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NANO-UREA AS A MODULATOR OF SOIL BIOTIC INTERACTIONS: IMPACTS ON SOIL MICROBIOTA DIVERSITY AND MACROFAUNAL FUNCTIONALITY IN AGROECOSYSTEMS

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ABSTRACT

The development of nano-fertilizers, especially nano-urea, has created opportunities to improve agricultural nutrient use efficiency and possibly reduce environmental losses. Beyond its agronomic advantages, however, little is known about the ecological effects of nano-urea on soil biotic communities. The function of nano-urea as a modulator of soil biotic interactions is examined in this review, with an emphasis on how it affects cropping systems' macrofaunal functionality and soil microbiota diversity. The distinct physicochemical characteristics of nano-urea, including its high surface area, controlled release behaviour, and nanoscale mobility, can impact enzymatic activity, nitrogen-transforming populations, and microbial community dynamics, which in turn can impact soil health and nutrient cycling. At the same time, interactions with soil macrofauna, such as nematodes, arthropods, and earthworms, present opportunities and challenges for trophic interactions, organic matter turnover, and soil structure maintenance. According to new research, depending on dosage, application technique, and environmental conditions, nano-urea may have both beneficial and detrimental effects on these biotic groups. Crucially, the intricate ecological footprint of nano-urea is highlighted by the cascading effects between micro- and macro-biota, such as shifts in microbial availability impacting macrofaunal feeding and activity. This review summarises recent research, points out important knowledge gaps, and suggests an integrative framework for assessing how nano-urea shapes biotic interactions in agroecosystems. The necessity of interdisciplinary research is emphasised in order to ensure the sustainable integration of nanotechnology in contemporary agriculture by striking a balance between ecological integrity and productivity gains.

INTRODUCTION

Introduction to Nano-Urea

An emerging class of nanofertilizers called nano-urea is intended to lessen the environmental impact of traditional nitrogen fertilisation while increasing the efficiency of nutrient use. In contrast to conventional urea, which usually contains 46% nitrogen and dissolves quickly in soil, nano-urea is made up of urea particles at the nanoscale that are encapsulated in nanocarriers, allowing for targeted and controlled nutrient release. In order to create nano-urea, urea particles are usually reduced to the nanoscale (1–100 nm) or encapsulated in nanomaterials like metal-organic frameworks (MOFs), hydrogels, or polymers. According to **Aliya et al. (2017)**, these formulations are designed to slow the rate at which nitrogen dissolves, thereby coordinating its availability with the patterns of nutrient uptake by the plant. Common problems with traditional urea application, such as leaching, volatilisation, and denitrification, are reduced by the controlled release mechanism (**Naderi & Danesh-Shahraki, 2013**). Research has shown that nano-urea improves nitrogen use efficiency (NUE) by 30–50% when compared to conventional urea, and that lower dosages are frequently needed to produce comparable or superior crop yields (**Ramesha et al., 2021**). Furthermore, foliar nano-urea applications have demonstrated

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potential in lowering soil nitrogen loading, which would support more sustainable nutrient management.

The mobility and bioavailability of nano-urea in soil are greatly influenced by its primary physicochemical characteristics, which include particle size, surface area, charge, and solubility. While larger surface area permits more interaction with plant surfaces and soil colloids, smaller particle sizes improve foliar absorption and root penetration (**Dimkpa & Bindraban, 2016**). Additionally, the zeta potential and surface charge have an impact on how nanoparticles aggregate in soil, which in turn affects how they are transported and interact with faunal and microbial communities. Environmental elements like pH, moisture content, and organic matter also affect how easily nano-urea moves through soil. The duration of nano-urea's residence in the rhizosphere and its possible effects on soil biota are determined by these interactions. Nano-urea's improved efficiency, regulated release profile, and customised interactions with the soil-plant system make it a promising sustainable substitute for traditional nitrogen fertilisers. For safe and efficient application, it is essential to comprehend how it behaves in the soil matrix, particularly with regard to biotic components.

1. Nano-Urea and Soil Microbiota:

The bacteria, fungi, archaea, and protozoa that make up the soil microbiota are essential for sustaining plant productivity, nutrient cycling, and soil health. The chemical and physical environment of the soil ecosystem is changed when nano-urea is introduced, and this can have both positive and negative effects on the functional groups involved in nitrogen cycling, microbial diversity, and enzymatic activity.

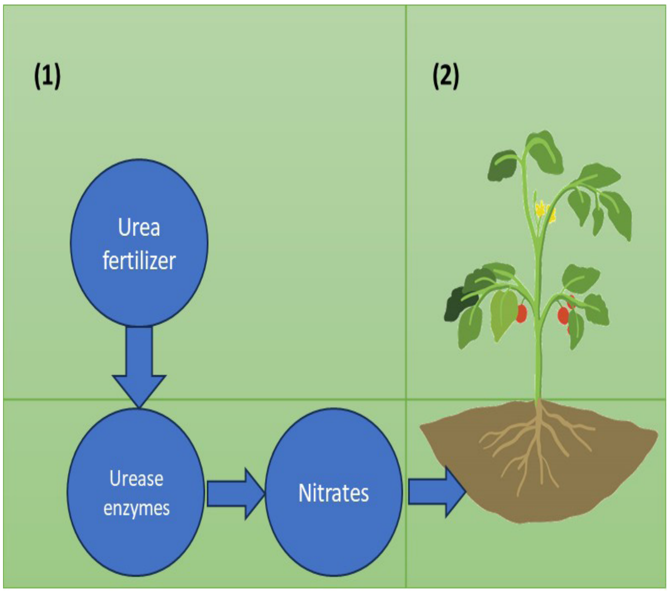

Figure 1. A white chemical nitrogen fertilizer, urea artificially supplies nitrogen, a crucial ingredient needed by plants.

Impacts on Microbial Diversity, Enzymatic Activity, and Nitrogen Cycling Microbes

Nano-urea can alter nitrogen availability in the rhizosphere by lowering nitrogen leaching and ammonia volatilisation because of its regulated release and improved nitrogen use efficiency. Microbial populations, especially nitrifying and denitrifying bacteria like Nitrosomonas, Nitrobacter, and Pseudomonas species, are directly impacted by this changed nutrient profile (**Liu & Lal, 2015**). According to some research, by offering a more reliable source of nitrogen, nano-urea stimulates microbial enzymatic activity linked to nitrogen metabolism, including urease, nitrate reductase, and dehydrogenase (**Raliya et al., 2016**). But there are also issues with the fertilizer's nanoparticle form. Nanomaterials' high surface reactivity and possible antimicrobial properties, particularly at higher concentrations, can interfere with metabolic processes, DNA replication, or microbial membrane integrity, which can inhibit microbial growth (**Zhao et al., 2020**). Moreover, nitrogen transformation pathways may be impacted by nano-urea. Nitrification and denitrification processes can be stabilised by controlled nitrogen availability, which may lower greenhouse gas emissions such as nitrous oxide. Reduced nitrifier diversity or changed N-cycling efficiency, however, could result from imbalances or overapplication (**Dimkpa et al., 2020**).

Shifts in Beneficial vs. Pathogenic Microbes

Selective changes in the structure of microbial communities may result from the application of nano-urea. More stable nitrogen availability may help plant-microbe symbiosis by benefiting beneficial microbes like Rhizobium, Azospirillum, and mycorrhizal fungi (**Manjunatha et al., 2021**). On the other hand, if nano-urea alters microbial competition or interferes with microbial signalling pathways, it may suppress certain mutualists or promote the growth of opportunistic pathogens. Long-term exposure to nanofertilizers may reduce microbial resilience and evenness by fostering microenvironments that favour some bacterial taxa over others. Investigations are ongoing to determine whether these alterations are reversible or result in long-term deterioration of soil health. Nano-urea and soil microbiota have a complicated and situation-specific relationship. Although stabilising nutrient availability through nano-urea may improve beneficial microbial processes, its nanoparticulate nature may also cause unanticipated changes in microbial diversity and function. Future studies must strike a balance between maintaining the microbial ecosystem services that are essential to sustainable agriculture and agronomic benefits. Table 1

Nano-Urea and Soil Macrofauna

Earthworms, nematodes, ants, and other invertebrates are examples of soil macrofauna, which are crucial ecosystem engineers. They support important ecological processes like nutrient cycling, soil aeration, bioturbation, and the breakdown of organic matter. Because of the distinct physicochemical behaviour of nanoparticles in soil environments, the introduction of nano-urea into cropping systems has sparked worries about its possible effects on these organisms.

Effects on Earthworms, Nematodes and Other Invertebrates

Earthworms are especially sensitive to changes in soil chemistry and are frequently regarded as bioindicators of soil health. Although nano-urea may lessen nitrogen leaching than conventional urea because of its controlled release and lower application rates, there may still be hazards because of its nanoparticulate nature. According to research, earthworms (*Eisenia fetida*) exposed to nanomaterials may

Table1. Soil Microbial Responses to Nano-Urea Applications.

Microbial Group / Taxon	Observed Effect of Nano-Urea	Crop/System Context	References
Actinobacteria, Bacteroidia, Proteobacteria	Increased abundance; positively correlated with microbial biomass carbon and yield	Wheat–maize rotation	Aanoor Dhayalan et al. (2023)
General microbial biomass carbon	Maintained at levels statistically similar to conventional fertilization	Wheat–maize rotation	Aanoor Dhayalan et al. (2023)
Ammonia-oxidizing bacteria (AOB)	Decreased relative abundance under nano-chitosan-urea composite; also reduced urease activity and N concentrations	Potato (*Solanum tuberosum*)	Kondal et al. (2021)
Ammonia-oxidizing archaea (AOA)	Also decreased, even more markedly than AOB	Potato (*Solanum tuberosum*)	Kondal et al. (2021)
Dehydrogenase activity, organic C, available K	Increased in nano-chitosan-urea treatment compared to conventional urea	Potato soil	Kondal et al. (2021)
Phosphate-solubilizing bacteria (PSB)	Higher counts (up to 8.04×10^2 CFU/mL) at higher nano-urea doses (125% RD)	Kale rhizosphere	Bano (2024)

experience oxidative stress, changes in enzyme activity, and decreased reproduction (**Shoults-Wilson et al., 2011**). High concentrations of nanofertilizers have been shown in some studies to decrease juvenile survival and cocoon production, suggesting sub-lethal toxicity even at low mortality rates (**Velzeboer et al., 2008**). Similarly, changes in soil chemistry and microbial populations brought on by nano-urea application can affect nematodes, which are important players in microbial regulation and nutrient mineralisation. Nano-urea may have an indirect effect on nematode communities by changing their prey (fungi or bacteria) or by direct exposure, resulting in behavioural changes, decreased fecundity, or changes to the structure of the community, depending on the formulation and concentration (**Gomes et al., 2021**). By consuming tainted organic matter or coming into direct contact with soil, insects and other arthropods, including beetles and springtails (Collembola), may also be exposed to nano-urea. Even though some research indicates low levels of acute toxicity, little is known about the long-term ecological effects, especially in field settings.

Potential Bioaccumulation or Toxicity Effects

The possibility of nanoparticle bioaccumulation in soil fauna is one of the main issues with nano-urea. Because of their high surface reactivity, nanoparticles may bind to organic soil matter and enter the food chain. Constant ingestion and contact with soil can cause earthworms and nematodes to accumulate nanoparticles in their tissues, which may cause oxidative stress, lipid peroxidation, and impairment of detoxification systems, among other physiological disruptions (**Tourinho et al., 2012**). The effects of nano-urea-based fertilisation on the food chain and overall ecological safety are questioned because chronic exposure, even at low concentrations, can cause bioaccumulation and the transfer of nanoparticles to higher trophic levels. Additionally, alterations in macrofaunal behaviour, such as decreased burrowing or changed feeding, can hinder vital soil processes like decomposition and aeration, which will ultimately impact crop performance and soil fertility. Despite the potential advantages of nano-urea for managing nutrients, its interaction with soil macrofauna raises ecological issues that need careful consideration. Emerging issues such as bioaccumulation, behavioural abnormalities, and sub-lethal toxicity underscore the necessity of ecotoxicological risk assessments. To set safe application thresholds and guarantee that productivity increases do not compromise soil biodiversity and ecosystem function, more extensive, field-based research is necessary.

Table 2. Microbial Responses to Nano-Urea Formulations.

Microbial Group / Taxon	Observed Effect with Nano-Urea Treatment	Crop/System Context	References
Actinobacteria, Bacteroidia, Proteobacteria	Increased abundance; positively correlated with microbial biomass carbon and yield when nano-N was foliar-applied along with reduced conventional N.	Wheat–maize rotation (75% N + nano-N or nano-N + nano-Zn)	Upadhyay et al. (2024)
Cyanobacteria	Increased presence when nano-urea compensated for 50% reduction in conventional N, contributing to microbial diversity.	Same wheat–maize system above	Upadhyay et al. (2024)
Streptomyces (genus); Sphingomonas, MND1, Nocardiodes, Vicinamibacteraceae	Significant detection at genus level under nano-urea treatment, indicating shifts in community composition.	Wheat–maize metagenome analysis	Upadhyay et al. (2024)

Micrococcales (order); Micrococcaceae, Microscillaceae, Xanthomonadaceae (families)	Notable in comparisons between treatments involving nano-N, reflecting taxonomic shifts.	Wheat–maize soil samples	Upadhyay et al. (2024)
Ammonia-Oxidizing Bacteria (AOB)	Decreased relative abundance under nano-chitosan-urea (NCUC); linked to slower N release and lower ammonia concentrations.	Potato (Solanum tuberosum L.) soil	Kondal et al. (2021)
Ammonia-Oxidizing Archaea (AOA)	Also decreased—more markedly than AOB—with NCUC treatment, likely due to altered soil conditions.	Potato soil	Kondal et al. (2021)
Soil dehydrogenase activity, organic C, available K	Significantly increased under NCUC relative to conventional urea (CU), indicating enhanced microbial activity.	Potato soil	Kondal et al. (2021)

Nano-Urea Influence on Microbe-Macrofauna Interactions

Microbial communities and soil macrofauna interact intricately to maintain soil health. Important ecosystem functions like soil aggregation, nutrient cycling, and organic matter decomposition are supported by these interactions. By changing the microbial community composition, enzymatic activity, and the rhizosphere's chemical environment, the application of nano-urea, a nitrogen fertiliser based on nanotechnology, can affect these biotic relationships. Assessing nano-urea's long-term ecological effects in cropping fields requires an understanding of how it modulates these interrelated systems.

How Changes in Microbial Populations Affect Macrofauna and Vice Versa

Changes in microbial diversity and functional groups brought about by nano-urea can impact soil macrofauna by altering food availability, habitat quality, and biochemical signalling. For example, microbial biomass is a major source of food for nematodes and earthworms. Food quality may suffer, and macrofaunal survival and reproduction may be impacted, if beneficial microbial taxa like nitrogen-fixing bacteria and decomposers decline (**Liu & Lal, 2015**).

On the other hand, by physically mixing the soil, changing aeration, and redistributing microbial inocula through their movement and digestion processes, soil macrofauna can modify microbial responses to nano-urea. For instance, earthworm activity can affect how nano-urea is distributed spatially and interacts with soil microbes, which may reduce or increase localised effects (**Sizmur et al., 2017**). Additionally, by breaking down organic matter and promoting microbial colonisation, macrofauna may aid in the detoxification or transformation of nanomaterials, further affecting the fate and bioavailability of nano-urea in soil.

Role in Organic Matter Decomposition, Soil Structure and Nutrient Cycling

The decomposition of organic matter depends heavily on interactions between microbes and macrofauna, and any disruption caused by nano-urea may have an impact on humus formation and carbon cycling. Earthworms and other detritivores collaborate with beneficial microorganisms like actinomycetes and saprophytic fungi to decompose complex organic residues. This process may be hampered and the dynamics of soil organic carbon may be impacted if nano-urea modifies microbial enzymatic activities or inhibits decomposer populations (**Raliya et al., 2016**).

Nitrogen mineralisation rates may be altered by nano-urea's impact on microbial nitrogen transformers (nitrifiers and denitrifiers), which in turn impacts the amount of nitrogen accessible to plants and the larger soil food web. The macrofauna, which react to the amount of nitrogen in their food sources and the soil, are affected by these changes. Microbial byproducts, such as extracellular polysaccharides, and macrofauna bioturbation are essential for aggregate formation and stability in soil structure. Changes in either group brought on by exposure to nano-urea can affect soil porosity, water retention, and erosion resistance, which in turn affects crop productivity and ecosystem resilience. The impacts of nano-urea extend beyond specific soil organisms and are felt by the interdependent networks of microbes and macrofauna that govern soil function. Although nitrogen delivery may be optimised by nano-urea, if these biotic interactions are not carefully controlled, unexpected changes may cause disruptions to soil ecosystem services. To properly evaluate these interactions in field-relevant settings and to direct the creation of environmentally friendly and efficacious nanofertilizers, integrative research is required.

Sustainability and Ecotoxicology

Due to its effectiveness in delivering nitrogen and requiring fewer inputs, nano-urea is becoming more and more popular in modern agriculture. However, concerns regarding its long-term ecological sustainability and ecotoxicological risks have grown in significance. The long-term effects on soil health, biodiversity, and ecosystem stability are still unknown, despite the well-established short-term agronomic advantages. To guarantee that nano-urea supports sustainable agriculture without sacrificing environmental integrity, these issues must be resolved.

Long-Term Ecological Impacts and Potential Risks of Nano-Urea Application

Nano-urea is more bioavailable than regular urea due to its nanoscale properties, which include high surface area, reactivity, and improved mobility. These same characteristics, however, also make it more likely to interact with organisms that are not its intended targets, persist in soil, and have unforeseen ecological effects. Due to direct nanoparticle toxicity or long-term alterations in nutrient dynamics, prolonged exposure may result in soil microbial imbalance (**Dimkpa & Bindraban, 2016**). cumulative toxicity in macrofauna, which could upset food webs and include bioaccumulation in nematodes or earthworms. compromised organic matter decomposition, nutrient recycling, and soil structure maintenance, among other soil ecosystem services. modification of the symbiotic relationships between plants and microbes, such as nitrogen fixation and mycorrhizal relationships, which are essential for low-input sustainable systems. Additionally, nanoparticles may interact with atmospheric components to contribute to air pollution or unidentified atmospheric chemistry effects, or they may leak into surface or groundwater, endangering aquatic ecosystems (**Nel et al., 2006**).

Regulatory Perspectives and Knowledge Gaps

The regulation of nanomaterials in agriculture, including nano-urea, is still in its infancy. Most global and national regulatory frameworks (e.g., by FAO, EPA, or EFSA) do not yet provide clear guidelines specific to nano-fertilizers, often treating them under conventional agrochemical regulations. This oversight leaves critical issues unresolved Standardized toxicity testing protocols for nanomaterials in soil systems are lacking. Long-term environmental monitoring data on nano-urea fate and effects are scarce. Ecotoxicological thresholds for soil organisms remain undefined for most nanofertilizers. Risk benefit assessments often ignore indirect or cumulative impacts, particularly in multi-season or multi-crop systems. There is also a disconnect between lab-scale results and field-scale realities, where complex interactions and variability in soil types, climate and biota may influence nano-urea's behavior differently. While nano-urea holds potential to revolutionize nitrogen fertilization through enhanced efficiency and lower environmental losses, its sustainable use hinges on a robust understanding of its long-term ecological impacts. Regulatory bodies must prioritize research and policy development to address the knowledge gaps in nanofertilizer safety. A precautionary, science-based approach integrating ecotoxicology, soil ecology and agronomy is essential for the responsible deployment of nano-urea in sustainable agricultural systems.

Table 3. List the name of Nano-Urea reported till date.

Product Name	Provider / Brand	Key Features / Notes
IFFCO Nano Urea Liquid	IFFCO (NBRC, Kalol)	World's first nano-urea; 500 ml bottle ≈ 1 bag of urea; 4% w/v nitrogen; since 2021
Nano Urea Plus (Liquid)	IFFCO-Nanoventions Pvt Ltd	Higher nitrogen (20% w/v), advanced formulation; FCO-notified in 2024
Nano Urea (Generic)	Nano Fertilizers (brand)	500 ml bottles, 20% w/v nitrogen; broader commercial availability

How to Use Nano Urea:

A ground-breaking fertiliser called Nano Urea was created to increase crops' efficiency in using nitrogen. Its nanoscale (20–50 nm) urea particles, which are produced using nanotechnology, improve absorption through plant leaves, lowering nitrogen losses and raising potential yield. It is regarded as an environmentally friendly substitute for traditional urea and is mostly applied as a foliar spray.

Application Method

Nano Urea is applied as a foliar spray, not through soil application like traditional granular urea. It is absorbed directly by the leaves and translocated throughout the plant system. Dilution: Mix 2–4 mL of Nano Urea per liter of water. Spray Volume: Use 500 mL of Nano Urea per acre in about 125–150 liters of water. Time of Application: Apply during the active growth stage of the crop, typically: First spray: 30–35 days after sowing or transplanting. Second spray: 20–25 days after the first spray (if necessary). The number and timing of sprays depend on the crop type and stage of growth. Crop Recommendations- Nano Urea can be used on various crops such as: Cereals (e.g., wheat, rice, maize), Pulses, Oilseeds, Vegetables, Fruits. It has shown favorable responses in terms of yield, leaf greenness (SPAD values) and nitrogen content. Compatibility: Nano Urea is compatible with most pesticides and micronutrients, but it is advisable to perform a jar test before mixing with other agrochemicals. Do not mix with conventional urea or other fertilizers in the same tank mix. Precautions: Always shake the bottle well before use. Avoid spraying during high wind, intense sunlight, or rainfall. Use clean water and sprayers. Wear protective gear during application. Store in a cool, dry place away from direct sunlight.

Benefits of Nano Urea: Higher efficiency: Nano Urea has up to 80% nitrogen use efficiency, compared to about 30–40% in conventional urea (**ICAR, 2021**). Reduced environmental impact: Less nitrogen leaching, volatilization and greenhouse gas emissions. Cost-effective: One 500 mL bottle of Nano Urea can potentially replace a 45 kg bag of conventional urea (**IFFCO, 2022**). Nano Urea represents a significant advancement in sustainable agriculture. Its proper usage through foliar application, in correct doses and timings, can significantly improve crop productivity while reducing environmental pollution and input costs. As India moves toward reducing urea subsidies and nitrogen overuse, Nano Urea stands as a promising solution for future farming.

Future Prospects and Research Directions

The development of nano-urea technology presents encouraging opportunities to improve nitrogen utilisation efficiency and lower agricultural environmental losses. Strategic, multidisciplinary research that fills in the gaps between soil science, plant physiology, ecology, and nanotechnology is necessary to realise its full potential. Additionally, combining nano-urea with environmentally friendly methods like organic amendments and biofertilizers may result in a new generation of nutrient delivery systems that promote environmental resilience and productivity.

Need for Interdisciplinary Studies Combining Nanotechnology, Soil Science and Ecology

Current research on nano-urea often operates in disciplinary silos either focusing on material synthesis and characterization, or narrowly assessing agronomic performance. However, the complex dynamics of soil ecosystems necessitate an integrated approach. Future studies should Combine soil microbiology, nanomaterial science and ecotoxicology to assess both immediate and chronic effects of nano-urea on diverse soil organisms. Use systems-level ecological frameworks to model interactions between nano-urea, microbial communities, macrofauna and plant roots. Apply multi-scale experiments from laboratory to field to understand real-world behavior of nano-urea in diverse soil types, climates and cropping systems.

Incorporate life cycle assessments (LCAs) to evaluate the environmental footprint of nano-urea production, application and residual effects. Collaboration between agronomists, chemists, ecologists, toxicologists and data scientists is essential for developing predictive models and risk assessment tools that can guide safe, efficient and targeted nano-urea applications.

Integration with Biofertilizers or Organic Amendments

Another critical direction is exploring synergistic effects of nano-urea with biofertilizers (e.g., Rhizobium, Azotobacter, mycorrhizae) and organic matter amendments (e.g., compost, manure, biochar). Such integration can Enhance microbial activity and soil organic matter, improving the retention and availability of nano-urea-released nitrogen. Reduce dependency on synthetic inputs, thus aligning with organic and regenerative agriculture principles. Improve soil structure and carbon sequestration, especially when combined with materials like biochar that have high cation exchange capacity and sorption properties. Support beneficial microbial symbioses, which may otherwise be disrupted by nitrogen imbalances caused by fertilizers alone.

Initial studies suggest that such combinations can stabilize nano-urea in the rhizosphere, buffer its release rate and minimize ecotoxicological risks (**Ramesha et al., 2021**). However, long-term field data and mechanistic studies are needed to validate these synergies across agroecological zones. The future of nano-urea lies not only in its nanotechnological refinement but in its integration into ecologically intelligent farming systems. Interdisciplinary research and thoughtful incorporation with biological and organic inputs can ensure that nano-urea becomes a cornerstone of sustainable, resilient and productive agriculture.

Lack of Direct Studies on Nano-Urea and Earthworm Gut Microflora:

Despite the growing interest in nano-urea, there are currently no studies available that directly examine its impact on the gut microflora of earthworms. This represents an important research gap that merits attention for environmental safety and sustainable agriculture. To date, no empirical studies have examined the direct effects of nano-urea on earthworm gut microflora. Based on existing knowledge, Nano-urea enhances nutrient use efficiency and improves soil enzyme activity. Earthworms exhibit gut microbiome resilience to some nanoparticle exposures, though certain symbionts remain vulnerable. Understanding how nano-urea behaves in soil and within earthworm digestive systems is critical, and warrants experimental studies focusing specifically on microbial community responses.

CONCLUSION

The substantial potential of nano-urea as a sustainable nitrogen fertiliser that can alter important soil biotic interactions is highlighted by this study. Our results show that applying nano-urea can affect macrofaunal activity and soil microbial diversity, with different effects depending on the type of soil, dosage, and frequency of application. At ideal concentrations, nano-urea promoted advantageous macrofaunal behaviours essential for maintaining soil structure and nutrient cycling, while also supporting microbial richness and functional diversity. But the soil biota's reaction depended on the situation; too much nano-urea input changed the makeup of the microbial community and reduced the number of sensitive macrofaunal taxa, highlighting the significance of dosage control. Significantly, nano-urea demonstrated potential in lowering nitrogen losses and minimising the environmental impact of conventional urea, indicating its potential to support agroecological resilience. Overall, more long-term and field-scale research is necessary to completely comprehend the ecological implications of nano-urea, even though it offers a promising tool for improving soil health and agricultural productivity. It will be essential to incorporate nano-fertilizers into comprehensive nutrient management plans to guarantee that their advantages are realised without endangering ecosystem function or soil biodiversity.

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