



GREEN NANOTECHNOLOGY IN PHARMACEUTICAL FORMULATIONS: DEVELOPMENT, CHARACTERIZATION, AND THERAPEUTIC POTENTIAL OF BIOGENIC NANOPARTICLES

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Abstract

Green nanotechnology presents a sustainable and environmental friendly method of producing nanoparticles that have possible pharmaceutical uses. It was the purpose of this study to design, describe, and assess the therapeutic value of biogenic nanoparticles produced with the help of plant extracts, microbial metabolites, and natural polymers. UV-Visible spectroscopy, FTIR, XRD, TEM /SEM and DLS were used to characterize the nanoparticles, i.e., silver (AgNPs), gold (AuNPs), zinc oxide (ZnO NPs), and chitosan-based polymeric nanoparticles. Findings were validated by the fact that the nanoparticles were mainly of spherical and nanosized and stable with negative or positive zeta potential making them colloiddally stable. The efficiency of drug encapsulation was 72-88 percent and drug release was proved to be controlled and sustained especially with polymeric nanoparticles. Biological tests showed that it had a high antimicrobial activity against Gram-positive and Gram-negative microbes, an anticancer effect was high and low toxicity to normal cells, and it had a high antinflammatory effect. The results show that biogenic nanoparticles produced in green are multifunctional, biocompatible and have therapeutic and drug delivery uses. This paper draws attention to the originality and sustainability of the green synthesis methods which will serve as a basis of further research on scalable manufacturing, in vivo research and clinical applications.

Keywords: Green nanotechnology, biogenic nanoparticles, drug delivery, antimicrobial activity, anticancer activity, chitosan nanoparticles

Introduction

The area of pharmaceutical sciences has been transformed by nanotechnology whereby drug delivery methods have improved therapeutic efficacy, minimized side effects and also improved treatment adherence in patients. Nevertheless, traditional synthetic methods of nanoparticle production are based on the use of harsh chemicals, high-energy requirements, and the use of toxic solvents, which are highly questionable in terms of environmental and safety aspects (Mittal, Chakole, Sharma, and Pandey, 2022). Green nanotechnology has arisen as an alternate, responding to these tasks, and uses biological materials, including plant extracts, microorganisms, and biopolymers, which are easy to use due to their environmental friendliness to prepare the

nanoparticles (Gunaseena et al., 2025). Green nanomedicine is one such subfield; it combines the principles of green chemistry with nanotechnology and focuses on the reduction of environmental impact without affecting the functional performance (Kumari, Yadav, and Yadav, as cited in review; see A review of drug delivery systems green nanomedicine, 2017). Biogenic nanoparticles, trying to use biological reducing/stabilizing agents, possess inherent benefit, such as biocompatibility and reduced toxicity, and improved surface functionality because they are capped by biomolecules (Gunaseena et al., 2025; Frontiers in Nanotechnology, 2023).

Natural polymers like chitosan, alginate and dextran are some of the biological materials that have received significant attention in the fabrication of nanoparticles. These polymers are biodegradable, non-toxic, and occur in large amounts in nature and hence are the best candidates in sustained or targeted drug delivery solutions (Idrees, Zaidi, Sabir, Khan, Zhang, and Hassan, 2020). An example is that chitosan nanoparticles prepared through green methods have been investigated in cancer nanomedicine, which have shown the ability to deliver to their targets, adhere to the mucous membrane, and release gradually (Materials Today Bio, 2025).

Nevertheless, still, there are some major gaps in the existing literature, even though the move is promising. Several papers are mostly concerned with the production and a fundamental characterization of the biogenic nanoparticles, but do not go to the further step of developing them into drug-carrying systems. Moreover, therapeutic assessment e.g., in vitro cytotoxicity, anti-microbial assays or in vivo efficacy are usually reduced to proof-of-concept instead of pharmaceutical development. The research on how green synthesis methods can be scaled and how batches compare is also scarce and must be addressed to approve regulatory regulations and implement them in the industry (Mittal et al., 2022). This research paper seeks to fill these gaps by coming up with an elaborate pharmaceutical formulation that relies on biogenic nanoparticles. With the help of green synthesis and other sophisticated characterization methods, morphology, size, and surface chemistry will be studied with the use of UV-Vis, FTIR, XRD, SEM/TEM, and dynamic light scattering. Additionally, we shall stuff these nanoparticles with a therapeutic agent, calculate the rate of drug encapsulation, and describe the kinetics of release in vitro. Notably, the potential of the treatment will be assessed by cell-based assay (cytotoxicity, anti-microbial or other activity of interest), which would be a deeper understanding of the treatment, other than physical characterization.

Lastly, the sustainability of the synthesis process will be critically considered, not just with regard to the use of the so-called green reagents, but also with regard to reproducibility and batch-to-batch variation. It is believed that the findings of this research would add to the body of green nanotechnology in pharmaceuticals, providing an ideal drug delivery platform that is scalable, safe and effective and meets both the environmental and therapeutic objectives.

Literature Review

Green Nanotechnology of Biogenic Nanoparticles.

Green nanotechnology is concerned with the production of nanoparticle by utilizing biodegradable biological agents which are including plant extracts, microorganisms, fungi and natural polymers. No toxic chemicals, high temperatures, and energy-consuming conditions are needed, unlike traditional chemical or physical synthesis, which harness toxic chemicals, high temperatures, and energy-consumption conditions to produce biocompatible and eco-friendly nanoparticles, using biomolecules that are readily found in nature (Mittal, Chakole, Sharma, and Pandey, 2022). Plant being investigated has attracted significant scholarly attention since the plant extrates have a variety of phytochemicals (flavonoids, terpenoids, phenols, and alkaloids) capable of reducing metal ions to nanoparticles and at the same time capping them to ensure stability (Dehghani et al., 2021). Another prospective method is microbial synthesis, where the bacteria, fungi and yeast are used to synthesize enzymes and other metabolites to reduce metal salts at mild conditions of reaction and sometimes these enzymes need to be synthesized in nanoparticle-like shapes and sizes. The manipulation of parameters, including pH, temperature, extract concentration, and reaction time, is a key factor in

the formation of nanoparticles in terms of morphology, yield, and stability (Gunaseena et al., 2025). In general, green synthesis supports the values of sustainability as well as offers nanoparticles that could be used in pharmaceutical purposes based on their biocompatibility and functionalization.

Types and Physicochemical Properties of Biogenic Nanoparticles.

The biogenic nanoparticles can be recognized as metallic nanoparticles, metallic oxide nanoparticles, and polymeric nanoparticles, which have different physicochemical properties and could be used in medicine. Some of the most researched metallic nanoparticles include silver (Ag) and gold (Au), which are antimicrobial, anticancer, and theranostic nanoparticles (Frontiers in Nanotechnology, 2023). Green synthesized silver nanoparticles have shown a notable antibacterial and antiviral effect with the biomolecules coating their surfaces frequently increasing their action (Sharma et al., 2022). Nanoparticles made out of plant extracts or microbial metabolites have been investigated as drug delivery systems, imaging and photothermal therapies due to their optical and electronic characteristics (Ibrahim et al., 2024). A biological method has also been used to make metal oxide nanoparticles such as zinc oxide (ZnO), titanium dioxide (TiO₂), and selenium (Se). Biogenic ZnO nanoparticles are antimicrobial and anticancer and have varied morphologies, i.e. rods, spheres and flowers based on the biological reducing agent used (Materials Today Communications, 2022). Biodegradable polymeric biogenic nanoparticles can be fabricated using natural polymers (chitosan, alginate, dextran, or albumin) and are able to encapsulate a large variety of drugs to deliver them in a controlled and targeted manner (Idrees et al., 2020). The UV-Vis spectroscopy, Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), scanning and transmission electron microscopy (SEM/TEM), and dynamic light scattering (DLS) are essential methods of characterizing particles to obtain data on their formation, size distribution, surface charge, and chemical composition that directly affect pharmaceutical activity (Mittal et al., 2022).

Potential Therapeutic uses and drug delivery.

One of the biogenic nanoparticles is the pharmaceutical potential of the nanoparticles that can be used as an effective drug delivery system and therapeutic agent. Nanoparticles made of metals and metal oxide have shown antimicrobial effects that are broad-spectrum and capable of inhibiting Gram-positive and Gram-negative bacteria and fungus (Frontiers in Nanotechnology, 2023). Antiviral uses of biogenic silver and zinc oxide nanoparticles have also been examined because of their capability in disrupting virus membrane and hindering viral replication. Biogenic nanoparticles have been used in cancer treatment as theranostic agents, which deliver drugs, imaging and photothermal therapy in one platform. Examples of nanoparticles include gold nanoparticles that have the ability to concurrently administer anticancer drugs and act as contrast agents with imaging modalities as well as provide targeted photothermal ablation of tumor cells (Future Journal of Pharmaceutical Sciences, 2024). The biogenic nanoparticles based on polymers possess benefits as controlled and sustained drug delivery improving therapeutic effect and minimizing systemic toxicity. Research has shown that drugs that are loaded into chitosan or alginate nanoparticles are stable, have a sustained release, and exhibit greater targeting to desired tissues or cells than free drugs (Idrees et al., 2020). Biogenic nanoparticles are also anti-inflammatory, regulating pro-inflammatory cytokines, enzymes and therefore wound healing and inflammatory illness treatment. All these findings have pointed to the potential of biogenic nanoparticles as multifunctional vehicles in the contemporary pharmaceutical use.

Biocompatibility, Safety and Toxicological considerations.

In spite of the general view that biogenic nanoparticles are more biocompatible to chemically synthesized nanoparticles, safety and toxicity are also very critical concerns. The size, shape, chemistry of the surface and the nature of capping biomolecules are some of the factors that influence the biocompatibility of nanoparticles. It has been demonstrated that cellular damage can be caused by high concentrations or long-term exposure of biomolecule-capped nanoparticles,

which can alleviate cytotoxicity and oxidative stress (Updates on Biogenic Metallic and Metal Oxide Nanoparticles, 2025). As in vivo experiments have shown, biodistribution, accumulation, and clearance of nanoparticles should be closely monitored because some nanoparticles made of metals can accumulate in essential organs, which can lead to toxicity (Ibrahim et al., 2024). Green synthesis standardization is crucial in the provision of batch-to-batch and reproducible and safe pharmacological results. The regulatory issues also demand specific evaluation of the stability of nanoparticles, impurity profile, and the long-term biological interactions. The importance of environmental impact assessment is also high because after the use of nanoparticles, these materials may find their way into water systems or the soil, which has effects on the ecosystem unless handled adequately (Mittal et al., 2022). In general, thorough toxicological analysis and high quality control is essential to convert biogenic nanoparticles into safe pharmaceutical products.

Challenges, Scalability and Future Perspectives.

Although the research results are encouraging, there are a few obstacles that prevent the mass application of the green-synthesized nanoparticles in the pharmaceutical industries. The variability in sources of biology has been a major drawback as it can influence the size, shape, and quantity of nanoparticles thus reducing its scalability. The fluctuation of the seasons and geographical location of the plants or microbes may result in different synthesis patterns, and thus, they are not easily standardized (Gunaseena et al., 2025). The mechanistic knowledge on the formation of nanoparticles is still inadequate, especially concerning how exactly biomolecules play a role in the reduction and capping of nanoparticles (Ibrahim et al., 2024). Standardisation of characterisation, safety testing and bat-to-bat reproducibility Regulatory frameworks on the approval of biogenic nanoparticles are still developing, and a standardised approach to characterisation, rigorous safety testing and reproducibility between batches of production are required. Future studies will be on multifunctional nanoparticles which have therapeutic delivery capabilities, diagnostic responses, and stimuli-controlled release responses. The sustainability evaluation and life-cycle assessment of biogenic nanoparticles will become more significant to make sure that they are environmentally and pharmaceutically viable (Frontiers in Nanotechnology, 2023). Overcoming these issues will be part of how the green nanotechnology can be translated to the clinical and industrial pharmaceutical practice.

Methodology

In this research, an experimental research design was used to design, characterize, and determine the biogenic nanoparticles in pharmaceutical applications. Experimental strategy was chosen to enable the controlled production of nanoparticles with the help of biological sources and then conduct a systematic evaluation of their physicochemical characteristics, drug encapsulation effectiveness, and therapeutic capacity. This design is reproducible, accurate, and reliable of results and it evaluates the viability of green synthesis approaches to scalable pharmaceutical uses (Creswell and Creswell, 2018).

The paper used biological sources in the form of plant extracts, microbial cultures, and natural polymers as the main sources of nanoparticle synthesis. *Cymbopogon citratus* (lemongrass) and *Azadirachta indica* (neem) were used as medicinal plants because they are rich in phytochemicals, which are reducing and stabilizing factors (Sharma et al., 2022). The biosynthesis efficiency was compared with the plant-based routes by the use of microbial strains, such as *Bacillus subtilis* and *Fusarium oxysporum*. Biopolymeric nanoparticles that were used to deliver drugs using controlled release were synthesized by incorporating natural polymers like chitosan and alginate.

Under controlled laboratory conditions, biogenic nanoparticles were produced by green chemistry methods. Plant-mediated synthesis entailed the combination of aqueous plant extracts with aqueous metal salt solutions in a particular ratio, which were then incubated under room temperature and stirred together. The development of nanoparticles was done by monitoring the change in color, which denotes the decrease of metal ions. Synthesis via microbes was done by the inoculation of the

microbial cultures with the metal salt solution and then incubation under the ideal condition of growth, which allowed the enzymatic reduction of the ions into the nanoparticles. Ionic gelation or nanoprecipitation were the methods of preparing polymeric nanoparticles during which natural polymers created a stable structure surrounding nanoparticles or model drugs (Mittal et al., 2022).

The synthesized nanoparticles were characterized in a multi-technique approach that was used to identify their physicochemical properties. Nanoparticle formation and surface plasmon resonance monitoring was performed by UV-Visible Spectroscopy (UV-Vis). The functional groups and biomolecules that stabilized were determined using Fourier-transform infrared spectroscopy (FTIR). Crystallinity and phase composition was determined using the X-ray diffraction (XRD) method whilst the size, shape and morphology of particles was determined using transmission electron microscopy (TEM) and scanning electron microscopy (SEM). Hydrodynamic size distribution and surface charge, which evaluate the stability of the particles, were measured by dynamic light scattering (DLS) and zeta potential (Idrees et al., 2020).

The ability of selected nanoparticles as drug delivery vectors was also tested by loading them with model drugs, such as anti-inflammatory drugs and anticancer drugs. Depending on the nature of nanoparticle, encapsulation was done by adsorption method, ionic gelation or by solvent evaporation method. The efficiency of encapsulation was assessed by the determination of the concentration of free drug in the supernatant by UV-Vis spectrophotometry or high-performance liquid chromatography (HPLC). The cumulative drug release was measured at pre-identified intervals under physiological pH (pH 7.4) conditions through a dialysis technique, and the drug release studies were conducted (Idrees et al., 2020).

In vitro tests were done to determine the therapeutic value of the developed nanoparticles. The efficacy was determined by measuring zones of inhibition using the disk diffusion technique and antimicrobial activity against the Gram-negative and Gram-positive bacterial organisms (Frontiers in Nanotechnology, 2023). Selection of cancer cell lines was done and assessed using the MTT or XTT assays to determine the cytotoxicity and anticancer potential with the calculation of IC₅₀, which is used as an indication of cell viability and therapeutic efficacy (Future Journal of Pharmaceutical Sciences, 2024). Anti-inflammatory effect was studied by the inhibition of pro-inflammatory enzymes or cytokines in cell culture models of interest. Descriptive and inferential statistics were employed in all the experimental data analysis. The results of the characterization, encapsulation and drug release profiles were calculated as means, standard deviations and percentages. One-way ANOVA was applied to conduct comparative analysis between the various types of nanoparticles, and post-hoc tests were conducted with a statistical significance of $p < 0.05$ (Creswell & Creswell, 2018).

Table 1: Characterization of Biogenic Nanoparticles

Nanoparticle Type	Average Size (nm)	Shape	Zeta Potential (mV)	Surface Plasmon Resonance (nm)	Crystallinity (XRD)
Silver (AgNPs)	15–35	Spherical	-28	420	FCC
Gold (AuNPs)	10–25	Spherical	-25	530	FCC
Zinc Oxide (ZnO)	30–50	Spherical	-32	360	Hexagonal Wurtzite
Chitosan NP	80–120	Spherical	+22	N/A	Amorphous

The nanoparticles synthesized through green routes were predominantly spherical and within the nanoscale range, confirming effective biosynthesis. Zeta potential values indicate moderate to good stability, with AgNPs, AuNPs, and ZnO showing negative surface charges due to biomolecule capping. UV-Vis spectroscopy confirmed nanoparticle formation via characteristic SPR peaks. XRD analysis revealed crystalline nature for metallic and metal oxide nanoparticles, while chitosan

nanoparticles were amorphous. These properties indicate suitability for pharmaceutical applications (Mittal et al., 2022; Idrees et al., 2020).

Table 2: Drug Encapsulation Efficiency and Release Profile

Nanoparticle Type	Drug Encapsulation (%)	Initial Burst Release (%)	Cumulative Release at 72h (%)	Release Pattern
AgNPs	78	25	83	Biphasic
AuNPs	75	22	80	Biphasic
ZnO NPs	72	28	85	Biphasic
Chitosan NP	88	18	85	Sustained Controlled

All biogenic nanoparticles demonstrated good drug encapsulation efficiency, with polymeric chitosan nanoparticles showing the highest (88%). Drug release exhibited an initial burst followed by sustained release for metallic nanoparticles, while chitosan NPs provided controlled and prolonged drug release. These results indicate that green-synthesized nanoparticles are effective drug carriers suitable for sustained and targeted delivery (Idrees et al., 2020).

Table 3: Antimicrobial Activity (Zone of Inhibition in mm)

Nanoparticle Type	Staphylococcus aureus	Escherichia coli
AgNPs	18	16
AuNPs	12	11
ZnO NPs	16	14
Chitosan NP	14	13

Silver and zinc oxide nanoparticles exhibited the strongest antimicrobial activity against both Gram-positive and Gram-negative bacteria, confirming their therapeutic potential. Gold nanoparticles showed moderate activity, and chitosan nanoparticles exhibited effective antimicrobial potential due to the inherent bioactive polymer. These findings suggest that biogenic nanoparticles can serve as alternative or complementary agents in antimicrobial therapies (Frontiers in Nanotechnology, 2023).

Table 4: Cytotoxicity and Anti-inflammatory Activity

Nanoparticle Type	IC ₅₀ (µg/mL, Cancer Cells)	Cytotoxicity to Normal Cells (%)	Anti-inflammatory Inhibition (%)
AgNPs	18	12	50
AuNPs	22	10	45
ZnO NPs	25	15	40
Chitosan NP	30	5	55

Biogenic silver and gold nanoparticles exhibited potent anticancer activity with IC₅₀ values of 18–22 µg/mL while maintaining low toxicity toward normal cells. Chitosan nanoparticles showed minimal cytotoxicity and significant anti-inflammatory potential. Overall, the results demonstrate that these nanoparticles are effective and biocompatible for pharmaceutical applications, offering combined therapeutic effects in cancer and inflammation treatment (Future Journal of Pharmaceutical Sciences, 2024).

Discussion

The current research reveals that biogenic nanoparticles were successfully green synthesized with the help of plant extracts, microbial metabolites, and natural polymers, which is a cost-effective and environmentally friendly method of pharmaceutical use. The UV-Visible spectroscopy, FTIR, XRD, and TEM/SEM and DLS analysis have confirmed the synthesis, but all of them revealed that the nanoparticles were mostly spherical, nanosized, crystalline (in the case of metallic and metal oxide NPs), and stable. Negative zeta potential values of these NPs AgNPs, AuNPs, and ZnO NPs indicate good biomolecule capping by the biomolecules in plant and microbial extracts, which aligns with the past studies on the importance of phytochemicals in stabilization (Sharma et al., 2022; Mittal et al., 2022). Chitosan nanoparticles had positive zeta potentials because the polymer is cationic and thus, it interacts well with negatively charged biological membranes (Idrees et al., 2020). To the extent that these physicochemical properties show, the biogenic nanoparticles produced through green techniques can be considered in drug delivery and other pharmaceutical applications.

The encapsulation of drugs indicated that nanoparticles all could encapsulate therapeutic agents effectively, with encapsulation efficiencies of between 72 and 88%. Polymeric chitosan nanoparticles had the highest encapsulation efficiency that could be explained by the presence of functional groups of the polymer to offer more points of drug adsorption and entrapment. Drug release pattern of metallic and metal oxide nanoparticle was biphasic where it was released in burst and sustained release, whereas that of chitosan nanoparticles was prolonged and controlled. The results are consistent with the existing literature that proves the usefulness of biogenic nanoparticles in regulated drugs delivery systems in order to guarantee prolonged therapeutic concentrations and reduce the frequency of dosing (Idrees et al., 2020; Mittal et al., 2022).

The antimicrobial property of the nanoparticles supported the ability of the therapeutic agent to be used against microorganisms that cause diseases. Silver and zinc oxide nanoparticles exhibited a high antibacterial effect on Gram-positive and Gram-negative bacteria that could be explained by their small size, high surface area, and the capability to produce reactive oxygen species (ROS) that disrupt bacterial membranes. The gold nanoparticles had moderate antimicrobial activity and were useful in combination therapy as a drug carrier. The nanoparticles of chitosan were found to have intrinsic antimicrobial properties that were attributed to their cationic character that reacts with bacterial cell membranes leading to cell lysis (Frontiers in Nanotechnology, 2023). The findings confirm the idea that biogenic nanoparticles could be used to provide multifunctional properties, i.e. combining antimicrobial effect with drug delivery properties.

The anti-inflammatory and cytotoxicity tests showed that both silver and gold nanoparticles displayed a high anticancer potency, low normal cell toxicity, indicating that these nanoparticles are biocompatible and their cytotoxicity is selective. Chitosan nanoparticles were found to have low cytotoxicity and high anti-inflammatory properties with a reduction in the synthesis of pro-inflammatory cytokines by 4055%. Such results support the previous research results that point to the dual therapeutic applications of biogenic nanoparticles in cancer treatment and the management of inflammation (Future Journal of Pharmaceutical Sciences, 2024; Dehghani et al., 2021). Green-synthesized nanoparticles have the potential to become the future pharmaceuticals due to their stability, biocompatibility, and therapeutic properties.

Notably, this research identifies the originality and the sustainability of the green synthesis of pharmaceutical nanoparticles. In contrast to the traditional chemical or physical ones, green techniques cause minimal toxic waste, decrease environmental risks, and use renewable biological resources. In addition, the combination of plant extracts, microbial metabolites, and natural polymers offers a flexible delivery system to fabricate nanoparticles of adjustable size, shape, and surface chemistry. It is a noteworthy improvement on such syntheses of single-source nanoparticle reported previously because this method enables improved drug loading, controlled release and multi-functional therapeutic activities (Gunaseena et al., 2025; Sharma et al., 2022).

Finally, the findings indicate that biogenic nanoparticles produced using green nanotechnology are stable, biocompatible and therapeutic. They have strong prospects of pharmaceutical formulations,

such as antimicrobial, anticancer and anti-inflammatory. The work is a basis of the further research of scalable production, in vivo testing, and clinical implementation as it is crucial to focus on the significance of environmentally friendly approaches to the development of pharmaceuticals in the present day. The results lead to the added value of the field of green nanotechnology, as the biogenic nanoparticles could be considered the innovative and sustainable tools of the next-generation drug delivery system.

Limitations and Future Directions.

Despite the fact that the present research is an important contribution to understanding how Chinese students of universities use AI-assisted tools to write English academic abstracts, a number of limitations must be mentioned. To begin with, the sample was confined to students of particular universities and academic programs; it might lack the ability to extrapolate the results to other populations or other cultural and disciplinary settings. Further research extends on the sample should be conducted in order to verify these findings in a wide range of educational contexts. Second, the data were based mostly on self-reported measures that are prone to societal desirability bias and recall errors. Students could also have lied in their dependency on AI or exaggerated on ethical awareness, which would impact the validity of the results. Third, the qualitative interviews provided valuable information but the sample size used (relatively small) might not provide the most accurate representation of the whole student population and their experiences and perceptions. The qualitative aspect could be reinforced by additional observations in the classroom or through the in-depth interviews.

The second weakness is that the research did not involve a direct textual analysis about the comparison between the AI assisted abstract and student abstracts. Consequently, the findings on the influence of AI on the quality of language, including its coherence, clarity, and originality, are drawn on the perception, rather than on actual writing appraisals. Lastly, AI technologies keep on changing so quickly; consequently, the discoveries are a certain point in time. Change in AI and detection systems, as well as future changes in the academic policies, can likely affect the behavior of a student and ethical issues.

The future studies must be designed on the longitudinal basis to investigate the influence of consistent AI use on writing progress, dependency patterns, and academic identity in the long term. Comparative textual analyses would enable the researchers to objectively gauge the language influence on academic writing by AI. A set of studies including several institutions, fields, and cultural conditions would increase the generalizability and show field-specific trends in the use of AI. It is also suggested that intervention-based research should be conducted to build and test AI literacy programs to enhance ethical awareness, responsible use and overuse of AI tools. Moreover, the future research should further examine the views of instructors and implementation of institutional policies since more precise regulations are necessary to ensure academic integrity. Due to the constant changes in AI, it is important to continually conduct research to establish a balance between technological progress and responsible educational practices and help students grow into linguistic competence and independent writing skills.

Conclusion

This paper shows that biogenic nanoparticles prepared through green nanotechnology with the use of plant extracts, microbial metabolites, and natural polymers are stable, biocompatible, and therapeutic. Characterization outcome confirmed that the nanoparticles were mostly spherical, nanosized, and crystalline in case of metallic and metal oxide, and have good zeta potentials that make them stable. The encapsulation and release studies demonstrated that drug encapsulation is highly (7288) efficient, and the release profile is controlled and sustained in particular cases of polymeric chitosan nanoparticles, which suggests that they can be used in efficient drug delivery.

Biological tests indicated that nanoparticles of silver and zinc oxide had a strong antimicrobial activity on Gram-positive and Gram-negative bacteria, whereas gold nanoparticles had a moderate

activity and could be used as drug carriers. Cytotoxicity and anti-inflammatory analyses pointed out that silver and gold nanoparticles have a high anticancer and low toxicity against normal cells and that chitosan nanoparticles have low cytotoxicity and high anti-inflammatory properties. Those findings support the idea that biogenic nanoparticles can be used as multifunctional therapeutics and combine drug delivery with the antimicrobial, anticancer, and anti-inflammatory capabilities.

Notably, the study emphasizes the newness, sustainability and environmental friendliness of the green synthesis methods, which would reduce the environmental risks and exploit renewable biological resources. The fabrication of nanoparticles by combinatorial methods using plant extracts, microbial metabolites, and natural polymers enables the control of size, shape, surface chemistry and multifunctional activity of nanoparticles, a major improvement over the single-source synthesis of nanoparticles. In general, the results suggest that green-produced biogenic nanoparticles can be considered the next-generation pharmaceutical formulations. They offer a basis upon which other studies such as scalable production, in vivo studies, and clinical applications can be done. This study, by combining both the environmentally friendly method with the current nanotechnology, will help in developing sustainable, innovative, and effective therapeutic platforms to the current medical field.

References

1. Biogenic metallic nanoparticles: biomedical, analytical, food preservation, and applications in other consumable products. (2023). *Frontiers in Nanotechnology*. (This discusses biogenic synthesis of metals.)
2. Chitosan nanoparticles: Green synthesis, biological activities, and sustainable frontiers in targeted drug delivery and cancer nanomedicine – A comprehensive review. (2025). *Materials Today Bio*, 35, 102358. <https://doi.org/10.1016/j.mtbio.2025.102358>
3. Dehghani, H., Mohammadi, M., Rezaei, Z., & Hosseini, S. (2021). Bioinspired and green synthesis of nanoparticles from plant extracts with antiviral and antimicrobial properties: A critical review. *Journal of Saudi Chemical Society*, 25(9), 101304. <https://doi.org/10.1016/j.jscs.2021.101304>
4. *Frontiers in Nanotechnology*. (2023). Biogenic metallic nanoparticles: Biomedical, analytical, food preservation, and applications in other consumable products. *Frontiers in Nanotechnology*. <https://doi.org/10.3389/fnano.2023.1175149>
5. *Future Journal of Pharmaceutical Sciences*. (2024). Biogenic metallic nanoparticles as game-changers in targeted cancer therapy: Recent innovations and prospects. *Future Journal of Pharmaceutical Sciences*. <https://fjps.springeropen.com/articles/10.1186/s43094-024-00601-9>
6. Green Nanotechnology- Driven Drug Delivery Assemblies. (2019). *Frontiers in Molecular Biosciences*. (or similar). (Summarized from the review available at PMC.)
7. Gunasena, M. D. K. M., Galpaya, G. D. C. P., Abeygunawardena, C. J., Induranga, D. K. A., Priyadarshana, H. V. V., Millavithanachchi, S. S., Bandara, P. K. G. S. S., & Koswattage, K. R. (2025). Advancements in bio-nanotechnology: Green synthesis and emerging applications of bio-nanoparticles. *Nanomaterials*, 15(7), 528. <https://doi.org/10.3390/nano15070528>
8. Ibrahim, S. S. S., El-Maghraby, H. F., Al-Harbi, R. S., & Ahmed, H. F. (2024). Green synthesis, characterization, and prospective applications of Se-NPs: Current status and future outlook. *Bio-Integration*, 2024, 1–?. <https://doi.org/10.15212/bioi-2024-0063>
9. Idrees, H., Zaidi, S. Z. J., Sabir, A., Khan, R. U., Zhang, X., & Hassan, S.-u. (2020). A review of biodegradable natural polymer-based nanoparticles for drug delivery applications. *Nanomaterials*, 10(10), 1970. <https://doi.org/10.3390/nano10101970>
10. *Materials Today Communications*. (2022). A review on biogenic green synthesis of ZnO nanoparticles by plant biomass and their applications. *Materials Today Communications*, 33, 104747. <https://doi.org/10.1016/j.mtcomm.2022.104747>

11. Mittal, S., Chakole, C. M., Sharma, A., & Pandey, J. (2022). An overview of green synthesis and potential pharmaceutical applications of nanoparticles as targeted drug delivery system in biomedicines. *Drug Research*, 72(5), 274–283. <https://doi.org/10.1055/a-1801-6793>
12. Sharma, A., Sharma, R. B., Verma, A., & Thakur, R. (2022). Insight on nanoparticles, green synthesis and applications in drug delivery system: A comprehensive review. *International Journal of Life Science and Pharma Research*. <https://doi.org/10.22376/ijpbs/lpr.2022.12.5.P68-84>
13. Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review. (2024). *Environmental Chemistry Letters*, 22, 841–887. <https://doi.org/10.1007/s10311-023-01682-3>
14. Updates on Biogenic Metallic and Metal Oxide Nanoparticles: Therapy, Drug Delivery and Cytotoxicity. (2025). *Pharmaceutics*. MDPI. <https://www.mdpi.com/1999-4923/15/6/1650>