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Review Article
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# GREEN SYNTHESIS OF NANOPARTICLES: BIOGENIC APPROACHES, MECHANISM, CHARACTERIZATION, APPLICATIONS AND FUTURE PERSPECTIVES

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## ABSTRACT

Green synthesis of nanoparticles has emerged as an environmentally sustainable and economically viable alternative to conventional physical and chemical synthesis methods. This approach utilizes biological resources, including plant extracts, bacteria, fungi, algae, and other naturally derived biomolecules, as reducing, stabilizing, and capping agents for nanoparticle fabrication. The growing interest in green nanotechnology is attributed to its potential to minimize hazardous chemical consumption, reduce environmental pollution, and produce nanoparticles with desirable physicochemical and biological properties. This review comprehensively discusses the fundamental principles, biological sources, synthesis mechanisms, and factors influencing the green synthesis of metallic, metal oxide, and other nanomaterials. Particular emphasis is placed on the roles of phytochemicals, proteins, enzymes, polysaccharides, and microbial metabolites in nanoparticle nucleation, growth, stabilization, and surface functionalization. Furthermore, the review examines advanced characterization techniques, including ultraviolet–visible spectroscopy, Fourier-transform infrared spectroscopy, X-ray diffraction, dynamic light scattering, zeta potential analysis, scanning electron microscopy, and transmission electron microscopy. The pharmaceutical and biomedical applications of green-synthesized nanoparticles, particularly in antimicrobial therapy, anticancer drug delivery, wound healing, antioxidant applications, diagnostics, and targeted drug delivery, are critically evaluated. The major challenges associated with batch-to-batch variability, reproducibility, stability, scalability, toxicity, and regulatory compliance are also addressed. Finally, emerging opportunities involving Quality by Design, statistical optimization, artificial intelligence, and sustainable manufacturing are highlighted. This review emphasizes the importance of integrating green chemistry principles with advanced nanotechnology to facilitate the development of safe, effective, reproducible, and environmentally responsible nanoparticle-based pharmaceutical products.

***Keywords:*** *Green synthesis; Nanoparticles; Biogenic synthesis; Plant extracts; Sustainable nanomedicine; Drug delivery; Quality by Design; Biomedical applications.*

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## 1. INTRODUCTION

Nanotechnology has revolutionized pharmaceutical sciences, biotechnology, medicine, agriculture, and environmental engineering through the development of materials possessing unique properties at the nanoscale [1]. Nanoparticles generally exhibit dimensions ranging from approximately 1 to 100 nm, although pharmaceutical nanocarrier systems may extend beyond this range depending on their composition and intended application [2]. Their large surface-area-to-volume ratio, tunable surface chemistry, and distinctive optical, electrical, catalytic, and biological properties make them promising candidates for diverse technological applications [3].

Conventional nanoparticle synthesis commonly involves physical and chemical approaches such as chemical reduction, sol–gel processing, hydrothermal synthesis, thermal decomposition, and laser ablation [4]. Although these methods can provide controlled particle formation, certain processes require hazardous reducing agents, organic solvents, high temperatures, substantial energy consumption, or specialized equipment [5]. Residual toxic chemicals and complex purification procedures may further limit their suitability for biomedical applications [6].

Green synthesis has therefore gained considerable attention as an alternative strategy that employs biological materials and environmentally preferable reaction conditions for nanoparticle production [7]. Plant extracts, microorganisms, algae, and naturally occurring biomolecules contain biologically active constituents capable of facilitating the conversion of suitable precursors into nanostructured materials [8].

Plant-derived phytochemicals, including flavonoids, polyphenols, terpenoids, alkaloids, and reducing sugars, may act as reducing and stabilizing agents during nanoparticle formation [9]. Similarly, microbial enzymes, proteins, and extracellular metabolites can participate in the biogenic synthesis of nanoparticles [10]. The resulting surface-associated biomolecules may influence colloidal stability, surface interactions, and biological activity [11].

From a pharmaceutical perspective, green-synthesized nanoparticles have attracted interest because of their potential applications in antimicrobial formulations, anticancer therapy, wound healing, diagnostic imaging, and drug delivery [12]. Nevertheless, biological synthesis does not automatically guarantee biocompatibility, low toxicity, or environmental sustainability. These properties must be established through appropriate experimental evaluation [13].The successful translation of green-synthesized nanoparticles into pharmaceutical products requires systematic optimization of synthesis conditions, comprehensive physicochemical characterization, evaluation of biological performance, and adherence to applicable quality and regulatory requirements [7, 14].

The primary objective of this review is to provide a comprehensive overview of green synthesis strategies employed in nanoparticle development, with particular emphasis on their underlying principles, biological resources, and mechanisms of nanoparticle formation. It aims to discuss the roles of plant extracts, microorganisms, algae, and naturally occurring biomolecules as reducing, stabilizing, and capping agents. The review further examines critical formulation and processing parameters influencing nanoparticle size, morphology, surface charge, stability, and biological performance. Special attention is given to physicochemical and analytical characterization techniques, the integration of statistical optimization and Quality by Design principles, and the pharmaceutical applications of green-synthesized nanoparticles. Additionally, the review critically evaluates current limitations associated with reproducibility, toxicity, large-scale manufacturing, quality control, and regulatory acceptance, while highlighting emerging technologies and future research opportunities for sustainable nanoparticle development.

## GREEN SYNTHESIS OF NANOPARTICLES

Green synthesis refers to the production of nanomaterials using environmentally preferable processes and biological substances that facilitate nanoparticle formation. It is generally considered a bottom-up approach in which atoms, ions, or molecular precursors undergo nucleation and growth to form nanoparticles. Biological constituents can function as reducing agents, stabilizers, and surface-capping materials [15].

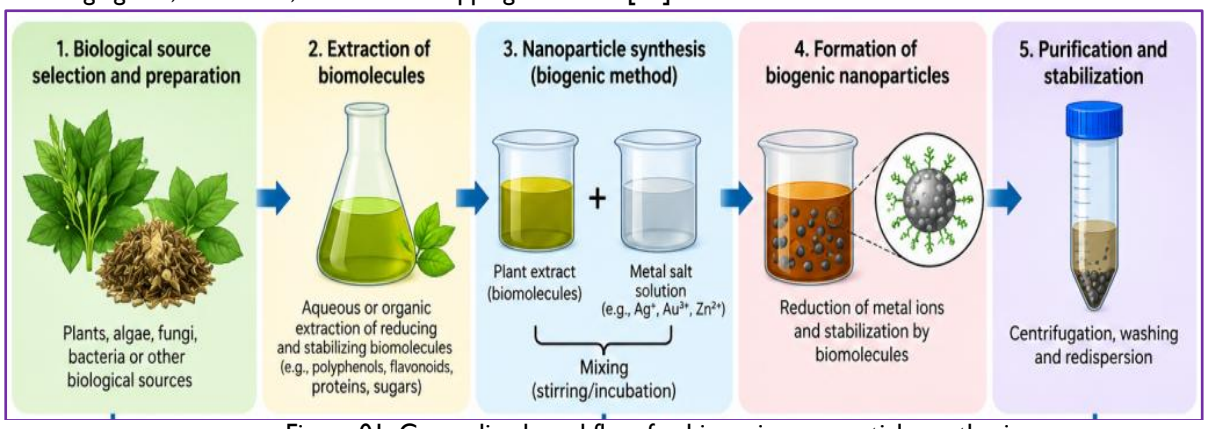



Figure 01: Generalized workflow for biogenic nanoparticle synthesis

The selection of a suitable biological source depends on the intended nanoparticle composition, desired particle size, availability of reducing biomolecules, reaction conditions, and intended pharmaceutical application [16]. Plant-mediated synthesis is particularly attractive because plant materials are widely available and frequently contain multiple phytochemicals capable of participating in nanoparticle formation. However, the complex chemical composition of extracts can make reaction mechanisms difficult to establish and standardize [17].

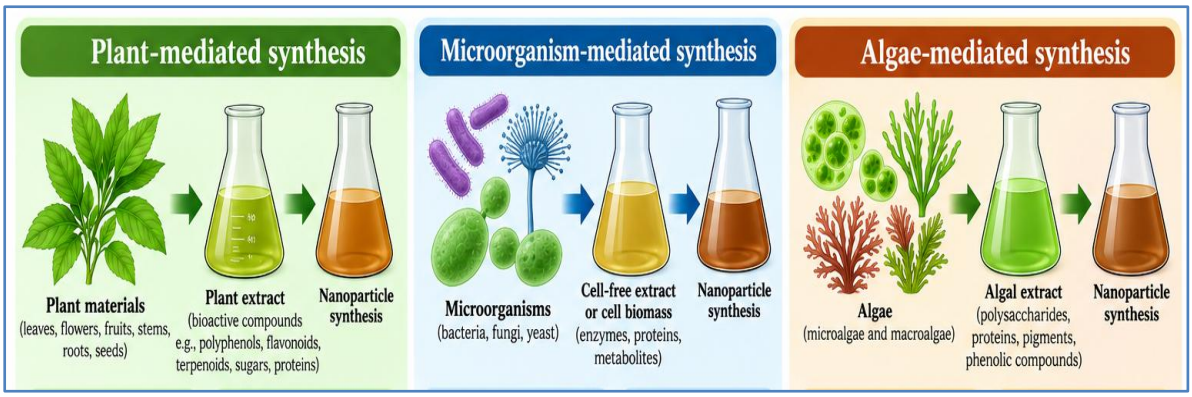



Figure 02: Schematic representation of green synthesis of nanoparticles through various approaches

## PLANT-MEDIATED SYNTHESIS

Plant-mediated synthesis utilizes extracts obtained from leaves, roots, flowers, fruits, seeds, and bark. These extracts contain polyphenols, flavonoids, tannins, alkaloids, proteins, and other compounds that may facilitate the reduction of metal ions and stabilization of newly formed nanoparticles [18]. Typically, the plant material is washed, dried, powdered, and extracted using water or an appropriate solvent. The extract is then mixed with a metal precursor solution under controlled experimental conditions. Changes in solution colour may provide preliminary evidence of nanoparticle formation, particularly for plasmonic metals such as silver and gold. The synthesized particles are subsequently isolated, purified, dried when appropriate, and characterized [19].

### Microorganism-mediated synthesis:

Microorganisms such as bacteria, fungi, and yeast can synthesize nanoparticles through intracellular or extracellular pathways. Microbial enzymes, proteins, and metabolites participate in metal-ion reduction and particle stabilization. Extracellular synthesis may simplify nanoparticle recovery, whereas intracellular synthesis generally requires additional processing to separate particles from cellular components [20].

Microbial methods offer opportunities for controlled biological production, but they require attention to culture conditions, contamination, biomass processing, and product purification [21].

### Algae-mediated synthesis:

Algae contain polysaccharides, proteins, pigments, and other metabolites that can participate in nanoparticle synthesis. Both microalgae and macroalgae have been investigated as biological resources for producing metallic and metal oxide nanoparticles [22].

Algae-mediated methods are attractive because of the availability of renewable biomass. However, variations in algal species, cultivation conditions, and extraction methods can influence nanoparticle properties [23].

### Mechanisms Involved in Green Nanoparticle Synthesis:

Biogenic nanoparticle formation is commonly described through three interconnected stages: reduction or precursor transformation, nucleation and growth, and stabilization.During the initial stage, suitable biological constituents interact with metal ions or other precursors. Electron-donating molecules may reduce metal ions into their elemental states, while metal oxide synthesis may involve additional hydrolysis, precipitation, and thermal conversion steps [24].

During nucleation, newly formed atomic or molecular species aggregate into small clusters. Continued growth produces nanoparticles whose dimensions and morphology depend on the availability of precursor species, reaction kinetics, temperature, pH, and the presence of capping molecules [25].

Finally, biological constituents adsorb onto nanoparticle surfaces and may reduce aggregation through electrostatic or steric stabilization. These surface-associated compounds can also influence biological interactions and colloidal stability [26].

### Factors Influencing Green Nanoparticle Synthesis

Several physicochemical and processing variables influence the formation and stability of green-synthesized nanoparticles. These parameters must be systematically evaluated to obtain reproducible products [27].

Table 01: Key parameters influencing the synthesis, growth, stability, and physicochemical properties of nanoparticles

| Parameter | Influence on nanoparticle properties |
|---|---|
| pH | Influences precursor speciation, biomolecule ionization, nucleation, and aggregation [14] |
| Temperature | Affects reaction kinetics, growth, and biomolecule stability [28] |
| Precursor concentration | Influences nucleation rate, particle yield, and aggregation [29] |
| Extract concentration | Affects availability of reducing and capping agents [28] |
| Reaction time | Influences precursor conversion and particle growth [30] |
| Mixing conditions | Affect mass transfer and uniformity [31] |
| Extraction method | Alters the composition and concentration of active metabolites [32] |

Statistical experimental designs are particularly valuable because these parameters may interact with one another. For example, the effect of precursor concentration on particle size may depend on both extract concentration and reaction pH [33].

**Physicochemical Characterization of Green-Synthesized Nanoparticles**

Characterization is essential to establish nanoparticle identity, morphology, surface properties, stability, and suitability for pharmaceutical applications [34].

Table 02: Common characterization techniques used to analyze nanoparticles

| Technique | Purpose |
|---|---|
| UV spectroscopy | To asses optical properties and Plasmon resonance [35, 36] |
| FTIR | To identify functional groups [37, 38] |
| DSC | To evaluate thermal transitions & the thermal stability [39-41] |
| XRD | To evaluate crystalline characteristics [42] |
| DLS | To measure hydrodynamic particle size & distribution [43] |
| ZP | To evaluateelectro kinetic surface properties [44] |
| SEM | To asses of surface morphology [45] |
| TEM | To visualize particle size and morphology [46] |
| TGA | To evaluate thermal behaviour and mass loss [47] |

**Applications**

Green-synthesized nanoparticles have been investigated for a wide range of pharmaceutical and biomedical applications. Most reported applications remain at the laboratory or preclinical stage, and their clinical relevance requires further validation [48].

**Antimicrobial activity**

Biogenically synthesized silver, copper, zinc oxide, and other nanoparticles have demonstrated antimicrobial activity in experimental studies. Proposed mechanisms include disruption of microbial membranes, generation of reactive oxygen species, release of metal ions, and interference with essential cellular processes [49].These properties have encouraged investigations into antimicrobial coatings, wound dressings, and topical formulations. However, antimicrobial activity must be balanced against potential toxicity to mammalian cells [50].

**Anticancer applications**

Green-synthesized nanoparticles have been investigated for anticancer applications because their physicochemical properties and surface functionalities can influence cellular uptake and interactions with tumor cells [51].Experimental studies have examined their effects on oxidative stress, mitochondrial function, apoptosis, and cell proliferation. Nevertheless, selective anticancer activity cannot be assumed, and evidence from cell culture studies alone is insufficient to establish therapeutic effectiveness [52].

**Drug delivery**

Green synthesis offers potential opportunities for producing functional nanomaterials that can be incorporated into drug delivery systems. Surface-associated biomolecules may support further functionalization, drug conjugation, or incorporation into composite carriers.The suitability of these systems depends on drug loading, release behaviour, chemical compatibility, pharmacokinetics, biodistribution, and safety [53].

**Wound healing**

Green-synthesized nanoparticles are being investigated as components of wound dressings, hydrogels, and topical systems. Their proposed benefits include antimicrobial activity and possible modulation of the local wound environment.Before clinical application, such formulations require assessment of tissue compatibility, healing performance, local toxicity, and long-term safety [54].

**Diagnostic and imaging**

Gold, iron oxide, and other functional nanomaterials have potential applications in biosensing, diagnostic assays, and imaging technologies. Their utility depends on properties such as optical behavior, magnetic response, colloidal stability, and compatibility with the intended biological environment [55].

## FUTURE PERSPECTIVES

Future research on green-synthesized nanoparticles should move beyond demonstrating particle formation toward establishing reproducible, mechanistically understood, and application-specific manufacturing processes [56].The integration of advanced analytical techniques, metabolomic profiling, statistical experimental designs, and machine learning may improve the identification of active biological constituents and their relationships with nanoparticle properties [57].Artificial intelligence-assisted optimization could also support prediction of particle size, morphology, and stability from experimental process data. However, reliable predictions will require standardized datasets, external validation, and appropriate model interpretability [58].Further progress is expected through continuous-flow synthesis,

improved bioreactor technologies, standardized plant extracts, hybrid nanomaterials, and more comprehensive environmental life-cycle assessments [59].
For pharmaceutical translation, greater emphasis must be placed on toxicological evaluation, pharmacokinetic investigations, process validation, impurity control, and compliance with relevant regulatory requirements [60-63].

## CONCLUSION

Green synthesis of nanoparticles represents a promising approach to sustainable nanomaterial development by utilizing biological resources and potentially reducing the environmental burden associated with conventional manufacturing methods. Plant extracts, microorganisms, and algae provide diverse biomolecules capable of facilitating nanoparticle formation and stabilization. The resulting nanomaterials have demonstrated potential in antimicrobial therapy, anticancer research, drug delivery, wound healing, and diagnostic applications. Nevertheless, variability in biological precursors, incomplete mechanistic understanding, particle heterogeneity, purification challenges, and limited scalability remain significant obstacles to industrial and pharmaceutical implementation. The integration of statistical optimization, advanced characterization, and artificial intelligence offers opportunities to improve reproducibility and process control. Future investigations should prioritize standardized manufacturing, comprehensive safety assessment, environmental sustainability, and rigorous preclinical and clinical evaluation to facilitate the responsible translation of green-synthesized nanoparticles into practical pharmaceutical applications.

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## INFORM CONSENT AND ETHICAL DECLARATIONS

Not Applicable

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## REFERENCES

1. Malik S, Muhammad K, Waheed Y. Nanotechnology: a revolution in modern industry. Molecules. 2023;28(2):661.
2. Yusuf A, Almotairy AR, Henidi H, Alshehri OY, Aldughaim MS. Nanoparticles as drug delivery systems: a review of the implication of nanoparticles' physicochemical properties on responses in biological systems. Polymers. 2023;15(7):1596.
3. Molahalli V, Sharma A, Bijapur K, Soman G, Shetty A, Sirichandana B, Patel BM, Chattham N, Hegde G. Properties, synthesis, and characterization of Cu-based nanomaterials. InCopper-based nanomaterials in organic transformations 2024 (pp. 1-33). American Chemical Society.
4. Rane AV, Kanny K, Abitha VK, Thomas S. Methods for synthesis of nanoparticles and fabrication of nanocomposites. InSynthesis of inorganic nanomaterials 2018 Jan 1 (pp. 121-139). Woodhead publishing.
5. Vinukonda A, Bolledla N, Jadi RK, Chinthala R, Devadasu VR. Synthesis of nanoparticles using advanced techniques. Next Nanotechnol 8: 100169 [Internet]. 2025
6. Rónavári A, Igaz N, Adamecz DI, Szerencsés B, Molnar C, Kónya Z, Pfeiffer I, Kiricsi M. Green silver and gold nanoparticles: Biological synthesis approaches and potentials for biomedical applications. Molecules. 2021;26(4):844.
7. Kirubakaran D, Wahid JB, Karmegam N, Jeevika R, Sellapillai L, Rajkumar M, SenthilKumar KJ. A comprehensive review on the green synthesis of nanoparticles: advancements in biomedical and environmental applications. Biomedical Materials & Devices. 2026;4(1):388-413.
8. Alsaiari NS, Alzahrani FM, Amari A, Osman H, Harharah HN, Elboughdiri N, Tahoon MA. Plant and microbial approaches as green methods for the synthesis of nanomaterials: synthesis, applications, and future perspectives. Molecules. 2023;28(1):463.
9. Singh H, Desimone MF, Pandya S, Jasani S, George N, Adnan M, Aldarhami A, Bazaid AS, Alderhami SA. Revisiting the Green Synthesis of Nanoparticles: Uncovering Influences of Plant Extracts as Reducing Agents for Enhanced Synthesis Efficiency and Its Biomedical Applications. Int J Nanomedicine. 2023;18:4727-50.
10. Bokolia M, Baliyan D, Kumar A, Das R, Kumar R, Singh B. Biogenic synthesis of nanoparticles using microbes and plants: mechanisms and multifaceted applications. International Journal of Environmental Analytical Chemistry. 2025;105(9):2069-97.
11. Sukdee S, Prajuabjinda O, Thepsilvisut O, Chutimanukul P. Physicochemical properties, selective cytotoxicity, and hemocompatibility of silver nanoparticles biosynthesized using Schizophyllum commune extract. Scientific Reports. 2026 Oct 1.

12. Petrovic S, Bita B, Barbinta-Patrascu ME. Nanoformulations in pharmaceutical and biomedical applications: green perspectives. International Journal of Molecular Sciences. 2024;25(11):5842.
13. Lakhani KG, Hamid R, Motamedi E, Marviya GV. A review on plant metabolite-mediated nanoparticle synthesis: sustainable applications in horticultural crops. Frontiers in Nanotechnology. 2025;7:1545413.
14. Edo GI, Mafe AN, Ali AB, Akpoghelie PO, Yousif E, Isoje EF, Igbuku UA, Ismael SA, Essaghah AE, Ahmed DS, Ozsahin DU. Green biosynthesis of nanoparticles using plant extracts: mechanisms, advances, challenges, and applications. BioNanoScience. 2025;15(2):267.
15. Gour A, Jain NK. Advances in green synthesis of nanoparticles. Artificial cells, nanomedicine, and biotechnology. 2019;47(1):844-51.
16. Kulkarni D, Sherkar R, Shirsathe C, Sonwane R, Varpe N, Shelke S, More MP, Pardeshi SR, Dhaneshwar G, Junnuthula V, Dyawanapelly S. Biofabrication of nanoparticles: sources, synthesis, and biomedical applications. Frontiers in bioengineering and biotechnology. 2023;11:1159193.
17. Rani N, Singh P, Kumar S, Kumar P, Bhankar V, Kumar K. Plant-mediated synthesis of nanoparticles and their applications: A review. Materials Research Bulletin. 2023;163:112233.
18. Damera S, Kuchukuntla M, Sharma M, Manda RM, Chettupalli AK, Jadi RK. Novel phytosomal drug delivery systems in cancer therapy: advances, mechanisms, and translational potential. Journal of Applied Pharmaceutical Research. 2026;14(3):18-35.
19. Crooks RM, Zhao M, Sun L, Chechik V, Yeung LK. Dendrimer-encapsulated metal nanoparticles: synthesis, characterization, and applications to catalysis. Accounts of Chemical Research. 2001;34(3):181-90.
20. Vena MP, Jobbágy M, Bilmes SA. Microorganism mediated biosynthesis of metal chalcogenides; a powerful tool to transform toxic effluents into functional nanomaterials. Science of The Total Environment. 2016;565:804-10.
21. Patel AK, Dong CD, Chen CW, Pandey A, Singhania RR. Production, purification, and application of microbial enzymes. InBiotechnology of microbial enzymes 2023 Jan 1 (pp. 25-57). Academic Press.
22. Chaudhary R, Nawaz K, Khan AK, Hano C, Abbasi BH, Anjum S. An overview of the algae-mediated biosynthesis of nanoparticles and their biomedical applications. Biomolecules. 2020;10(11):1498.
23. Doan L, Pham NV, Nguyen PB, Le QN, Phung TK, Ngo TT. Marine algae as sustainable platforms for the green synthesis of metal nanoparticles. Acs Omega. 2026;11(10):15598.
24. Singh J, Dutta T, Kim KH, Rawat M, Samddar P, Kumar P. 'Green'synthesis of metals and their oxide nanoparticles: applications for environmental remediation. Journal of Nanobiotechnology. 2018;16(1):84.
25. Thanh NT, Maclean N, Mahiddine S. Mechanisms of nucleation and growth of nanoparticles in solution. Chemical reviews. 2014;114(15):7610-30.
26. Storm G, Belliot SO, Daemen T, Lasic DD. Surface modification of nanoparticles to oppose uptake by the mononuclear phagocyte system. Advanced Drug Delivery Reviews. 1995;17(1):31-48.
27. Patra JK, Baek KH. Green nanobiotechnology: factors affecting synthesis and characterization techniques. Journal of Nanomaterials. 2014;2014(1):417305.
28. Dos Santos SS, De Moraes GE, Cerqueira MÂ, Aouada FA, Tanaka FC, Grillo R, Perotti GF, de Moura MR. Green synthesis of silver nanoparticles mediated by plant extracts: a critical review and experimental insights on the integrated effects of pH, temperature, and concentration. Bioscience Nanotechnology. 2026;2(1):24.
29. e Silva FA, Salim VM, Rodrigues TS. Controlled nickel nanoparticles: a review on how parameters of synthesis can modulate their features and properties. AppliedChem. 2024;4(1):86-106.
30. Shaba EY, Jacob JO, Tijani JO, Suleiman MA. A critical review of synthesis parameters affecting the properties of zinc oxide nanoparticle and its application in wastewater treatment. Applied Water Science. 2021;11(2):48.
31. Hickey JW, Santos JL, Williford JM, Mao HQ. Control of polymeric nanoparticle size to improve therapeutic delivery. Journal of Controlled Release. 2015;219:536-47.
32. Arsene MM, Viktorovna PI, Alla MV, Mariya MA, Sergei GV, Cesar E, Davares AK, Parfait K, Wilfrid KN, Nikolay TS, Rehailia M. Optimization of ethanolic extraction of Enantiachloranta bark, phytochemical composition, green synthesis of silver nanoparticles, and antimicrobial activity. Fermentation. 2022;8(10):530.
33. Menon S, Agarwal H, Rajeshkumar S, Jacquline Rosy P, Shanmugam VK. Investigating the antimicrobial activities of the biosynthesized selenium nanoparticles and its statistical analysis. Bionanoscience. 2020;10(1):122-35.
34. Eker F, Akdaşçi E, Duman H, Bechelany M, Karav S. Green synthesis of silver nanoparticles using plant extracts: A comprehensive review of physicochemical properties and multifunctional applications. International Journal of Molecular Sciences. 2025;26(13):6222.
35. Jadi RK, Bomma R, Sellappan V. Development of a new single unit dosage form of propranolol HCl extended release non-effervescent floating matrix tablets: In vitro and in vivo evaluation. Journal of applied pharmaceutical science. 2016;6(5):112-8.
36. Togaru V, Venisetty RK, Bakshi V, Jadi RK. Formulation development and in vitro evaluation of propranolol hydrochloride extended release matrix tablets. Emergent Life Sciences Research. 2017;3:38-47.
37. Prasad RR, Kumar JR, Vasudha BA, Kumar CA. Formulation development and evaluation of allopurinol solid dispersions by solvent evaporation technique. Int J Appl Pharm. 2018;10(4):168-71.

38. Pandala S, Bakshi V, Jadi RK. Formulation development and in vitro characterization of zolmitriptan controlled release drug delivery systems. INNOSC Theranostics Pharmacol. Sci. 2019;2(1):6-11.
39. Sapavatu SN, Jadi RK. Formulation development and characterization of gastroretentive drug delivery systems of loratadine. International journal of applied pharmaceutics. 2019;11(6):91-9.
40. Eslavath RN, Bakshi V, Jadi RK. Formulation Development and In Vitro Release Studies of Tenofovir-containing Microsponges. INNOSC Theranostics and pharmacological sciences. 2019;2(2):16-24.
41. Sapavatu SN, Jadi RK. Development of floating drug delivery system for loratadine: in vitro and in vivo evaluation. International Journal of Pharmaceutical Sciences and Research. 2020;11:3021-2.
42. Avula PR, Chettupalli AK, Chauhan V, Jadi RK. Design, formulation, in-vitro and in-vivo pharmacokinetic evaluation of Nicardipine-nanostructured lipid carrier for transdermal drug delivery system. Materials today: Proceedings. 2023 Jul 12.
43. Chettupalli AK, Kakkerla A, Jadi RK, Uppu P, Ghazwani M, Hani U, Amarachinta PR, Sarvani P, Haque MA. Design, development, and preclinical evaluation of pirfenidone-loaded nanostructured lipid carriers for pulmonary delivery. Scientific Reports. 2025;15(1):11390.
44. Chettupalli AK, Unnisa A, Peddapalli H, Jadi RK, Anusha K, Amarachinta PR. Development and evaluation of empagliflozin-loaded solid lipid nanoparticles: Pharmacokinetics and pharmacodynamics for oral delivery. Intelligent pharmacy. 2025;3(3):193-206.
45. Chaudhary AL, Barthwal K, Agarwal R, Prasad RR, Pavani U, Jadi RK. Nanotechnology-based drug delivery systems for targeted cancer therapy: molecular perspect. Genetics and Molecular Research. 2026 May 15.
46. Ahsan MN, Chettupalli AK, Pathak P, Amaravadi D, Jadi RK. Colloidal nanomedicine approaches for regulating cell death mechanisms in tumours. Therapeutic Delivery. 2026:17(8):853–76.
47. Sapavatu SN, Chinthala R, Jadi RK. An overview on Pharmacokinetics of Polymeric Nanoparticles Intended for Oral Delivery. Journal of Young Pharmacists. 2020;12(3):187.
48. Samuel MS, Ravikumar M, John J A, Selvarajan E, Patel H, Chander PS, Soundarya J, Vuppala S, Balaji R, Chandrasekar N. A review on green synthesis of nanoparticles and their diverse biomedical and environmental applications. Catalysts. 2022;12(5):459.
49. Wang L, Hu C, Shao L. The antimicrobial activity of nanoparticles: present situation and prospects for the future. Int J Nanomedicine. 2017;12:1227-49.
50. Mondal SK, Chakraborty S, Manna S, Mandal SM. Antimicrobial nanoparticles: current landscape and future challenges. RSC Pharmaceutics. 2024;1(3):388-402.
51. Graham W, Torbett-Dougherty M, Islam A, Soleimani S, Bruce-Tagoe TA, Johnson JA. Magnetic nanoparticles and drug delivery systems for anti-cancer applications: a review. Nanomaterials. 2025;15(4):285.
52. Zhu Y, Liao L. Applications of nanoparticles for anticancer drug delivery: a review. Journal of nanoscience and nanotechnology. 2015;15(7):4753-73.
53. Rizvi SA, Saleh AM. Applications of nanoparticle systems in drug delivery technology. Saudi pharmaceutical journal. 2018;26(1):64-70.
54. Kumar SS, Rajendran NK, Houreld NN, Abrahamse H. Recent advances on silver nanoparticle and biopolymer-based biomaterials for wound healing applications. International journal of biological macromolecules. 2018;115:165-75.
55. Parveen S, Misra R, Sahoo SK. Nanoparticles: a boon to drug delivery, therapeutics, diagnostics and imaging. Nanomedicine. 2012;8(2):147-66.
56. Halder B, Satpathy A, Kumari K, Nigam VK. Sustainable nanomedicine: green synthesis of functional nanomaterials and its applications. Frontiers in Chemistry. 2026;14:1890004.
57. Ali S, Khalil AA, Akhtar MS, Amin A, Zaman W. Comprehensive insights into natural bioactive compounds: From chemical diversity and mechanisms to biotechnological innovations and applications. ChemistryOpen. 2026;15(4):e202500469.
58. Zhu Z, Zhang Y, Wang Z, Tang W, Wang J, Gong J. Artificial intelligence assisted pharmaceutical crystallization. Crystal Growth & Design. 2024;24(10):4245-70.
59. Thang NH, Hien NC. Environmental and energy applications of green-synthesized semiconductor nanomaterials: from photocatalysis to smart sensors. Ionics. 2026;32(3):2521-56.
60. World Health Organization. Quality assurance of pharmaceuticals: a compendium of guidelines and related materials, Volume 1. Good practices and related regulatory guidance. World Health Organization; 2024 Oct 24.
61. Neelaveni K, Uzma S, Vaishnavi N, Ambika K, Gayatri Devi Y, Narender B. Importance of Green Chemistry in Synthesis of Heterocyclic Compounds: An Overview. Bulletin of Environment, Pharmacology and Life Sciences. 2024;13(11):01-09.
62. Chettupalli AK, Bukke SPN, Babu MR, Amarachinta PR, Boggula N, Mohammed A. Mucoadhesive lyophilized wafers loaded with nano-spanlastic felodipine formulation: development and characterization. Sci Rep. 2025;15(1): 39037.
63. Geetha K, Jithendar Reddy M, Sridevi B, Bhavani D,Narender B.Evolution of Green Chemistry and its Multifaceted Effects. Modern Trends in Chemical Science,Helmand Books, New Delhi, 2024, pp. 51-75.