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Nanotechnology Meets Phytomedicine Toward Smarter Drug Delivery Systems

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Abstract

Using bioactive substances derived from plants, or phytomedicine, has long shown promise in treating a variety of illnesses with fewer adverse effects than synthetic medications. Nevertheless, a lot of phytochemicals have issues with inadequate targeting in vivo, low bioavailability, poor solubility, and chemical instability. By enabling encapsulation, controlled release, targeted delivery, and stimuli responsive behavior, nanotechnology provides effective tools to get around these restrictions. This review examines the intersection of nanotechnology and phytomedicine, providing an overview of recent developments in nanocarrier systems, including micelles, lipid-based nanoparticles, polymeric nanoparticles, nanoemulsions, and hybrid materials, intended for the intelligent delivery of therapeutic agents derived from plants. We look at how these nano-formulations reduce off-target effects, improve pharmacokinetics, increase therapeutic efficacy, and enable controlled or triggerable release in response to environmental cues (pH, redox, enzymes, etc.). We also discuss important issues like cost, regulatory barriers, manufacturing scalability, and safety/toxicity. Lastly, we point out potential future paths that could result in the next generation of intelligent phytomedicine delivery systems, such as theranostics, green synthesis, and AI-guided design.

Keywords: Bioavailability, nanocarrier, nanoemulsions, nanotechnology, phytomedicine

INTRODUCTION

A promising area of therapeutic innovation is the fusion of modern nanotechnology and conventional plant-based medicine. Because of its natural origin, safety profile, and pharmacological potential, phytomedicine – which consists of physiologically active compounds derived from medicinal plants – has attracted significant attention. Despite benefits, various phytochemicals have issues that limit clinical translation and therapeutic efficacy, including poor water solubility, low bioavailability, fast metabolism, and lack site-specific action. By making it possible to create nanoscale drug delivery systems that can encapsulate, shield, and deliver phytoconstituents to specific locations, nanotechnology provides innovative ways to get around these restrictions. By reducing systemic toxicity and increasing therapeutic efficacy, these clever nanocarriers – which include liposomes, polymeric nanoparticles, dendrimers, nanoemulsions, and metallic nanoparticles – can enhance the pharmacokinetic and pharmacodynamic characteristics of phytochemicals. Furthermore, precision medicine approaches – where drug release is controlled by internal or external physiological triggers like pH, redox status, enzymes, or magnetic fields – are being made possible by stimuli-responsive and targeted nanocarriers. By analyzing recent developments in nanocarrier systems created especially for plant-based bioactive, this review seeks to thoroughly investigate the synergy between nanotechnology and phytomedicine. The ways in

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which these nanoformulations improve drug performance are also covered, along with the difficulties that formulation development is currently facing, safety concerns, regulatory issues, and potential directions for clinical translation in the future. This new interdisciplinary approach has enormous potential to redefine drug delivery paradigms and provide more sustainable and effective treatment options by bridging the gap between nature and nanoscience [1, 2].

NANOTECHNOLOGY

The study of materials and devices at the nanoscale, usually between 1–100 nanometers (1 nanometer = one-billionth of a meter), is known as nanotechnology. Materials may display distinct physical, chemical, and biological characteristics at this incredibly small scale that are very different from those at larger scales. High surface-area-to-volume ratio of nanoparticles and quantum effects are to blame for these alterations.

Key Points

- *Range of Sizes:* 1–100 nm.
- Distinctive qualities include improved electrical conductivity, greater chemical reactivity, reduced weight, and increased strength.
- *Medicine:* Cancer treatment, drug delivery methods, and diagnostic instruments.
- *Energy:* Better batteries and more effective solar panels.
- *Electronics:* More compact, quicker, and more effective chips. Materials: Lighter, stronger materials for construction, sports, and aircraft. Environmental: pollution sensors, water purification.

FUNDAMENTALS OF NANOTECHNOLOGY IN DRUG DELIVERY

Fundamentals of Nanoscale Drug Delivery Systems: Nanotechnology enhances the performance and delivery of therapeutic agents by using materials at the nanoscale (1–100 nm). Drug loading, stability, and controlled release are improved by the special physicochemical characteristics of nanoparticles at this scale, including a high surface area-to-volume ratio, adjustable surface charge, and improved solubility. Drugs that are hydrophobic or unstable can be encapsulated by nanoscale carriers, which also shield them from deterioration and allow for site-specific or prolonged delivery. Drug pharmacokinetics and biodistribution can be precisely adjusted by altering particle size, composition, and surface chemistry, which reduce off-target effects and increase therapeutic efficacy [3].

Mechanisms of Uptake and Interactions Between Nanoparticles and Cells

Size, shape, surface charge, and surface functionalization are examples of physicochemical parameters that control the interactions between nanoparticles and cells. These properties affect the way that nanoparticles engage with cellular constituents and biological membranes. Endocytic pathways like macropinocytosis, caveolae-mediated, or clathrin-mediated are commonly used for cellular uptake. Once internalized, nanoparticles can target particular organelles or break free from endosomal compartments to release their payload in the cytoplasm. Active targeting is made possible by surface ligands, such as antibodies, peptides, and sugars, which can improve recognition of receptors that are overexpressed on diseased cells. Designing nanocarriers that achieve effective delivery with low toxicity requires an understanding of these interactions.

SMART NANOCARRIERS

Targeted, Stimulus-Responsive, and Managed Delivery: Smart nanocarriers are sophisticated devices designed to release medications in reaction to particular external or internal stimuli. Over time, controlled-release nanocarriers sustain the ideal drug concentration. Stimuli-responsive systems react to changes in pH, temperature, redox potential, enzymes, or external triggers (light, magnetic fields, and ultrasound) to release their payload precisely at the target site. Targeted nanocarriers are functionalized with ligands that recognize disease-specific markers, ensuring selective accumulation in diseased tissues (e.g., tumor or inflamed sites). These intelligent systems reduce systemic toxicity, enhance therapeutic precision, and represent the frontier of modern nanomedicine [4–5].

Photochemical Delivery Using Nanoformulations

Low solubility, poor stability, fast metabolism, and limited bioavailability are common issues with phytochemicals, or bioactive compounds derived from plants. By encapsulating, shielding, directing, and regulating the release of phytochemicals, nanoformulations aid in resolving these issues. The primary categories of nanoformulations, their benefits and drawbacks, and case studies or examples are listed below.

- *Lipid-Based Nanocarriers:* Liposomes, SLNs, NLCs, and Nanoemulsions.
- *Idea & Types:* Hydrophilic (in the core) and lipophilic (within the bilayer) phytochemicals can be encapsulated in liposomes, which are spherical vesicles made of phospholipid bilayers encircling an aqueous core.
- *Slns, or Solid Lipid Nanoparticles:* The medication is embedded in a solid lipid matrix, which is made up of lipids that are solid at body temperature and stabilized by surfactants.
- *Nanostructured Lipid Carriers (NLCs):* Like SLNs, but with a mixture of liquid and solid lipids to lessen crystalline; this allows for greater drug loading and stops the drug from escaping while being stored.
- *Nanoemulsions:* Fine emulsions, such as water in oil or oil in water, are effective at delivering lipophilic phytoactives because their droplets are usually smaller than 100–200 nm.

Advantages

- Make hydrophobic phytochemicals more soluble and bioavailable.
- Use encapsulation to safeguard labile phytochemicals, which are susceptible to oxidation, light, and enzymatic degradation.
- Depending on the formulation, provide controlled or sustained release; lessen burst release.
- *Biocompatibility:* due to lipids' greater physiological tolerance, they are typically less toxic.

Challenges

Issues with stability include the possibility of liposomes undergoing physical instability (leakage or fusion) and the possibility of nanoemulsions separating or coalescing.

- Limited drug loading, which is contingent upon the type of lipid and the drug's compatibility with it.
- Cost, reproducibility, and scale-up challenges Current Instances.

Chitosan: A natural polysaccharide that is mucoadhesive, biodegradable, and frequently administered orally or mucosally; a positive charge can improve cell uptake. Polyethylene glycol, or PEG, or PEGylation, is frequently used to increase solubility, decrease immunogenicity, and increase circulation time.

Dendrimers: are tree-like, highly branched polymers with numerous surface functional groups that are useful for high drug loading and targeting.

Advantages

- Modifiable release profiles (based on copolymer ratio, molecular weight, and polymer composition).
- The ability to alter or functionalize the surface (for example, by adding ligands for shielding or targeting).
- *Good Structural Stability:* compared to certain lipid systems, it is frequently more stable in systemic circulation. Challenges:
    - Potential toxicity based on size and polymer (particularly with dendrimers).
    - Depending on formulation, there may be a burst or incomplete release.
    - If polymer-drug compatibility is suboptimal, hydrophobic drugs have lower drug loading.
    - Sometimes more complicated synthesis, which could be more expensive [6–7].

CONCEPT & TYPE

- *Metal Nanoparticles:* such as gold (AuNPs), silver (AgNPs), and others, are frequently produced chemically or environmentally (plant-mediated); they can serve as carriers as well as therapeutic agents (e.g. photothermal, antimicrobial).
- *Metal Oxide Nanoparticles:* ZnO and iron oxide, for instance, can offer certain functions (such as imaging, magnetic targeting, and ROS generation). Mesoporous silica nanoparticles are useful for loading medications and releasing them through functionalization or gating because of their large pore volumes, adjustable pore sizes, and high surface area.

Benefits

- Additional features include antimicrobial activity, photothermal therapy, and imaging (such as gold or iron oxide).
- High stability, frequently with good surface chemistry and size control.
- Plant extracts can be used as capping or reducing agents using green synthetic techniques, adding to their bioactivity.

Challenges

- Long-term safety issues, accumulation/residue, and possible toxicity.
- Clearance may be challenging; biodegradability is frequently slow or poor.
- If a drug is not functionalized or adsorbed well, there may be a decrease in drug loading.

Examples

- AuNPs functionalized with quercetin or catechin for targeted delivery and photothermal therapy, as well as AgNPs with antimicrobial synergy, is described in Nano-Phytomedicine: Harnessing Plant-Derived Phytochemicals in Nanocarriers (MDPI).
- Nano-Phytomedicines that are hybrid and carrier-free.

HYBRID NANOCARRIERS

To take advantage of synergistic benefits (such as stability + targeting + controlled release), combine two or more materials (lipid + polymer, inorganic + lipid, polymer + metal, etc.). Systems without carriers: Phytochemicals themselves can sometimes self-assemble or form into nano- or microparticles without the need for an external carrier; these can include drug nanocrystals, pure phytochemical nanoparticles, or multifunctional organosilica derived from the phytochemical.

Advantages

Multiple desired properties, such as high drug loading from one component, stability from another, and targeting from a third, can be optimized by hybrid systems. Carrier-free systems reduce “inert” carrier burden and maximize drug loading (100 percent or close to 100 percent), potentially lowering toxicity.

Challenges

Design and fabrication complexity; maintaining homogeneity and reproducibility; and the possibility of instability, aggregation, or early release in the event of weak self-assembly.

Examples

Different hybrid architectures (lipid core + polymer shell) and hybrid functions are described in the review of Polymer-Lipid Hybrid Nanoparticles for Phytochemical Delivery [8].

CASE STUDIES

Important Phytochemicals (Curcumin, Quercetin, Resveratrol, etc.) Nanoencapsulated – The following are illustrative case studies that demonstrate how the performance of particular phytochemicals is enhanced by nanoformulation. Issue(s) with the “free” (unformulated) form of

phytochemistry Strategies for Nanoformulation: Examples of Results and Advantages Curcumin Extremely low water solubility, quick metabolism, low bioavailability, and instability in physiological settings. Liposomes, SLNs/NLCs, polymeric nanoparticles (PLGA, etc.), self-assembling nanocrystals, and hybrid/inorganic supports, such as curcumin solid lipid nanoparticles for anticancer and curcumin NPs that cross the blood-brain barrier for neuroprotection. Superior to free curcumin in terms of increased bioavailability, extended circulation, improved uptake in target tissues, and enhanced therapeutic effect (anticancer, neuroprotection). Reduced systemic toxicity. Quercetin Low stability, low absorption, poor solubility, and quick first-pass removal. Encapsulated in SLNs/NLCs; conjugated to carriers; lipid-polymer hybrid nanoparticles; occasionally a component of a combination (co-delivery). Improved in vitro and in vivo performance, slower release, increased cellular uptake, and improved antioxidant and anticancer effects. Other phytochemicals, like silymarin and naringenin, have comparable advantages in anticancer (SLN/NLC) systems [9].

NANO-PHYTOMEDICINES' THERAPEUTIC USES

The combination of nanotechnology and phytomedicine has created new opportunities for effective, biocompatible, and disease-targeted treatments. Plant-derived compounds' stability, solubility, and bioavailability are improved by nano-phytomedicines, allowing for their clinical application in a variety of therapeutic domains. Applications for Anticancer: Curcumin, resveratrol, quercetin, epigallocatechin gallate (EGCG), and berberine are examples of phytochemicals that have strong anticancer effects by altering several signaling pathways (e.g., NF-ΐB, PI3K/Akt, MAPK). However, their quick metabolism and poor solubility restrict their therapeutic use.

Polymeric nanoparticles, liposomes, nanomicelles, and gold nanoparticles are examples of nanoformulations that improve cellular uptake and allow for targeted delivery to tumor sites through ligand-mediated targeting (e.g., folate, transferrin) or the enhanced permeability and retention (EPR) effect. For instance, PLGA nanoparticles loaded with curcumin exhibit enhanced apoptosis induction in colon and breast cancer cells. PLGA nanoparticles loaded with curcumin exhibit enhanced induction of apoptosis in colon and breast cancer cells. Liposomes loaded with quercetin show increased tumor accumulation and cytotoxicity [10–11].

ANTIMICROBIAL AND ANTIVIRAL USES

Terpenoids, alkaloids, flavonoids, and phenolics are examples of plant-derived antimicrobials that exhibit efficacy against viruses, fungi, and bacteria. Through enhanced penetration, prolonged release, and synergistic effects with antibiotics, nano-phytomedicines increase their potency.

For Instance

Strong antibacterial and antifungal properties are demonstrated by silver nanoparticles made with extracts of neem, green tea, or turmeric.

WOUND HEALING AND REGENERATIVE MEDICINE

Nanotechnology has improved the bioavailability and controlled release of bioactives, which has sped up tissue regeneration and repair based on phytomedicine. Angiogenesis, collagen deposition, and fibroblast proliferation are all aided by phytochemicals like curcumin, aloe vera extract, asiaticoside, and polyphenols derived from honey. Uses: Nanoparticles of chitosan and curcumin enhance wound closure and lessen bacterial infection [12].

FUTURE PERSPECTIVES AND EMERGING TRENDS

The next generation of therapeutic systems is being redefined by the convergence of digital innovation, phytochemistry, and nanotechnology. It is anticipated that future nano-phytomedicines will be more intelligent, selective, and computationally optimized, combining precision nanomedicine with traditional herbal knowledge.

SMART AND STIMULI-RESPONSIVE NANO-PHYTOMEDICINES

"Smart" nano-phytomedicines are advancement over traditional delivery systems. By releasing phytoconstituents only at the disease site in response to particular physiological or external stimuli – such as pH, temperature, redox gradients, enzymes, magnetic fields, ultrasound, or light – these systems are designed to increase precision and reduce side effects.

MECHANISTIC OVERVIEW

pH-responsive systems: Make use of polymers that selectively release medications like quercetin or curcumin by swelling or degrading in acidic tumor microenvironments or inflammatory tissues. Systems that respond to redox: Use cancer cells' increased intracellular glutathione (GSH) levels to target drug release.

AI AND MACHINE LEARNING IN PHYTOCHEMICAL NANOFORMULATION DESIGN

Nanomedicine research is undergoing a rapid transformation thanks to artificial intelligence (AI) and machine learning (ML), which make it possible to design and optimize formulations in a predictive, data-driven manner. AI offers tools to speed up screening, optimize nanoformulation parameters, and forecast biological outcomes given the chemical diversity and formulation complexity of phytochemicals. Applications of AI/ML: The best ratios of polymer, lipid, and surfactant to attain the required nanoparticle size, zeta potential, and encapsulation efficiency can be predicted by machine learning models (ML models), such as random forest, support vector machines, and neural networks [13–14].

Future Trends & Emerging Innovations (Detailed)

Smart / Stimuli-Responsive Nanocarriers – Precision on-Demand Release

- *What:* Nanocarriers are engineered to release plant bioactives only when they encounter specific internal (pH, redox, enzymes, hypoxia) or external (light, heat, magnetic field, ultrasound) triggers.
- *How It Helps Phytomedicine:* Many phytochemicals are poorly soluble or get metabolized before reaching disease sites. Stimuli-responsive systems protect payloads and then release them selectively at target tissue (e.g., acidic tumor microenvironment or enzyme-rich inflammation sites), increasing local drug concentration and lowering systemic side effects.
- *Examples & Mechanisms:* pH-sensitive polymeric nanoparticles that swell/cleave in acidic tumor interstitium; redox-sensitive linkers that break in high intracellular glutathione; light-activated systems for spatial control. These designs have been used to deliver flavonoids, curcumin, and other phytochemicals with improved therapeutic indices.
- *Opportunities:* More precise cancer/anti-inflammatory therapies; combination regimens (chemo + phytochemical) with synchronized release [15].
- *Challenges:* Scaling complex responsive chemistries, ensuring biocompatibility and predictability in vivo triggering.

AI-Driven Design, High-Throughput Screening & Personalized Nano-Phytomedicine

Use of machine learning and computational design to predict optimal nanocarrier formulations, select phytochemical-carrier combinations, and personalize therapy based on patient-specific data.

- *How It Helps:* Reduces experimental cycles (formulation by design), predicts stability, biodistribution, and toxicity from physicochemical parameters, and supports patient stratification (who will benefit most from a given nano-phytomedicine).
- *Examples & Potential Use:* ML models that predict encapsulation efficiency, release kinetics, or protein corona composition; linking patient omics to select targeted phytochemical regimens.
- *Opportunities:* faster lead optimization, rational scale-up, and movement toward precision botanical nanomedicine.
- *Challenges:* need for high-quality labeled datasets, model interpretability for regulatory acceptance, integration with wet-lab validation.

- *Key Source:* overviews and forward-looking sections in recent nano-phytomedicine reviews highlighting AI and computational trends [16–22].

CONCLUSION

Summary of Key Insights

The combination of nanotechnology and phytomedicine has transformed drug delivery, bioavailability, and therapeutic precision in the last ten years. The inherent limitations of phytochemicals, such as their poor solubility, instability, rapid metabolism, and low systemic absorption, have been effectively addressed by nanocarriers, which range from lipid-based systems (liposomes, SLNs, and NLCs) to polymeric, inorganic, and hybrid nanoparticles. In a variety of therapeutic areas, such as anticancer, anti-inflammatory, antimicrobial, neuroprotective, and wound-healing applications, nano-phytomedicines have demonstrated impressive promise. Nanocarriers greatly improve pharmacokinetic profiles and reduce systemic toxicity by offering targeted and controlled release. Additionally, green synthesis techniques that use plant extracts to create nanoparticles provide economical and environmentally beneficial substitutes that support sustainability objectives.

REFERENCES

1. Parvin N, Aslam M, Joo SW, Mandal TK. Nano-phytomedicine: Harnessing plant-derived phytochemicals in nanocarriers for targeted human health applications. Molecules. 2025;30 (15):3177.
2. Bonifácio BV, da Silva PB, Ramos MAS, Negri KM, Bauab TM, Chorilli M. Nanotechnology-based drug delivery systems and herbal medicines: A review. Int J Nanomedicine. 2013;8:3271–3287.
3. Jalili A, Zarei M, Ahmadi M, Ghasemi F. Current advances in nanotechnology-mediated delivery of phytochemicals. Pharmaceutics. 2023;15(2):456.
4. Novel drug delivery systems for phytomedicines. Pharmaceutics. 2024;16(8):1059.
5. Dashchenko AI. Nanotechnology. In: Dashchenko AI, editor. CIRP Encyclopedia of Production Engineering. 1st ed. Berlin (Germany): Springer; 2020. p. 1–10.
6. Bhushan B, editor. Encyclopedia of Nanotechnology. 1st ed. Dordrecht (Netherlands): Springer; 2016. p. 1–10.
7. Zhang YB, Li X, Wang Y, Chen Z. Nano-based drug delivery systems for active ingredients of traditional medicine. Front Pharmacol. 2024;15:1342211.
8. Siafaka PI, Okur ME, Ayla Ş, Er S, Çağlar EŞ. Nanoformulations loaded with phytochemicals for wound healing and regenerative applications. Nanomaterials. 2025;15(3):412.
9. Rahat I, Khan S, Ahmad Z, Ullah R. Polymer–lipid hybrid nanoparticles for phytochemical delivery: Progress, challenges, and future perspectives. Pharmaceutics. 2024;16(4):512.
10. Solid lipid nanoparticles and nanostructured lipid carriers for anticancer phytochemical delivery: Advances, challenges, and future prospects. Drug Deliv Transl Res. 2023;13(6):1789–1812.
11. Kothapalli CR, Vasanthan T. Lipid-based nanocarriers for enhanced delivery of plant-derived bioactive molecules: A comprehensive review. Food Chem. 2022;370:131034.
12. Guillén-Meléndez GA, López-Cervantes J, Sánchez-Machado DI. Nanoencapsulation of extracts and isolated compounds of plant origin used in antineoplastic therapy. Pharmaceutics. 2024;16(3):389.
13. Fahim M, Rahman MM, Hossain MA. Green synthesis of silver nanoparticles: A comprehensive review. Nanomaterials. 2024;14(2):178.
14. Eker F, Aydın A, Şahin F. Green synthesis of silver nanoparticles using plant extracts and their biomedical applications. Molecules. 2025;30(6):1423.
15. Tenchov R, Bird R, Curtze AE, Zhou Q. Cutting-edge applications of nanoscale materials in drug delivery. ACS Nano. 2021;15(11):17882–17915.
16. Balcerak-Woźniak A, Lewandowska-Łańcucka J. Stimuli-responsive smart polymers and their biomedical applications: A comprehensive review. Polymers (Basel). 2024;16(4):512.

17. Saxena R, Sharma P, Gupta VK. Green synthesis of nanoparticles toward sustainable nanotechnology: A review. J Clean Prod. 2025;402:136818.
18. Liu X, Wang J, Zhang Y. New opportunities of stimulus-responsive smart nanocarriers for precision drug delivery. Adv Ther (Weinh). 2025;8(2):2300456.
19. Samuel MS, Ravikumar M, John JA, Selvarajan E, Patel H, Chander PS, et al. Green synthesis of nanoparticles and their diverse biomedical and environmental applications. Catalysts. 2022;12(5) :459.
20. Nanoparticle-based delivery systems for phytochemicals in cancer therapy: Molecular mechanisms, clinical evidence, and emerging trends. Semin Cancer Biol. 2024;89:56–72.
21. Phytochemical delivery through nanocarriers: Principles and therapeutic applications. Adv Drug Deliv Rev. 2020;154–155:1–25.
22. Usmani A, Dash PP, Mishra A. Metallic nanoformulations: Green synthetic approaches for advanced drug delivery. Mater Sci Eng C. 2025;156:113765.

