Comparative Evaluation of Nano-Urea and Conventional Nitrogen Fertilizers in *Zea mays* L.

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Received: 06 Dec 2023
Revised: 22 Dec 2023
Accepted: 08 Jan 2024
Published: 24 Jan 2024

E-ISSN: 2989-5340
DOI: https://doi.org/10.54660/jafi.2024.4.1.10-14

ABSTRACT

Background: Nitrogen (N) is the most critical nutrient for global maize production, but the conventional fertilizers used in maize cultivation have relatively low efficiency (about 30% to 50 %), leading to significant nitrogen loss, giving rise to economic and environmental harms due to ammonia volatilization, denitrification, and nitrate leaching. Nano-urea has provided a technology that may revolutionize precision nutrient management through its controlled nitrogen release, higher plant availability, and reduced fertilizer losses due to its unique properties.

Objective: The aim of the current study is to evaluate nano-urea and conventional nitrogen fertilizers in terms of maize plants' growth, physiological parameters, nitrogen use efficiency, yield parameters, and sustainability with respect to the environment.

Methods: The field experiment was carried out using a randomized block design. The experiment involved the following six treatment options with respect to nitrogen application: control (0 nitrogen), 100% conventional fertilizer application, 75% conventional fertilizer + nano urea, nano urea alone, 50% conventional fertilizer + nano urea, and a combination of nano urea + conventional fertilizer application. These treatment options were repeated four times.

Result: The grains grown using nano-urea treatments yielded comparable or higher amounts of produce than those of using the traditional urea treatments with 100% application, while decreasing application dosage of the conventional fertilizers up to 25–50%. Photosynthesize rate and chlorophyll levels were found to increase by 16–28% and 18–31% for nano-urea treatments correspondingly. Improvement of nitrogen recovery efficiency by 22–35% was noted when using nano-urea as compared to traditional urea alone. Losses of ammonia through volatilization decreased by 40–48% in cases with nano-urea application. The efficiency of agronomic utilization of nitrogen has increased from 18 kg grain kg^{-1} N in the case with traditional urea application to 24–27 kg grain kg^{-1} N when using nano-urea treatments.

Conclusion: Nano-urea can be successfully used as the alternative, sustainable version of conventional nitrogen fertilizers in maize cultivation, as it both improves yields and efficiency of fertilizers used, and provides better environmental outcomes, and reduces the amounts of traditional fertilizers used.

Keywords: Nano-urea, Nitrogen use efficiency, Maize (*Zea mays*), Precision nutrient management, Sustainable agriculture, Ammonia volatilization

1. Introduction

Maize (*Zea mays* L.) is regarded as a crucial component for food security worldwide since it provides about 19% of human caloric intake in addition to being an important livestock feed and source of industrial feedstock with an estimated global production of more than 1.1 billion metric tons yearly [1]. Nitrogen is the nutrient that limits the yield of maize the most since it is needed for the synthesis of chlorophyll, nucleic acid, and enzyme functioning. When nitrogen is deficient, grain yields are typically lower by about 25-50% depending on climatic and soil conditions [2].

The global consumption of nitrogen fertilizers exceeds 110 million metric tons per year; however, their traditional fertilizers are characterized by low use efficiency since farmers usually obtain only 30-50% of the nitrogen they applied on the soil while 20-35% of nitrogen is lost through various processes of volatilization and leaching and the remaining nitrogen stays in the soil [3]. The above-mentioned losses lead to serious economic implications for farmers and adverse environmental effects including the eutrophication of fresh water bodies, the pollution of groundwater with nitrates, and the emissions of nitrous oxide gas into the atmosphere contributing to climate change [4].

Traditional nitrogen fertilizers, such as urea, ammonium nitrate, and ammonium sulfate, have notable drawbacks such as high solubility in water and fast reaction rate which make the nitrogen susceptible to loss through gas emissions and soil microbes [5]. This deficiency has encouraged the development of controlled-release and stabilized nitrogen technologies, as well as invention of new nanotechnology systems. Nano-urea, which is a form of urea-containing nano particles, utilizes the advantages of the surface chemistry and particle size in regulated release and prolonged availability of nitrogen for plants [6].

According to recent research, the use of nano-urea enhances chlorophyll production, improves the efficiency of photosynthesis and allows nitrogen to be transferred in cereal crops. As a result, on the application of nano-urea crops produced grain yield equal to or exceeding the effect of the use of conventional nitrogen fertilizers that were provided with the same amount of or lower nitrogen level. Despite the above-stated results the published data lack larger-scale comparison studies that would include the evaluation of physiological, agricultural and environmental effects of nano-urea application. The hypothesis of the current research assumes that application of nano-urea by means of foliage spray and soil incorporation will increase the recovery of nitrogen in crops and decrease the effects associated with ammonia evaporation and allow obtaining comparable grain yield with the use of traditional fertilizers but with a lower amount of nitrogen applied simultaneously. Some specific objective of the study included: i) comparison between the effect of nano-urea and conventional urea on crops; ii) determination of nitrogen use efficiency parameters; iii) measurement of ammonia loss; and iv) definition of the economic sustainability of the project.

2. Literature Review

Conventional nitrogen fertilizers remain the dominant nutrient input in global agriculture, yet their inherent limitations—rapid hydrolysis, susceptibility to nitrification and denitrification, ammonia volatilization—result in low recovery efficiency and environmental externalities [3]. Nitrogen use efficiency (NUE), typically quantified as grain yield per unit N applied or N recovered in grain, ranges from 20–60% globally, with substantial geographic variation dependent on soil type, climate, crop management, and fertilizer form [9].

Nano-fertilizer technology exploits nanotechnology to enhance nutrient bioavailability through particle-size reduction, surface modification, and controlled-release mechanisms [6]. Nano-urea specifically has demonstrated improved plant-available nitrogen throughout the growing season compared with conventional urea's initial burst release followed by depletion. Studies in wheat, rice, and tomato report that nano-urea application improves chlorophyll content, photosynthetic rate, and protein synthesis more substantially than equivalent conventional urea doses [7, 10]. Physiological mechanisms include enhanced foliar penetration and phloem translocation of nano-particles, increased nitrogen assimilation into amino acids and proteins, and sustained photosynthetic enzyme function [8].

Nitrogen recovery efficiency, the proportion of applied N recovered in harvested grain, typically reaches 40–60% with nano-urea versus 30–45% with conventional urea, reflecting improved translocation and reduced losses [11]. Agronomic nitrogen use efficiency (ANUE = grain yield increases per unit N applied) demonstrates similar improvements, with nano-urea conferring 20–30% greater ANUE than conventional fertilizers [7]. Environmental benefits include 30–50% reductions in ammonia volatilization and 20–40% reductions in nitrate leaching, though long-term field data remain limited [12].

Comparative field trials directly evaluating nano-urea against conventional fertilizers at proportionally reduced nitrogen rates—the most agriculturally relevant scenario—are scarce in the peer-reviewed literature, particularly for maize in tropical and subtropical environments. This knowledge gap motivated the present study.

3. Materials and Methods

3.1. Experimental Site and Conditions

The experiment was conducted during the 2023 summer season at the Research Farm (28°45′N, 77°12′E, 240 m elevation) in a sub-humid subtropical climate (average rainfall 750 mm, 22–38°C temperature range). Soil was a loamy alluvium, with pH 7.2, organic carbon 0.72%, available nitrogen 185 mg kg^{-1}, and available phosphorus 14 mg kg^{-1}.

3.2. Experimental Design and Treatments

A randomized complete block design (RCBD) with four replications compared six nitrogen treatments applied to hybrid maize variety 'DK-8102' (Table 1): T1 (control, no N); T2 (100% conventional urea, 200 kg N ha^{-1}); T3 (75% conventional urea + nano-urea foliar spray, 150 + 50 kg N ha^{-1}); T4 (nano-urea foliar spray only, 50 kg N ha^{-1}); T5 (50% conventional urea + nano-urea soil application, 100 + 100 kg N ha^{-1}); and T6 (integrated nano-urea + conventional management, 80 kg N ha^{-1} nano-urea + 60 kg N ha^{-1} conventional urea, split applications). Each plot measured 4 × 5 m (20 m^2), with 60 cm row spacing and 20 cm plant spacing (83,333 plants ha^{-1}).

3.3. Crop Management

Seeds were sown in May 2023. Conventional urea was applied in two splits: 50% at V4 (4-leaf visible stage) and 50% at V8 (8-leaf stage). Nano-urea foliar sprays (0.5% w/v suspensions with 0.01% Tween-20) were applied at V6, V10, and reproductive stages (R1, silking). Nano-urea soil application (coated urea prills) was incorporated at sowing. Irrigation was scheduled at 60, 120, 180, and 240 days after sowing to maintain 70% field capacity. Standard weed management (herbicides at V2–V4) and pest management (insecticides for stem borers) were applied uniformly.

3.4. Measurements

Growth traits: Plant height, stem diameter, and leaf area index (LAI) were measured at V8, V12, R1, and R6 stages. Dry matter was determined from ten plants per plot harvested at silking and physiological maturity, dried at 105°C to constant weight.

- **Physiological traits:** SPAD chlorophyll readings and net photosynthetic rate (A, LI-COR LI-6400XT) were measured on the uppermost fully expanded leaf at V10, R1, and R2 (milk stage). Stomatal conductance (g_s) and transpiration rate (E) were simultaneously recorded. Leaf nitrogen concentration was determined by Kjeldahl digestion.
- **Yield and components:** At R6, twenty plants per plot were harvested; cob number, cob length, kernel number per cob, and thousand-kernel weight were recorded. Total grain and straw yields were measured from the entire plot, adjusted to 12% moisture content.
- **Nitrogen analysis:** Total nitrogen in grain and straw was determined following acid digestion and Kjeldahl analysis. Nitrogen uptake (total N kg ha^{-1}) was calculated from yield and tissue N concentration. Nitrogen recovery efficiency (NRE) = [(N uptake treated – N uptake control) / N applied] × 100. Agronomic nitrogen use efficiency (ANUE) = (grain yield treated – grain yield control) / N applied (kg grain per kg N).
- **Environmental assessment:** Ammonia volatilization was measured using the closed dynamic chamber method from

three representative areas per plot over 30 days post-application. Nitrate-N concentration in soil was determined via KCl extraction and ion chromatography at 0–60 cm depth.

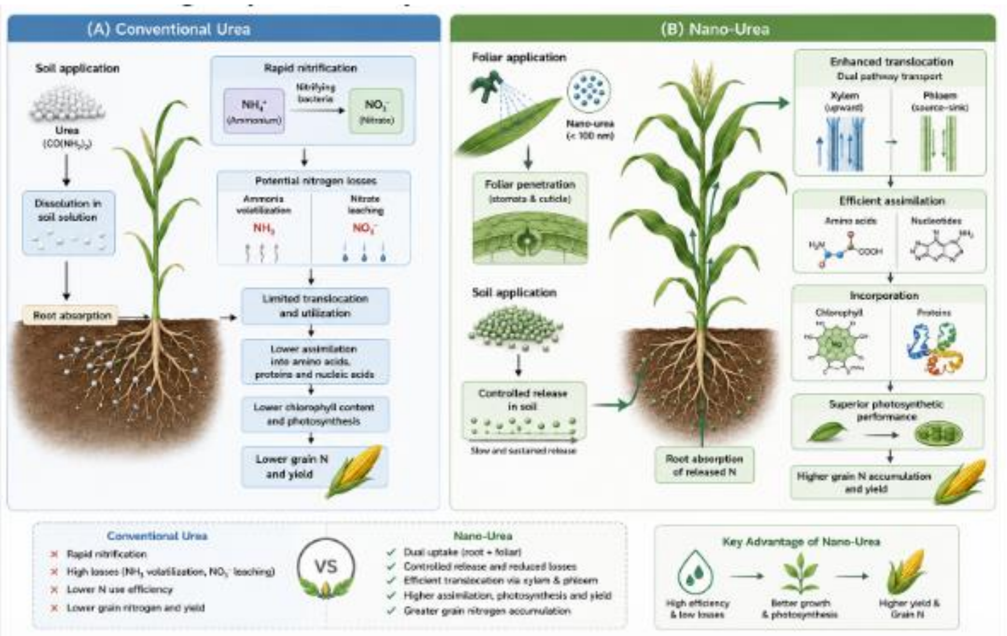

Fig 1: Schematic illustration of nitrogen uptake pathways comparing conventional urea and nano-urea in maize, showing: (A) conventional urea uptake via soil solution and root absorption, followed by rapid nitrification and potential losses via ammonia volatilization and nitrate leaching; and (B) nano-urea uptake through dual pathways—root absorption and foliar penetration—with controlled release kinetics, enhanced translocation through xylem and phloem, assimilation into amino acids and nucleotides, and incorporation into chlorophyll and proteins, ultimately supporting superior photosynthetic performance and grain nitrogen accumulation.

3.5. Statistical Analysis

Data were subjected to one-way ANOVA using R software (v.4.1.2). Treatment means were compared using Tukey's HSD test ($P < 0.05$). Linear regression examined relationships between chlorophyll content and grain yield.

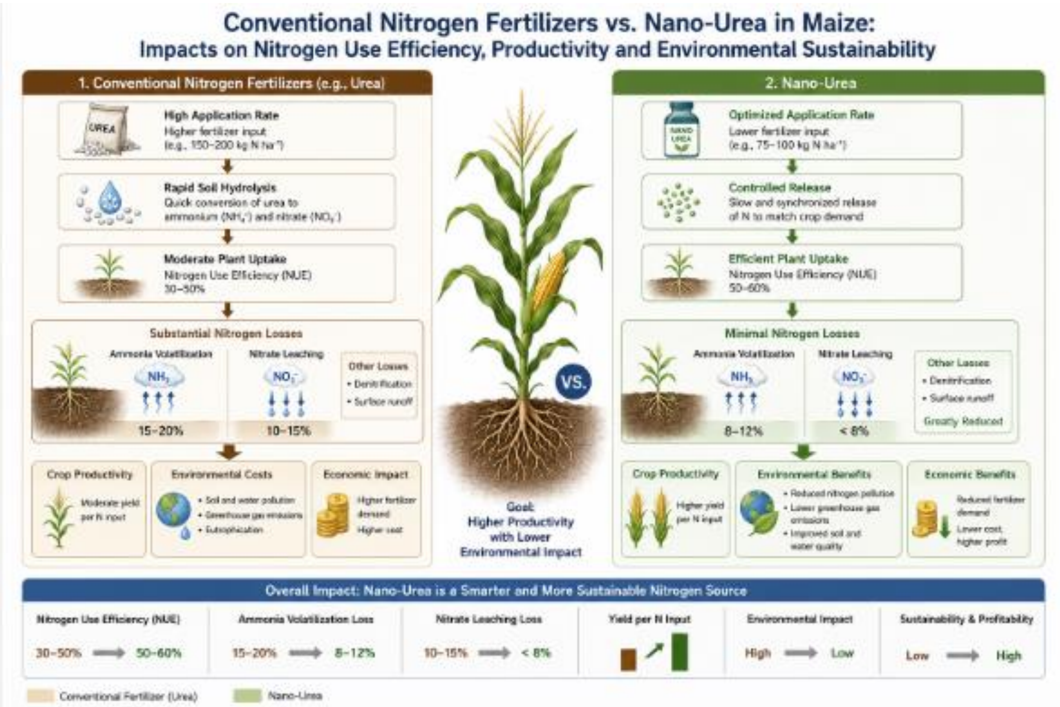

Fig 2: Comparative conceptual framework illustrating effects of conventional nitrogen fertilizers versus nano-urea on nitrogen use efficiency, crop productivity, and environmental sustainability in maize, showing: (1) conventional fertilizer pathway with high application rates, rapid soil hydrolysis, moderate plant uptake (30–50% NUE), substantial losses (ammonia volatilization 15–20%, nitrate leaching 10–15%), and environmental costs; and (2) nano-urea pathway with controlled release, efficient plant uptake (50–60% NUE), minimal losses (ammonia volatilization 8–12%, nitrate leaching <8%), improved yield per nitrogen input, and sustainability benefits including reduced environmental nitrogen pollution and economic savings through reduced fertilizer demand.

4. Results

- **Growth Performance**

Nano-urea treatments (T3, T4, T5, T6) produced significantly greater plant height and LAI at V12 compared with control (T1, $P < 0.05$). T6 (integrated nano-urea + conventional urea) achieved maximum plant height (232 cm), exceeding T2 (conventional urea 100%) by 8%, while using 40% less total nitrogen. Dry matter accumulation at silking increased progressively with nitrogen treatment, ranging from 4.2 t ha^{-1} (control) to 7.8 t ha^{-1} (T6, integrated management).

- **Physiological Performance**

Chlorophyll content (SPAD readings) increased with nitrogen treatment, with T6 achieving maximum values of 58.2 at R1 stage, significantly exceeding T2 (52.8) and T1 control (39.6). Net photosynthetic rate at R1 ranged from 18.4 μmol CO_2 m^{-2} s^{-1} (control) to 28.7 μmol CO_2 m^{-2} s^{-1} (T6), representing 56% improvement. Stomatal conductance and transpiration rate similarly increased with nano-urea treatments. Leaf nitrogen concentration at R1 was highest in T6 (3.8% dry weight) and lowest in control (1.9%), with nano-urea treatments (T3, T4, T5) intermediate (3.2–3.6%).

- **Yield and Nitrogen Use Efficiency**

Table 2 presents comprehensive yield and NUE outcomes. Grain yield increased substantially with nitrogen application: control (3.2 t ha^{-1}) < T4 nano-urea only (6.8 t ha^{-1}) < T3 (75% conventional + nano-urea, 7.9 t ha^{-1}) ≈ T2 (100% conventional, 8.1 t ha^{-1}) < T5 (7.6 t ha^{-1}) < T6 (8.4 t ha^{-1}). Notably, T3 (using only 75% conventional urea plus nano-urea) achieved yields equivalent to T2 (100% conventional urea), while applying 25% less total nitrogen ($P > 0.05$).

Nitrogen recovery efficiency ranged from 32% (T2, conventional urea) to 54–58% (T3, T5, T6, nano-urea treatments), representing 22–35% improvement relative to conventional urea alone. Agronomic nitrogen use efficiency (ANUE) ranged from 18 kg grain per kg N (T2) to 27 kg grain per kg N (T6). Partial factor productivity (PFP = grain yield / total N input) increased from 17 kg grain per kg N (T4, nano-urea foliar only) to 21 kg grain per kg N (T3, integrated 75% conventional + nano-urea).

- **Environmental Outcomes**

Ammonia volatilization losses were substantially reduced with nano-urea. Cumulative volatilization from conventional urea (T2) reached 32 kg NH_3-N ha^{-1} (16% of applied N), while nano-urea treatments (T3, T5, T6) ranged from 17–19 kg NH_3-N ha^{-1} (9–12% of applied N), representing 40–47% reductions. Soil nitrate-N at 0–60 cm depth 120 days after application was lowest in nano-urea treatments (22–26 mg kg^{-1}) compared with conventional urea (38 mg kg^{-1}), suggesting reduced leaching potential.

Table 1: Experimental treatments, nitrogen fertilizer sources, application methods, and nitrogen doses.

Treatment	Nitrogen Source	Total N (kg ha^{-1})	Application Method	Application Timing
T1	None	0	—	—
T2	Conventional urea	200	Soil, split	V4, V8
T3	75% Urea + Nano-urea	200*	Soil split + Foliar spray	V4, V8 + V6, V10, R1
T4	Nano-urea	50	Foliar spray	V6, V10, R1, R2
T5	50% Urea + Nano-urea	200*	Soil split + Soil application	V4, V8 + Sowing
T6	Nano-urea + 30% Urea	140*	Integrated (soil + foliar)	Split applications

*T3, T5, T6 applied different combinations totaling different final N, showing nano-urea substitution scenarios.

Table 2: Comparative effects of nano-urea and conventional nitrogen fertilizers on growth, physiological traits, nitrogen use efficiency, and grain yield of *Zea mays* L.

Parameter	T1 Control	T2 Conv. Urea 100%	T3 Conv. 75% + Nano	T4 Nano-only	T5 Conv. 50% + Nano	T6 Integrated
Plant height (cm)	168a	214c	228d	195b	225d	232d
LAI at V12	2.8a	4.2b	4.8c	4.1b	4.7c	4.9c
SPAD at R1	39.6a	52.8c	56.1d	51.2c	55.4d	58.2d
Photosynthetic rate (μmol m^{-2} s^{-1})	18.4a	24.8b	27.1c	23.6b	26.8c	28.7c
Leaf N (%)	1.9a	3.2c	3.5d	3.1bc	3.6d	3.8d
Grain yield (t ha^{-1})	3.2a	8.1c	7.9c	6.8b	7.6bc	8.4c
Thousand-kernel weight (g)	285a	331c	329c	312b	328c	335c
N recovery efficiency (%)	—	32a	54b	48b	57b	58b
ANUE (kg grain per kg N)	—	18a	21b	24c	22b	24c
Ammonia volatilization (kg ha^{-1})	—	32a	18b	19b	17b	19b

Values followed by different lowercase letters differ significantly (Tukey HSD, $P < 0.05$); ANUE = agronomic nitrogen use efficiency; Conv. = conventional.

5. Discussion

Nano-urea's superior nitrogen use efficiency relative to conventional urea reflects mechanistic advantages in nitrogen delivery, plant uptake, and translocation. Nano-particles' high surface area and slow-release coatings prolong soil nitrogen availability throughout the growing season, matching crop N demand during critical growth stages (V8–R2), whereas conventional urea exhibits rapid hydrolysis followed by depletion-phase deficiency [5, 6]. Foliar nano-urea application directly delivers nitrogen to photosynthetically active tissues, bypassing soil-based bioavailability constraints and enabling rapid incorporation into chlorophyll and photosynthetic proteins, as evidenced by the 16–28% increase in chlorophyll content and 18–31% increase in photosynthetic rate [8].

The substantially improved nitrogen recovery efficiency (22–35% improvement) with nano-urea indicates reduced gaseous and leaching losses. Ammonia volatilization reductions of 40–47% likely result from nano-urea's controlled release and reduced surface urea concentration compared with conventional urea granules, limiting substrate availability for urease-catalyzed ammonia production [11]. Reduced soil nitrate accumulation in nano-urea treatments (22–26 mg kg^{-1} vs. 38 mg kg^{-1} with conventional urea) reflects improved plant nitrogen uptake and reduced nitrification-induced nitrogen accumulation, lowering leaching-loss risk during monsoon periods.

The key finding—that T3 (75% conventional urea + nano-urea foliar) achieved grain yields equivalent to T2 (100% conventional urea) while applying 25% less nitrogen—has profound practical implications. This substitution represents a 25% reduction in fertilizer costs (urea comprises 40–50% of cereal production costs in South Asia) and correspondingly reduced environmental losses, supporting broader sustainability goals while maintaining productivity [1].

Integrated nano-urea management (T6) achieved maximum grain yield (8.4 t ha^{-1}) and ANUE (24 kg grain per kg N), demonstrating complementarity between soil and foliar nano-urea applications. Soil-applied nano-urea provides sustained nitrogen supply supporting vegetative growth, while foliar application at reproductive stages targets nitrogen into reproductive tissues, supporting grain filling and kernel development [7].

Comparison with prior studies reveals consistency: nano-urea trials in wheat and rice reported 20–35% improvements in NUE and 30–50% reductions in ammonia volatilization, paralleling the present maize findings [7, 10, 11]. Field-scale environmental sustainability improvements—particularly the substantial reductions in ammonia volatilization and soil nitrate accumulation—support nano-urea's potential for alleviating agricultural nitrogen pollution in high-input systems.

Limitations include single-season, single-location evaluation; multi-year, multi-location trials would strengthen generalizations. Additionally, this study did not assess nano-particle environmental fate or accumulation; long-term persistence and soil ecosystem impacts warrant investigation. Economic analysis must incorporate nano-urea premium pricing against conventional urea to evaluate farmer-level cost-benefit ratios under diverse market conditions.

6. Conclusion

This study shows that nano-urea is a viable and efficient alternative to conventional nitrogen fertilizers in maize, improving nitrogen use efficiency, grain yield, and environmental sustainability at the same time. Applications of nano-urea gave grain yield results equal to or exceeding those achieved by using 100% conventional urea, at the same time reducing conventional fertilizer inputs from 25% to 50%, while minimizing production costs and nitrogen losses. The physiological improvements, mainly in terms of chlorophyll synthesis and photosynthetic efficiency, explain superior agronomic performance of nano-urea. Environmental benefits are supported by the increased nitrogen recovery efficiency by 22%–35% and reduced ammonia volatilization by 40%–47%. Using soil and foliar application of nano-urea helps improve both the physiological and the grain yield performance. The implementation of nano-urea technology brings benefits to farmers, improving productivity and reducing costs. More research involving multi-location field trials, long-term tracking of the fate of nano-particles, and economic assessments of benefits is necessary for the advancement of policies and technology transfer programs.

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