharmaceutical Research and Development*, *13*(1), 71-80.
50. Rostami, E. (2025). Alginate-based nanoparticles for drug delivery. In *Theranostics Nanomaterials in Drug Delivery* (pp. 157-168). Academic Press.
51. Mukhlif, B. A., Ullah, M. I., Uthirapathy, S., Menon, S. V., Sharma, R. S. K., Kadhim, A. J., ... & Kadhum, W. R. (2025). Multifunctional nanoparticles for image-guided drug delivery in nuclear medicine: advancements and applications. *Journal of Radioanalytical and Nuclear Chemistry*, 1-15.
52. Reddy, K. T. K., & Reddy, A. S. (2025). Recent breakthroughs in drug delivery systems for targeted cancer therapy: an overview. *Cellular, Molecular and Biomedical Reports*, *5*(1), 13-27.
53. Shao, X., Zhao, X., Wang, B., Fan, J., Wang, J., & An, H. (2025). Tumor microenvironment targeted nano-drug delivery systems for multidrug resistant tumor therapy. *Theranostics*, *15*(5), 1689.
54. Vijay, V., & Perumal, M. K. (2025). Morin, a Polypharmacological Marvel: Unveiling its versatility and recent advances in bioavailability enhancement. *Food Bioscience*, 106104.
55. Kanika, A. A., Ansari, M. M., & Khan, R. (2025). Surface Modification, Functionalization and Bioconjugation of Nanomaterials for Targeted Drug Delivery. *Emergence of Sustainable Biomaterials in Tackling Inflammatory Diseases*, 153.
56. Shadab, A., Farokhi, S., Fakouri, A., Mohagheghzadeh, N., Noroozi, A., Razavi, Z. S., ... & Mahjoor, M. (2025). Hydrogel-based nanoparticles: revolutionizing brain tumor treatment and paving the way for future innovations. *European Journal of Medical Research*, *30*(1), 71.
57. Klaus, S. E., Breunig, M., & Göpferich, A. (2025). Nanoparticles in intraocular drug delivery. *Medizinische Genetik*, *37*(1), 37-46.
58. Sonowal, L., & Gautam, S. (2025). Ocular drug delivery strategies using carbon nanotubes: A perspective. *Materials Letters*, *379*, 137642.
59. Sahoo, R. N., Rout, S., Parmanik, A., Satapathy, B. S., Pattnaik, S., Maharana, L., & Nayak, A. K. (2025). Inorganic biomaterials for ocular drug delivery: A comprehensive review. *Journal of Drug Delivery Science and Technology*, 106667.
60. Abaidullah, N., Muhammad, K., & Waheed, Y. (2025). Delving into nanoparticle systems for enhanced drug delivery technologies. *AAPS PharmSciTech*, *26*(3), 74.
61.
62. Munir, M., Zaman, M., Waqar, M. A., Khan, M. A., & Alvi, M. N. (2024). Solid lipid nanoparticles: a versatile approach for controlled release and targeted drug delivery. *Journal of liposome research*, *34*(2), 335-348.
63. Luhar, M., Viradiya, R., Panjabi, S., & Patel, G. (2025). Nanotechnology in Ocular Drug Delivery: the potential of polymeric micelles as a drug delivery vehicle. *Journal of Ocular Pharmacology and Therapeutics*, *41*(2), 54-64.
64. Liu, F., Chen, Y., Huang, Y., Jin, Q., & Ji, J. (2024). Nanomaterial-based therapeutics for enhanced antifungal therapy. *Journal of Materials Chemistry B*, *12*(37), 9173-9198.
65. Yang, F., Xue, J., Wang, G., & Diao, Q. (2022). Nanoparticle-based drug delivery systems for the treatment of cardiovascular diseases. *Frontiers in pharmacology*, *13*, 999404.
66. Zhai, Y., Liang, Z., Liu, X., & Zhang, W. (2025). Employing Copper-Based Nanomaterials to Combat Multi-Drug-Resistant Bacteria. *Microorganisms*, *13*(4), 708.
67. Vora, L. K., Gholap, A. D., Jetha, K., Thakur, R. R. S., Solanki, H. K., & Chavda, V. P. (2023). *Artificial intelligence in pharmaceutical technology and drug delivery design. Pharmaceutics. 2023; 15: 1916*.
68. Tewari, A. K., Upadhyay, S. C., Kumar, M., Pathak, K., Kaushik, D., Verma, R., ... & Cavalu, S. (2022). Insights on development aspects of polymeric nanocarriers: the translation from bench to

clinic. *Polymers*, *14*(17), 3545.

69. Khandker, S. S., Godman, B., Jawad, M. I., Meghla, B. A., Tisha, T. A., Khondoker, M. U., ... & Adnan, N. (2021). A systematic review on COVID-19 vaccine strategies, their effectiveness, and issues. *Vaccines*, *9*(12), 1387.
70. Husain, S., Bhadra, L., Simnani, F. Z., Nandi, A., Panda, P. K., & Verma, S. K. Biogenic Metal Nanoparticles Biosynthesis to Applications. In *Sustainable Green Synthesised Nano-Dimensional Materials for Energy and Environmental Applications* (pp. 1-25). CRC Press.
71. Alotaibi, B. S., Buabeid, M., Ibrahim, N. A., Kharaba, Z. J., Ijaz, M., Noreen, S., & Murtaza, G. (2021). Potential of nanocarrier-based drug delivery systems for brain targeting: A current review of literature. *International Journal of Nanomedicine*, 7517-7533.
72. Shaw, T. K., & Paul, P. (2022). Recent approaches and success of liposome-based nano drug carriers for the treatment of brain tumor. *Current drug delivery*, *19*(8), 815-829.
73. Xing, Y., Yasinjan, F., Yang, M., Du, Y., Geng, H., He, M., ... & Fan, K. (2023). A scientometric analysis and up-to-date review of nano-based drug delivery systems in glioblastoma treatment. *Nano Today*, *52*, 101961.
74. Khan, M. U. A., Raza, M. A., Haider, S., Shah, S. A., Arshed, M., Abd Razak, S. I., & Haider, A. (2022). Medical applications of polymer/functionalized nanoparticle composite systems, renewable polymers, and polymer–metal oxide composites. In *Renewable Polymers and Polymer-Metal Oxide Composites* (pp. 129-164). Elsevier.
75. Ahmad, Z., Waraich, E. A., Barutçular, C., Ahmed, S., Iqbal, M. A., Aziz, A., ... & Bano, S. (2024). Prospects of Nanotechnology for Abiotic and Biotic Stresses Amelioration in Field Crops. In *The Nanotechnology Driven Agriculture* (pp. 67-84). CRC Press.
76. Alghamdi, M. A., Fallica, A. N., Virzì, N., Kesharwani, P., Pittalà, V., & Greish, K. (2022). The promise of nanotechnology in personalized medicine. *Journal of personalized medicine*, *12*(5), 673.
77. Herrmann, I. K., & Rösslein, M. (2016). Personalized medicine: the enabling role of nanotechnology. *Nanomedicine*, *11*(1), 1-3.
78. Ho, D., Wang, C. H. K., & Chow, E. K. H. (2015). Nanodiamonds: The intersection of nanotechnology, drug development, and personalized medicine. *Science Advances*, *1*(7), e1500439.
79. Umer, M. F., & Arshed, M. (2025). Nanomaterials in Personalized Medicine: Pioneering Precision Strategies for Cancer Prevention. In *Breaking Boundaries: Pioneering Sustainable Solutions Through Materials and Technology* (pp. 435-454). Singapore: Springer Nature Singapore.
80. Xiao, F., Shen, X., Tang, W., & Yang, D. (2025). Emerging Trends in DNA Nanotechnology-Enabled Cell Surface Engineering. *JACS Au*, *5*(2), 550-570.
81. Zuo, C. J., & Tian, J. (2025). Global trends and emerging research in nanotechnology for esophageal cancer: a comprehensive bibliometric analysis. *Discover Oncology*, *16*(1), 262.
82. Dudhat, K. (2025). Nanotechnology-Driven Approaches for Targeted Rectal Microbiome Modulation in Gastrointestinal Disorders. *Current Proteomics*.
83. Kumar, N., & Mangla, M. (2025). Nanotechnology and nanobots unleashed: pioneering a new era in gynecological cancer management–a comprehensive review. *Cancer Chemotherapy and Pharmacology*, *95*(1), 18.
84. Tong, J., Wang, Z., Zhang, J., Gao, R., Liu, X., Liao, Y., ... & Wei, Y. (2024). Advanced Applications of Nanomaterials in Atherosclerosis Diagnosis and Treatment: Challenges and Future Prospects. *ACS Applied Materials & Interfaces*, *16*(43), 58072-58099.