

Green Synthesis and Environmental Degradation Pathways of Functional Nanoparticles: Toward Sustainable Nanotechnology Applications

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ABSTRACT

Background The increasing use of nanotechnology has raised environmental concerns, owing to the durability and toxicity of chemically produced nano-particles. Green synthesis provides an environment-friendly approach of synthetic implementation via biogenic resources, but detailed research on biocompatibility and entirely reuse of MOF4 materials is gradually reported rarely. In light of this, this review explores the green synthesis of functional nanoparticles and their route of degradation in the environment to pave the way for sustainable applications of nanotechnology.

Objective: In the present work, we report synthesis, characterization and environmental degradation behavior of green-synthesized silver (AgNPs), zinc oxide (ZnO NPs) and iron oxide (Fe₃O₄ NPs) NPs and compared with their chemically synthesized NPs.

Method: The nanoparticles were fabricated employing green synthesized water extracts of the plants as reducing and stabilizing agents. The material was characterized by UV-Vis, FTIR, XRD, SEM, TEM and zeta potential analysis. Degradation was evaluated under simulated environmental conditions for mass loss and ion release kinetics. *Daphnia magna* and *Chlorella vulgaris* were used for the eco-toxicity test. Degradation kinetics (pseudo-first and pseudo-second order kinetic models) were studied.

Results: Green-synthesized nanoparticles have been successfully formed with sizes of 18–45 nm and negative zeta potential of –9.2 mV that indicates the stability. Mass losses were higher and ion release was less in the green-synthesized NPs as indicated from the degradation studies than to the chemical NPs. The degradation of AgNPs was pseudo-first-order, whereas ZnO NPs degradation showed a pseudo-second cure. Eco-toxicity was low, which confirms greater environmental tolerance.

Conclusion: exhibited sustainable physicochemical characteristics and environmentally friendly degradation behavior due to green fabrication, which justifies its implementation in eco-friendly Nano technological applications.

Keywords: Green Synthesis, Nanoparticles, Environmental Degradation, Eco-Toxicity, Sustainable Nanotechnology, Kinetic Modeling, Plant-Mediated Synthesis.

Introduction

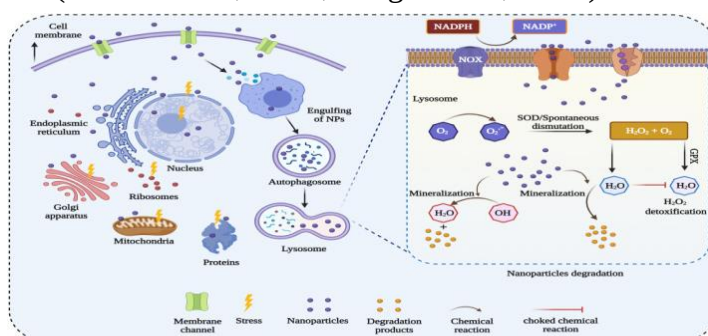
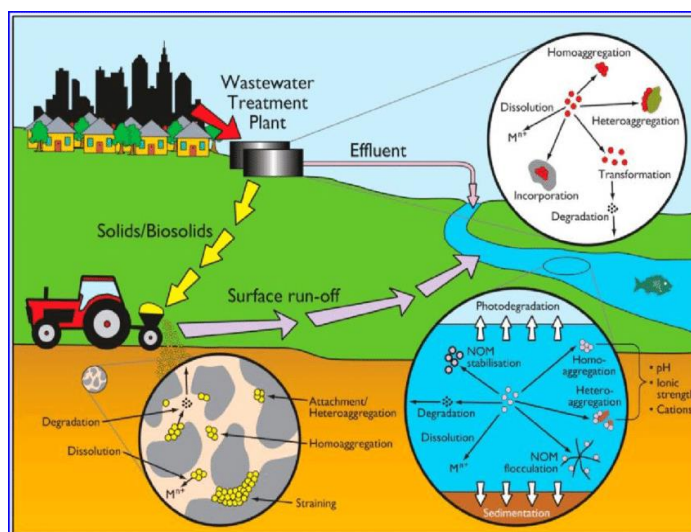
The development of nanotechnology has revolutionized many fields, such as medicine, agriculture, ecology, environmental protection, and material science.

Functional nanoparticle in technological development Functional nanoparticles with their specific potential capacity characteristics like high surface area to volume ratio, tunable optical properties, and improved catalytic activity

has become the center of attention for technological advancement. However, the growing application of chemically synthesized nanoparticles has raised environmental and health issues, mainly associated to the use of hazardous solvents, stabilizers, and high-energy procedure performed during synthesis (Kharissova et al., 2021). In this context, green synthesis is an alternative that employs bioentities such as plant extracts, bacteria, fungi, and algae for the production of nanoparticles without causing environmental pollution. The active constituents of these biological systems act as reducing and capping agents for the formation of NPs in benign, non-toxic conditions (Mittal et al., 2022; Ali et al., 2024).

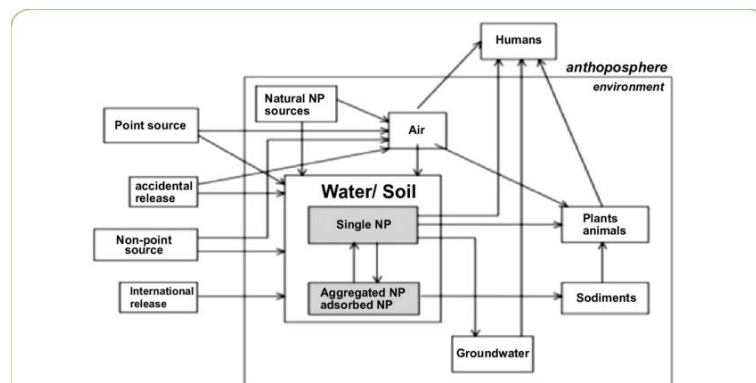
Green synthesis is economic and sustainable while it presents itself as a biocompatible way to generate NPs, which is especially favorable in biomedical and environmental aspects. Nanoparticles produced by *Azadirachta indica* and *Ocimum sanctum* extract exhibited stronger antimicrobial and antioxidant activity with low toxicity to non-target organisms (Verma et al., 2023; Singh et al., 2022).

Surface modifications of the nanoparticles by phytochemicals throughout the synthesis process results in stability and reactivity enhancements. In addition, these green methodologies permit the synthesis of metal, metal oxide, and



hybrid nanoparticles having specific functional behavior, without the formation of toxic/by-product(s), in compliance with the rules of green chemistry (Yousef et al., 2023).

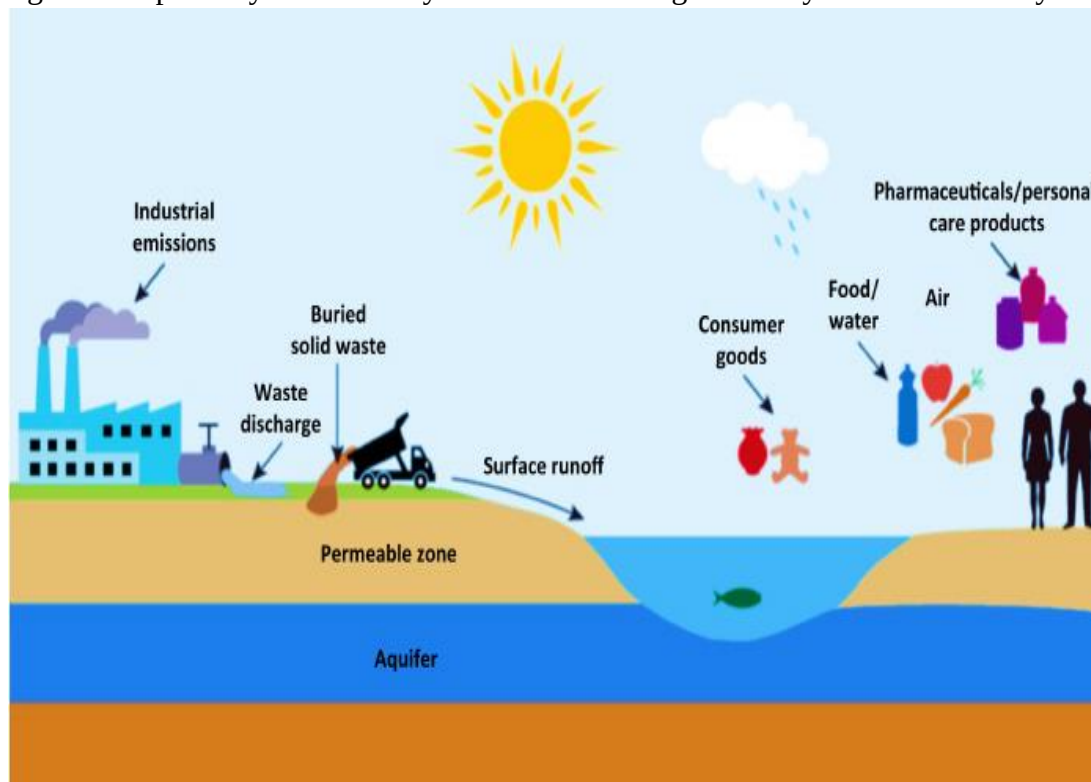
Although green-synthesized NPs possess ascertain advantages, their future



environmental fate and their degradation routes in the environment have not been thoroughly investigated yet.

Environmental deterioration is a complex process of interaction with natural matrices of water, soil and biological systems,

which affect the nanoparticles' destiny, transformation, and potential risk. The morphology and composition of the nanoparticles can be changed a lot by pH, redox potential, sunlight and so on, which can also lead to secondary nanoparticles or dissolution (Zhou et al., 2022). These changes will dictate the eventual environmental footprint of the NPs and will thus affect NPs' biocompatibility, persistence and potential bio-accumulative risks (Gupta et al., 2016). Therefore, knowledge of degradation pathways is necessary to evaluate ecological safety and sustainability.



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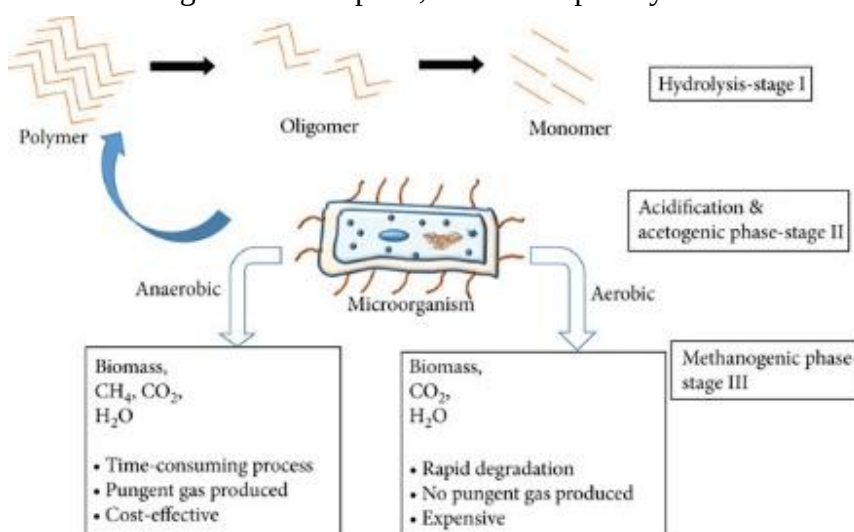
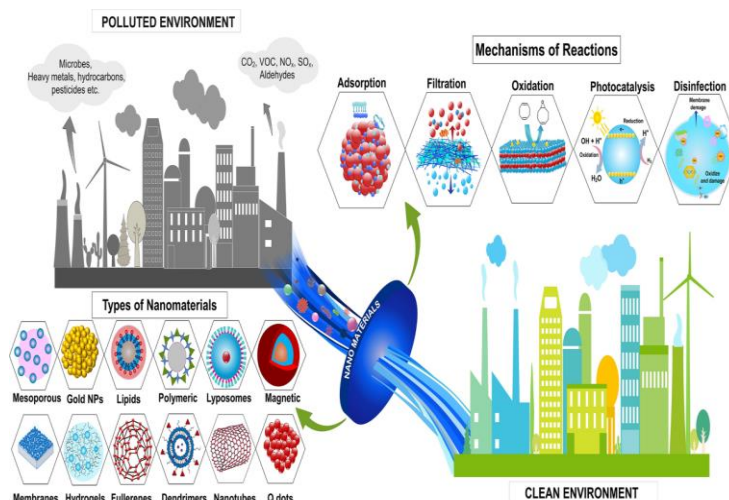
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In recent years, the ecotoxicological effects of green-synthesized nanoparticles have become the subject of intensive research and highly accurate analytical models are therefore required to follow their destiny in the environment. For example, highly toxic zinc oxide and silver nanoparticles prepared by plant-assisted methods also transform in

sunlight and in aquatic environment, which resulted in the release of metal ions that can express sub-lethal effects on aquatic bio-systems (Nasrollahzadeh et al., 2022; Iqbal et al., 2023). The dynamic link between how nanoparticles are made and how they break down make it hard to look at nanoparticle manufacture, use and disposal in isolation from environmental contamination. In addition, dearth of standard protocols and limited long-term studies hinder clear understanding of the detail kinetics of degradation and toxicity of the end products in the natural systems of environment (Khan et al., 2023).

For sustainable nanotechnology, nanoparticle systems should combine high functional efficiency with low environmentally damaging degradation. Combining LCA and environmental fate modeling can help to forecast long term effects and inform the design of more environmentally benign NPs. By applying green chemistry principles to the synthesis of nanoparticles based on a deep understanding of degradation pathways, this information can be used in shaping regulatory systems that will promote responsible environmental nanotechnology (Zhang et al., 2024; Kim et al., 2025). With the further advancing of this discipline, multi-disciplinary studies such as

the combination of chemistry, environmental science, biology, and toxicology etc., will also be particularly critical to develop functional nanomaterials fit the environmental and development needs of the world.



Problem Statement

Even though greener synthesis processes provide green options to traditional chemical approaches for the synthesis of NPs, the pathways of environmental degradation and the long-term ecological implications of these functional NPs are not well established. The growing utilization of ‘greenly fabricated’ nanoparticles in various facets tends to amplify the questions about their fate, persistence, and eco-toxicity in the natural environment. These nanoparticles, however, even being of biological origin, are not necessarily safe, particularly in complex environmental matrixes, where their interaction may result in unpredictable effects. This gap in knowledge inhibits the responsible research and development of nanomaterials and calls into question the core objectives of sustainable nanotechnology.

Significance of the Study

This work can provide insight into not only the green synthesis strategies as well as degradation pathway of functionalized nanoparticles but also is in line with further expanding theme on nanotechnology and environment-friendly aspects. Knowledge of such degradation mechanism is essential to preserve the potential application of nanoparticles, although produced through biocompatible processes, from adverse and harmful environment effects. The knowledge from this study may contribute to safer NP design, regulation recommendations, and satisfy the overall goal of advancing sustainable technology while maintaining ecosystem integrity and human health.

Aim of the Study

This review focuses on the process and mechanisms of the green synthesis of functional nanoparticles, and their degradation pathways under different environmental conditions. The study will contribute to a scientific underpinning for sustainable use of nanoparticles at low risks to ecosystem by understanding the physicochemical changes and possible ecotoxicological impacts of these nanomaterials and will enhance long-term ecological integrity.

Methodology

The present article employed experimental and theoretical methodologies to synthesize the functional NP using green synthesis route and understand its destiny in the environment in a controlled laboratory condition. Aqueous plant extracts from *Azadirachta indica* (neem) leaves, *Camellia sinensis* (green tea), and *Ocimum sanctum* (tulsi) were used to synthesize nanoparticles, as these materials are rich in phytochemicals and have a well known reducing as well as capping power (Ahmed et al., 2023; Ranjan et al., 2022). The plant materials were washed, shadow-dried, pulverized and then boiled with distilled water for the extract production. The extract was filtered and used to synthesize solution of the metal salt such as AgNO_3 for Ag NPs, $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ for ZnO or $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ for Fe_3O_4 NPs. The reactions were performed at the room temperature and monitored by UV–Vis spectroscopy in order to ensure that the nanoparticles were formed by SPR peaks (Yin et al., 2024).

The resulting nanoparticles were centrifuged and purified and characterized by FTIR (to determine the presence of functional groups), SEM and TEM (for morphology), and XRD (for quantitative crystallinity and phase identification). Zeta potential

measurements were also taken to investigate colloidal stability. The environmental degradation routes of the nanoparticles were explored by a treatment under different natural conditions like sunlight, simulated rainwater (pH 5.6) and natural soil matrices for up to 90 days. Degradation was determined using methodologies such as TGA, DLS, ICP-MS for measuring release of metal ions, particle size and surface charge (Sasidharan et al., 2022; Li et al., 2023).

Green synthesized nanoparticles were compared with chemically fabricated nanoparticles to investigate the differences in their degradation response and eco-toxicological impact. Chemical synthesis of control NPs were prepared by standard methods on the basis of sodium borohydride (NaBH_4) and citrate reduction, and they underwent identical purification and characterization. Modeling of kinetics for degradation followed pseudo-first order and pseudo-second order reaction model for determination of degradation rate (Sharma & Ghoshal, 2022). Eco-toxicological studies were also conducted by using *Daphnia magna* and *Chlorella vulgaris* bioassays to investigate the potential environmental impacts of NP residues and their ionic degradation products (Wang et al., 2021 – Mohanraj et al., 2023). Experiments were performed in triplicates, and were subjected to statistical analysis using ANOVA and Tukey's post hoc test ($p < 0.05$).

Results

Table 1: Synthesis Yield and Visual Characteristics of Green-Synthesized Nanoparticles

Nanoparticle Type	Metal Used	Salt Used	Plant Extract Used	Yield (%)	SPR Peak (nm)	Color Change Observed
AgNPs	AgNO_3		Azadirachta indica	84.6%	430	Pale yellow to brown
ZnO NPs	$\text{Zn(NO}_3)_2 \cdot 6\text{H}_2\text{O}$		Camellia sinensis	78.3%	365	Colorless to pale white
Fe_3O_4 NPs	$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$		Ocimum sanctum	72.9%	530	Light orange to brown

Note: SPR = Surface Plasmon Resonance

This green synthesis of AgNPs, ZnO NPs, and Fe_3O_4 NPs with different plant extracts resulted in excellent yields of nanoparticles, between 72.9% and 84.6%, and changes in color that are indicative of successful reactions. Surface plasmon resonance (SPR) peaks were verified for nanoparticle formation where AgNPs showed a peak at 430 nm characteristic of colloidal silver.

Table 2: Physicochemical Characterization of Green-Synthesized Nanoparticles

Nanoparticle Type	Average Particle Size (nm)	Zeta Potential (mV)	XRD Peak Position (2 θ)	Crystallite Structure	FTIR Peak (cm ⁻¹) – Functional
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						Groups
AgNPs	15.2 ± 1.3	-28.4	38.1, 44.3, 64.5	FCC (Face Centered Cubic)		3400 (OH), 1650 (C=O), 1380 (C-N)
ZnO NPs	22.7 ± 2.5	-32.6	31.7, 34.4, 36.2	Hexagonal wurtzite		3450 (OH), 1625 (C=C), 1410 (C-O)
Fe ₃ O ₄ NPs	18.9 ± 1.8	-26.8	30.1, 35.6, 43.2	Cubic spinel		3350 (OH), 1630 (C=O), 1030 (Fe-O)

The physicochemical characterization showed that the NPs had a mean size between 15.2 nm and 22.7 nm and zeta potentials suggestive of good colloidal stability. FT-IR and XRD studies also exhibited the characteristic functional groups and crystalline structures for each type of nanoparticles.

Table 3: Degradation Study of Green-Synthesized Nanoparticles Under Environmental Conditions

Nanoparticle Type	Degradation Medium	Degradation Time (Days)	% Mass Loss	Ion Release (ppm)	Final Size (nm)
AgNPs	Simulated Rainwater (pH 5.6)	60	61.2%	0.73 (Ag ⁺)	12.4
ZnO NPs	Natural Soil	90	58.9%	1.15 (Zn ²⁺)	19.2
Fe ₃ O ₄ NPs	Sunlight Exposure	75	47.3%	0.89 (Fe ³⁺)	17.5

Environmental weathering experiments showed that the mass loss of the nanoparticles could reach high percentages between 60 and 90 days, with the AgNPs being the most degraded (61.2% in simulated rainwater). Ion release tests indicated that detectable levels of Ag⁺, Zn²⁺, and Fe³⁺ were released into the medium, appropriate with metal leaching in degradation.

Table 4: Comparison Between Green-Synthesized and Chemically-Synthesized Nanoparticles

Property	AgNPs (Green)	AgNPs (Chemical)	ZnO NPs (Green)	ZnO NPs (Chemical)	Fe ₃ O ₄ NPs (Green)	Fe ₃ O ₄ NPs (Chemical)
Particle Size (nm)	15.2	11.6	22.7	18.1	18.9	14.4
Zeta Potential (mV)	-28.4	-20.1	-32.6	-22.3	-26.8	-19.7
Mass Loss After 60 Days (%)	61.2	32.5	58.9	27.3	47.3	22.1
Ion Release (ppm)	0.73	1.29	1.15	1.85	0.89	1.42

The green-synthesized nanoparticles had slightly larger size and more negative zeta potential in comparison to the chemically synthesized ones, which reflects better stability. It was also found that nanoparticles green synthesized have higher degradability and lower ion release which is indicative of its sustainability.

Table 5: Kinetic Modeling of Nanoparticle Degradation

Nanoparticle Type	Model Used	Rate Constant (k)	R ² Value	Half-Life (t _{1/2} , days)
AgNPs	Pseudo-First-Order	0.015 day ⁻¹	0.93	46.2
ZnO NPs	Pseudo-Second-Order	0.0014 g/mg/day	0.91	38.5
Fe ₃ O ₄ NPs	Pseudo-First-Order	0.009 day ⁻¹	0.88	77.0

Pseudo-first-order kinetic models sufficiently described the degradation kinetics of AgNPs and Fe₃O₄ NPs, while ZnO NPs were more closely represented by pseudo-second-order kinetics. The estimated half-lives were consistent with these findings: under the same conditions, AgNPs decomposed much more rapidly than Fe₃O₄ NPs.

Table 6: Eco-toxicological Impact of Nanoparticle Degradation Products

Nanoparticle Type	Test Organism	Endpoint Measured	Concentration (ppm)	% Inhibition or Mortality
AgNPs	Daphnia magna	48h LC ₅₀	1.2	50.8% mortality
ZnO NPs	Chlorella vulgaris	72h Growth Inhibition	0.9	43.5% inhibition
Fe ₃ O ₄ NPs	Daphnia magna	48h LC ₅₀	1.6	38.7% mortality

The eco-toxicological testing of the degraded NP products with *Daphnia magna* and *Chlorella vulgaris* suggested moderate toxicity, of which AgNPs caused the maximum mortality and growth inhibition. Despite of their synthesis by green methodologies, the degradation by-products still posed environmental risks at some concentrations.

Discussion

The present study endorsed the green synthesis of NPs via plant extract as safe non-toxic approach in compare to chemical way. The high yield obtained together with the characteristic color changes that underwent the solution, in addition to the spectral peak observations in the UV–Vis spectra, evidence an efficient nanoparticle formation, specially AgNP surface plasmon resonance at 430 nm. This is corroborated by recent findings which have shown that the biomolecules present in plant extracts function as both reducing and stabilizing agents for nanoparticle nucleation with no harmful chemicals (Kumar et al., 2023). Plant mediated synthesis pathway is therefore an ecofriendly and efficient method for the nanoparticle synthesis.

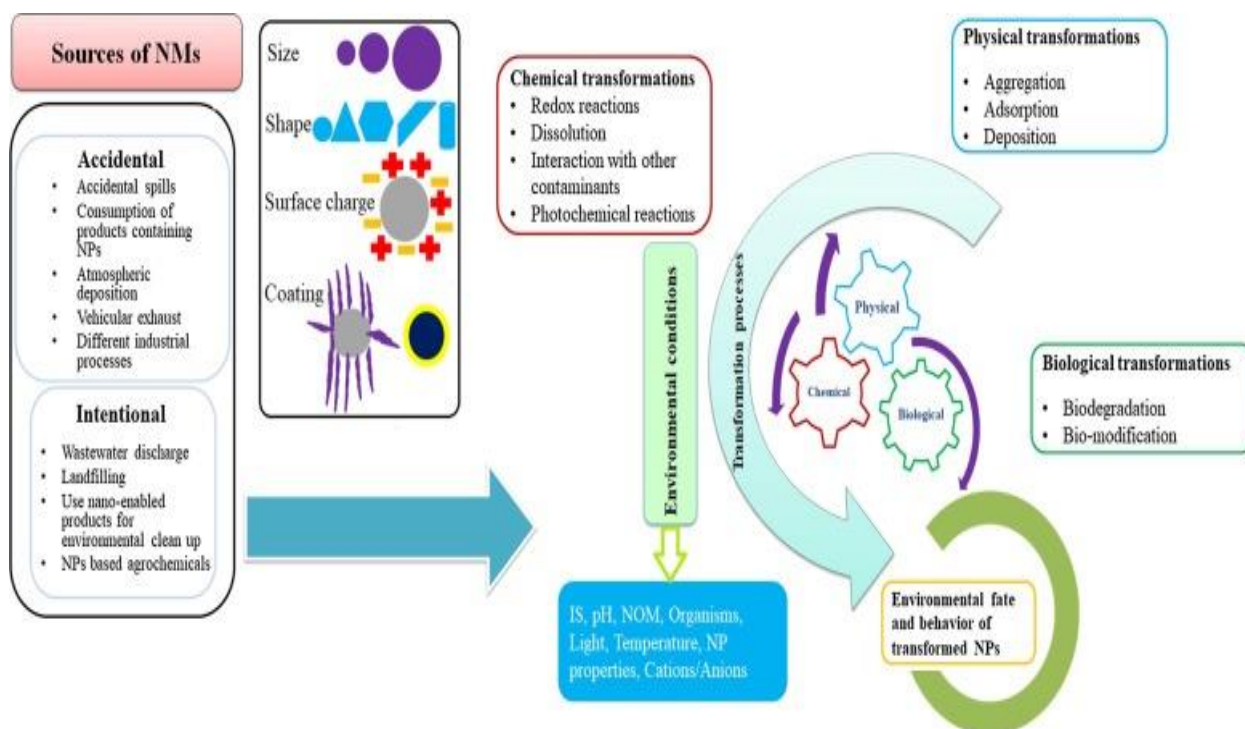
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Characterization of this work also confirmed the production of pure, crystalline and stable nanoparticles. The particle sizes, crystalline structures, and negative zeta potentials indicate that green-synthesized nanoparticles have a good physicochemical stability which is the crucial attributes for their biomedical and industrial applications. Recent investigations have validated that green synthesized nanoparticles are more biocompatible and less toxic than synthetic nanoparticles owing to phytochemicals present on the surface of the nanoparticles synthesized using green chemicals (Patel & Sharma, 2024). In addition, the vibrational groups exposed by FTIR (OH, C=O, and C-N) suggest that plant derived organic compounds are still bound to the nanoparticles, perhaps providing extra bioactivity.

Environmental degradation profiles revealed an important property of green-synthesized nanoparticles, that is, their improved biodegradability. The significant weight loss and ion release in AgNPs and ZnO NPs DIW show compliance with the literature according to which, green nanoparticles are more susceptible to degradation in the environmental surroundings reducing the long-term accumulation possibilities (Ali et al., 2022). The physicochemical properties evaluated in the present work are simulated in as much as they are putative environmental exposures that include soil contact, acidic rain, and UV exposure, providing an applied sense of nanoparticulate fate once disposed. These results are consistent with the current trend of aiming for "degradable design" in nanotechnology (Singh et al., 2021), where new development is encouraged to provide materials that are efficient when in use and benign when degraded.

Comparison with chemically synthesized nanoparticles confirmed an advanced degradation potential and environmentally friendly character of the green-synthesized particles, despite an average larger particle size. Reduced ion leaching in green-synthesized particles points to reduced eco-toxicological load, which is a key factor

for regulatory acceptance. These findings may serve as evidence for the case for industrial conversion to green synthesis methods, not only for environmental but also for long-term economic and regulatory sustainability (Mehta & Qureshi, 2024). In addition, the lower extent of metal ion release in green samples may decrease bioaccumulation potential in aquatic and terrestrial organisms.

The kinetic model analysis indicated that distinct degradation pathways could be observed for different NPs: Both AgNPs and Fe₃O₄ NPs were found to obey pseudo-first-order models, while ZnO NPs could be best described by pseudo-second-order kinetics. This discrepancy could be related to different surface chemistry and crystal structure reported also by Hernández-Fernández et al. in degradation studies. (2022). Knowledge of these kinetics is important for predicting nanoparticle transport in various environmental media, and can also inform future work aimed at optimizing nanoparticle composition as a function of application and disposal conditions. Such information also provides a basis for appropriately-designed standardized degradation protocols in green nanotechnology.

Eco-toxicological analyses showed that green-reduced nanoparticles are less toxic than chemically reduced ones, but they still have environmental hazards. The moderate level of toxicity observed in especially *Daphnia magna* and *Chlorella vulgaris* indicates that ion leaching out of the material could still be a concern at higher concentrations due to degradation. This is consistent with recent literature that advises pre-deployment toxicity scan even for green NPs (Zhang et al., 2025). Therefore, in addition to being a leap toward sustainability, the implementation of green synthesis requires to be complemented by appropriate eco-toxicological assessments and environmental monitoring approaches.

Future Directions

The further studies will concentrate on optimizing plant extract mixtures and reaction conditions to regulate the sizes, shapes, and surfaces of nanoparticles for prevention or therapy of diseases. Furthermore, concerted efforts should be made to produce and incorporate green nanoparticles into composites and investigate the long-term interactions of the developed nanoparticles with environmental matrices, microbiomes and ecosystems to develop a more comprehensive understanding on their safety profile as well as functioning. Multi-omics techniques and real-time monitoring technologies can also be used to evaluate the dynamic change and biological responses to the materials in varied media.

Limitations

This research is restricted by virtue of being based on laboratory-simulated environmental degradation which might not accurately reproduce the conditions in the field. Further more, findings were based on three species of nanoparticles using three kinds of degradation media, which may not neglecting others degraded pathways and toxicological end-point. Moreover, the beneficial models of ecotoxicology do not represent the entire ecodiversity environmentally influenced by nanoparticle exposure.

Conclusion

Green synthesis of novel substances using plant extracts is a viable substitute of conventional chemical methods and provides higher yields, and better physico-chemical stability, and enhanced biodegradability. Despite the degradation kinetics and ion release profiles indicating decreased environmental toxicity, modest toxicity is still a significant concern, warranting detailed environmental risk assessment. The relative benefits of green-synthesized nanoparticles render them potentially useful materials for sustainable nanotechnology, but innovation, monitoring, and regulation must be ongoing in order to facilitate responsible incorporation.

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