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Synergistic impact of nano-fertilisers and seed priming on sugar beet (*Beta vulgaris* L.) yield and quality traits

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Abstract: Enhancing sustainability in agriculture requires innovative practices that boost crop productivity while conserving natural resources. This two-season field study (2023–2025) in sandy soils of El Sadat City, Egypt, evaluated the combined effects of nano-fertilisers and seed priming on the growth and yield of sugar beet (*Beta vulgaris* L.). Five fertilisation regimes, ranging from 100% conventional to 100% nano-formulations, were tested under both primed and unprimed seed treatments. The results demonstrated that the integration of nano-fertilisers with seed priming significantly improved sugar yield (up to 36.1 t/ha), sucrose content (20.35%), and nitrogen use efficiency (55.1 kg sugar/kg N). Post-harvest soil analysis showed improved nutrient retention, indicating enhanced environmental performance. This approach supports climate-smart agriculture by optimising nutrient input, reducing losses, and improving soil sustainability. Our findings highlight the potential of nano-agronomic inputs to contribute to global food security under conditions of climate change.

Keywords: climate-smart farming; nutrient dynamics; controlled release; sustainable cropping; soil health

Despite advances in fertiliser technologies, the global nutrient use efficiency of mineral fertilisers remains suboptimal, with current estimates indicating crop uptake efficiencies of approximately 30–35% for nitrogen (N), 15–20% for phosphorus (P), and 35–45% for potassium (K) in major cropping systems (Liu et al. 2022).

The persistent inefficiency in conventional fertiliser use has led to their excessive application, resulting in nutrient accumulation in soils and eutrophication of aquatic systems (Park et al. 2025). To address these issues, improving nutrient use efficiency (NUE) while minimising environmental harm has become a central goal of sustainable agriculture. Among emerging strategies, nanotechnology-based fertilisers (nanofertilisers) offer promising solutions by improving nutrient bioavailability, reducing losses, and enhancing crop productivity. Recent advances in nanoagriculture have demonstrated that nanofertilisers can correct multi-nutrient deficiencies, mitigate imbalanced fertilisation, and promote soil health by minimising nutrient leaching and degradation of soil organic matter (Bhardwaj et al. 2022).

Nanofertilisers, synthesised *via* physical, chemical, or biological routes, exhibit unique physicochemical characteristics, including a high surface-area-to-volume ratio and controlled release mechanisms. These properties enable precise, sustained nutrient delivery, thereby enhancing absorption efficiency while significantly reducing nutrient losses due to leaching and volatilisation (Stojanova et al. 2025, Tarafdar 2025). Greenhouse-based studies have dem-

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onstrated that nano-mineral fertilisers significantly enhance nutrient uptake and soil fertility under sandy soil conditions, thereby reinforcing their potential role in sustainable sugar beet cultivation (Hamed et al. 2025a).

Compared to conventional fertilisers, nanofertilisers (NFs) offer prolonged nutrient release, often extending 40–50 days *versus* 4–10 days in traditional systems. This extended availability supports lower application rates, improved nutrient-use efficiency, and potential cost savings (Stojanova et al. 2025). Importantly, NFs can synchronise nutrient delivery with specific developmental stages of crops, thereby improving yield, biochemical quality, and stress resilience (Tarafdar 2025). Furthermore, the use of nano-encapsulation and membrane-controlled release systems enables precision agriculture by minimising losses and enhancing the uptake of both macro- and micronutrients, as well as bioactive compounds (Demirkıran and Sohrabi 2024).

Sugar beet (*Beta vulgaris* L.) is cultivated worldwide as a major sugar crop due to its high sucrose content (typically 14–20%) and relatively short growth cycle (5–6 months). These traits make it a suitable alternative to sugarcane, particularly in temperate and semi-arid regions with water constraints (Hamed et al. 2025b).

Sugar beet (*Beta vulgaris* L.) contributes approximately 20–40% of global sugar production. It is increasingly recognised as a valuable feedstock for ethanol production due to its high fermentable sugar yield (Alsanad and Emara 2024). Its ability to thrive in saline, low-fertility, and arid soils makes it an ideal crop for marginal lands, including arid regions such as Upper Egypt, where conventional crops often fail to perform efficiently (Mahmoud et al. 2018).

In Egypt, the expansion of sugar beet (*Beta vulgaris* L.) cultivation serves as a strategic approach to address the growing gap between domestic sugar production and rising demand for consumption. Reclaimed sandy soils, especially in newly developed agricultural zones, offer promising opportunities due to their availability and reduced competition with winter cereals (Verma et al. 2023). Recent studies suggest that integrating mineral nitrogen fertilisers with nano-calcium foliar applications and biofertilisers significantly enhances both root biomass and sucrose yield, contributing to more sustainable and efficient cropping systems under new reclaimed soil (Verma et al. 2023). Field-scale applications and long-term ecological assessments remain under investigation.

Accordingly, this study aimed to investigate the effects of conventional and nano-formulated nutrient applications on the performance of sugar beet under sandy soil conditions. Specific objectives included evaluating their influence on crop yield, quality traits, nutrient uptake, post-harvest soil nutrient availability, and nitrogen use efficiency.

MATERIAL AND METHODS

Experimental site. A two-field experiment was conducted during the winter seasons of 2023/2024 and 2024/2025 at a private field located in El Sadat City, Menoufia Governorate, Egypt (30°22'11.0"N, 30°47'41.3"E). Meteorological data for the 2023/2024 and 2024/2025 growing seasons, along with long-term climatic averages, are presented in Figure 1.

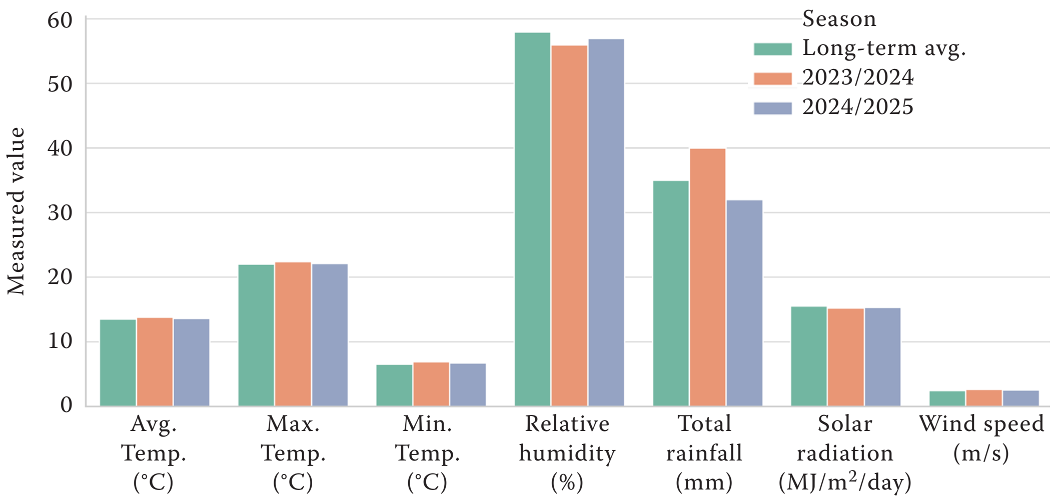

Figure 1. Meteorologic conditions during experimental seasons *vs.* long-term average

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During both seasons, average temperatures ranged between 13.6–13.8 °C, with total rainfall between 32 and 40 mm, slightly above the 30-year average of 35 mm. Relative humidity and solar radiation values remained stable across seasons.

Irrigation was applied through a drip irrigation system. The total seasonal irrigation water applied amounted to approximately 5 750 m^3/ha during each growing season.

The study aimed to evaluate the impact of nano- and conventional fertilisers, in conjunction with seed priming, on sugar beet (*Beta vulgaris* L., cv. BTS 645) yield, quality traits, post-harvest soil nutrients, and nitrogen use efficiency under sandy soil conditions.

Soil sampling and characterisation. Before sowing, five soil samples (surface to 40 cm depth) were collected randomly from the experimental field. The samples were air-dried, homogenised, and sieved through a 2 mm mesh. A composite sample was prepared and analysed to determine its physico-chemical characteristics. Physical properties were assessed according to the methods outlined by Klute (1986), while chemical and nutrient analyses were conducted following the protocols described by Cottenie et al. (1982) and Page et al. (1982). Based on the particle size distribution (86.5% sand, 8.3% silt, and 5.2% clay), the soil was classified as "sand" according to the FAO soil textural triangle (Table 1).

Plant material. Sugar beet seeds (*Beta vulgaris* L., cv. BTS 645) were obtained from a fine seeds company in Egypt.

Experimental treatments. Phosphorus was applied for each treatment in both nano-formulated and conventional forms before sowing and was incorporated into the soil. The applied treatments of conventional and nano fertilisers are presented in Table 2.

Nano-fertiliser preparation. All nano-fertilisers employed in this study were supplied by Nanotech for Photo Electronics (Giza, Egypt) at a concentration of 20%. Rutin-loaded chitosan nanoparticles were synthesised by dissolving rutin in 70% ethanol, blending it with a chitosan solution, and subsequently incorporating NFs containing nitrogen, phosphorus, and potassium. The resultant colloidal suspension was stirred for 2 h to ensure complete particle hardening, following the procedures outlined by Makvandi et al. (2020), Abdel-Hakim et al. (2023), and Hamed et al. (2025a). The nano-mineral fertilisers (NMFs) were characterised using transmission electron microscopy (TEM), which revealed well-defined nanoparticles with mean diameters of 34 nm for ammonium nitrate, 30 nm for phosphoric acid, and 31 nm for potassium sulfate (Figure 2).

Seed soaking and field layout. Half of the sugar beet seeds were primed by soaking for 4 h in a solution containing 1 mL/L of nano-copper (4%) and 1 mL/L of a nano-micronutrient mix (20%). The field experiment was arranged in a split-plot design within a randomised complete block layout, comprising four replicates. Seed treatment (primed *vs*. unprimed) was assigned to the main plots, while fertiliser treatments (T_1–T_5) were allocated to the subplots.

Each subplot measured 4 × 3 m (12 m^2), with rows spaced 50 cm apart and hills 15 cm apart within rows. Plants were thinned at the 4–6 leaf stage to ensure one plant per hill. Sowing was conducted on 14 October

Table 1. Physico-chemical characteristics and nutrient content of the experimental site pre-sowing

Parameter	Value	Parameter	Value
Particle size distribution (%)		**Soil organic and inorganic components**	
Sand	86.50	Organic carbon (%)	0.30
Silt	8.30	Carbonate content ($CaCO_3$)	2.50
Clay	5.20	Exchangeable cations ($cmol_+$/kg)	
Textural class (FAO)	Sandy	Ca^{2+}	1.98
pH (1:2.5 soil:water)	7.90	Mg^{2+}	0.61
Electrical conductivity (dS/m)	1.69	Na^+	0.46
Available macronutrients (mg/kg)		Cation exchange capacity ($cmol_+$/kg)	3.20
N	17.99	**Available micronutrients** (mg/kg)	
P	2.88	Fe	8.91
K	59.49	Zn	3.02
		Mn	4.01
		Cu	0.99

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Table 2. Application of conventional and nano-scale fertiliser treatments

Treatment		Nitrogen	Phosphorus	Potasium	Micronutrient
T_1	conventional 100%	240 kg N/ha (716.4 kg of AN/ha)	74.4 kg P/ha (480 kg of SP/ha)	115.2 kg K/ha (240 kg of KS/ha)	1.92 L/ha (100% RD)
T_2	conventional + nano K	240 kg N/ha (716.4 kg of AN/ha)	74.4 kg P/ha (480 kg of SP/ha)	720 mL nano K/ha (30% of nano from RD)	1.92 L/ha (100% RD)
T_3	conventional + nano micronutrients	240 kg N/ha (716.4 kg of AN/ha)	74.4 kg P/ha (480 kg of SP/ha)	115.2 kg K/ha (240 kg of KS/ha)	576 mL/ha (30% of Nano from RD)
T_4	conventional + nano K + nano micronutrients	240 kg N/ha (716.4 kg of AN/ha)	74.4 kg P/ha (480 kg of SP/ha)	720 mL nano K/ha (30% of Nano from RD)	576 mL/ha (30% of nano from RD)
T_5	nano 100%	2.4 L nano N/ha (30% of nano from RD)	1.44 L nano P/ha (30% of nano from RD)	720 mL nano K/ha (30% of nano from RD)	576 mL/ha (30% of nano from RD)

RD – recommended dose; SP – superphosphate; AN – ammonium nitrate; KS – potassium sulfate. Macronutrients were applied to the soil, whereas micronutrients were supplied *via* foliar application. Nano-fertilisers were applied at 10% of the recommended dose for conventional fertilisers. They were prepared from a nano solution containing 20% nanoform, which, by volume, corresponds to approximately 50% of the total quantity of conventional fertilisers

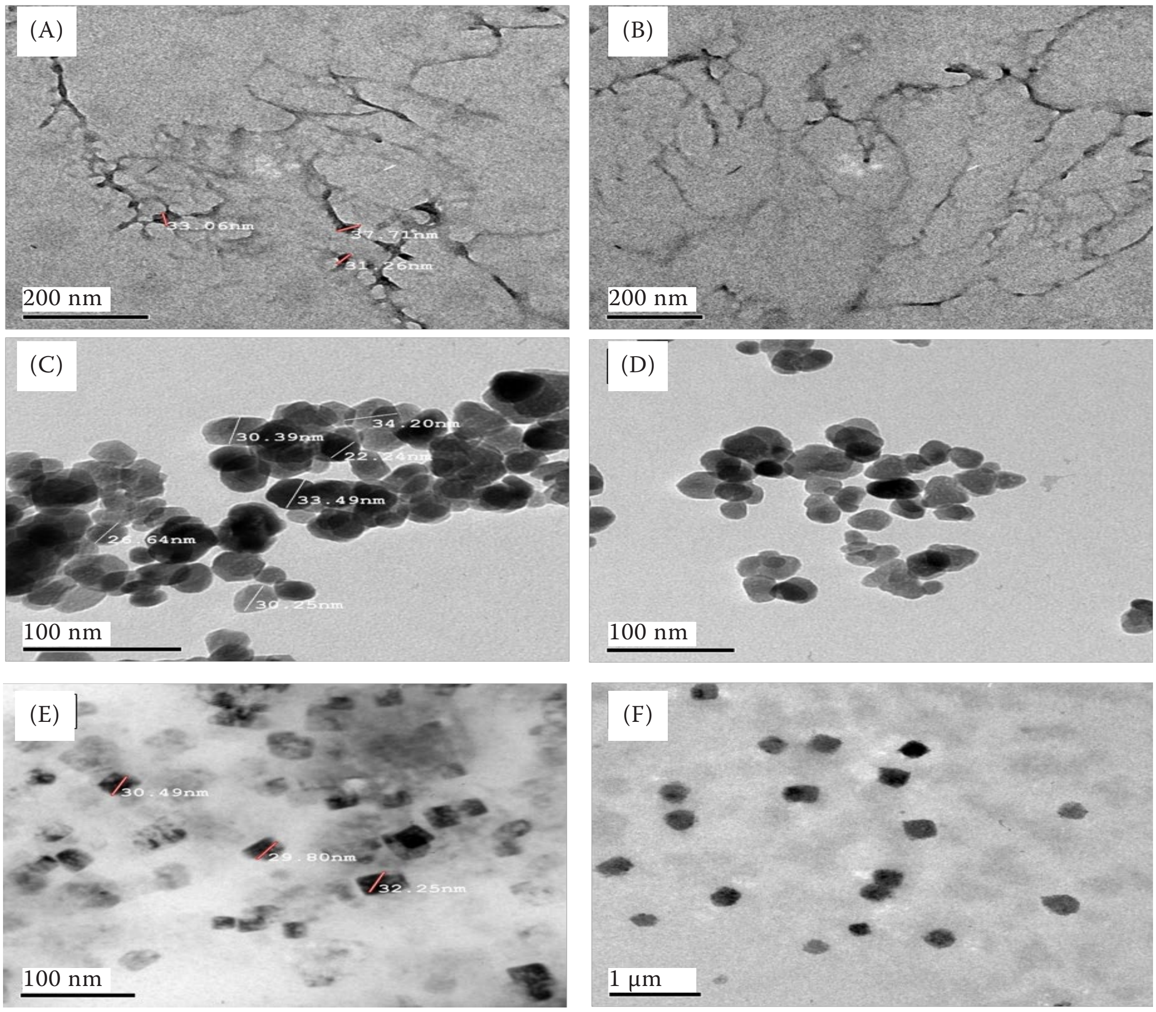

Figure 2. Transmission electron microscopy images of nanomineral fertilisers: (A, B) ammonium nitrate; (C, D) phosphoric acid, and (E, F) potassium sulfate

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2023, during the first season, and on 10 October 2024, during the second season.

The application timing for both conventional and nano-fertilisers is detailed in Table 3. All standard agronomic practices, including irrigation, weed control, and pest management, were implemented in accordance with the recommendations of the Egyptian Ministry of Agriculture for sugar beet cultivation.

Studied traits

Quality parameters. At harvesting (200 days after planting), a sample of 10 roots was taken at random from each sub-plot, cleaned and sent to Sugar Beet Laboratory at Nubaria Sugar Factory, El-Beheira Governorate, Egypt, to determine the following:

Impurity components, i.e. alpha amino N, Na, and K (mmol/100 g fresh beet) according to the method as described by AOAC (2012).

The sucrose percentage was estimated using a saccharometer and lead acetate extract of fresh, macerated roots, according to Carruthers and Oldfield (1960).

The impurity percentage was determined according to Carruthers and Oldfield (1960) as follows:

$$\text{Impurities} = ((K + Na) \times 0.0343) + (\text{alpha amino N} \times 0.094) + 0.29$$

Sucrose loss to molasses percentage (SLM) according to Renfield et al. (1993);

$$LM = (0.343 \times (Na + K) + 0.94 \times (\text{alpha amino N}) - 0.31)$$

Sugar recovery percentage (SR%): was estimated according to Renfield et al. (1993) by using the following formula:

$$SR\% = pol - [0.343 (K + Na) = 0.094\ \alpha - \text{amino N} + 0.29]$$

Where: Pol – sucrose percentage.

Yields. At harvest, plants from the middle three rows of each subplot were manually collected. Foliage was removed by topping, and roots were separated and thoroughly cleaned of soil. Fresh root yield was recorded immediately in (t/ha) using a field-calibrated scale to ensure precision, and sugar yield (t/ha) as per the following equation:

$$\text{Sugar yield (t/ha)} = \text{root yield (t/ha)} \times SR\%$$

Post-harvest soil analysis and nitrogen use efficiency. At harvest, soil samples were collected from each experimental plot to a depth of 0–40 cm to determine the residual concentrations of available nitrogen, phosphorus, and potassium. The samples were air-dried, passed through a 2-mm mesh, and analysed in accordance with the standard procedures described by Cottenie et al. (1982).

Available nitrogen was measured using the Kjeldahl method; phosphorus was determined *via* the molybdenum blue method following extraction with sodium bicarbonate; and potassium was analysed by flame photometry after extraction with ammonium acetate. These residual nutrient levels were used to assess the nutrient retention efficiency of each fertilisation regime under both primed and unprimed seed conditions.

Table 3. Application timing of conventional and nano-fertiliser treatments

Treatment	At soil preparation	30 DAP	50 DAP	60 DAP	80 DAP	85 DAP
T_1	480 kg SP	358.2 kg AN, 120 kg KS	960 mL MN	358.2 kg AN, 120 kg KS, 720 mL B	960 mL MN	720 mL B
T_2	480 kg SP	358.2 kg AN, 360 mL N-KS	960 mL MN	150 kg AN, 360 mL N-KS, 720 mL B	960 mL MN	720 mL B
T_3	480 kg SP	358.2 kg AN, 120 kg KS	336 mL N-MN	358.2 kg AN, 120 kg KS, 720 mL B	–	240 mL N-MN, 720 mL B
T_4	480 kg SP	358.2 kg AN, 360 mL N-KS	336 mL N-MN	358.2 kg AN, 360 mL N-KS, 720 mL B	–	240 mL N-MN, 300 mL B
T_5	–	480 mL N-AN, 360 mL N-KS, 480 mL N-SP	480 mL N-SP, 336 mL N-MN, 360 mL B	960 mL N-AN, 360 mL N-KS	960 mL N-AN, 480 mL N-SP	240 mL N-MN, 360 mL B

DAP – days after planting; N-AN – nano ammonium nitrate; N-KS – nano potassium sulfate; B – boron; N-B – nano boron; MN – micronutrient; N-MN – nano micronutrient; N-K – nano potassium; N-SP – nano superphosphate

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Nitrogen use efficiency (NUE) was evaluated to quantify the effectiveness of nitrogen uptake and its utilisation in sugar beet production. NUE was calculated using the partial factor productivity (PFP) approach, as expressed by the following equation:

$$\text{NUE (kg sugar per kg N)} = \frac{\text{Total sugar yield (kg/ha)}}{\text{Total nitrogen applied (kg/ha)}}$$

Statistical analysis. The field experiments were conducted using a split plot design within a randomised complete block design (RCBD) with four replicates. The main plot factor consisted of the two seed treatments, while the subplot factor included the five fertiliser treatments. The data collected were subjected to analysis of variance (ANOVA) appropriate for the split-plot structure. Least significant difference (*LSD*) tests were performed at the 5% probability level to separate treatment means. Standard error (SE) values were calculated to express variability within replicates. Statistical analyses were conducted using the MSTAT-c package (1991, Michigan, USA).

RESULTS

Alpha amino nitrogen (%). Alpha amino nitrogen (α-N), an indicator of soluble nitrogen and amino acid availability, was significantly influenced by fertiliser type and seed priming across both seasons (Figure 3). For untreated seeds, comparatively higher α-N concentrations were observed under nano MN, reaching over 4.3% in 2023–2024 and slightly lower in 2024–2025. By contrast, the lowest α-N values (~3.3–3.5%) were found in the 100% nano and nano K + MN treatments, suggesting more efficient nitrogen utilisation and reduced residual amino compounds. In treated seeds, α-N levels generally increased, with comparatively higher values under nano K and nano K + MN (exceeding 4.0%), particularly in 2024–2025.

Potassium (K%). Potassium concentration was strongly affected by fertiliser formulation and seed treatment (Figure 4). In untreated seeds, nano MN and nano K produced comparatively higher K levels (~8.0–8.2%), whereas nano K + MN recorded the lowest (~7.6–7.7%). In treated seeds, uptake was further enhanced, especially under nano K, which reached 8.5% in 2023–2024. Nano K + MN and 100% nano also maintained promising increases in K (~8.2–8.3%). Seasonal variation was minor, though slightly higher values were observed in the first season.

Sodium (Na%). Sodium concentrations exhibited an inverse relationship with potassium, consistent with their antagonistic uptake (Figure 5). For untreated seeds, sodium was comparatively higher under nano MN and 100% conventional (~2.2–2.3%), while nano K + MN and 100% nano maintained the lowest levels (~1.7–1.8%). In treated seeds, sodium levels increased under nano K (up to 2.6% in 2023–2024), but nano K + MN and 100% nano continued to limit Na accumulation, maintaining levels at or below 2.0%.

Sucrose percentage (%). Sucrose content responded positively to nano-fertilisers, with 100% nano

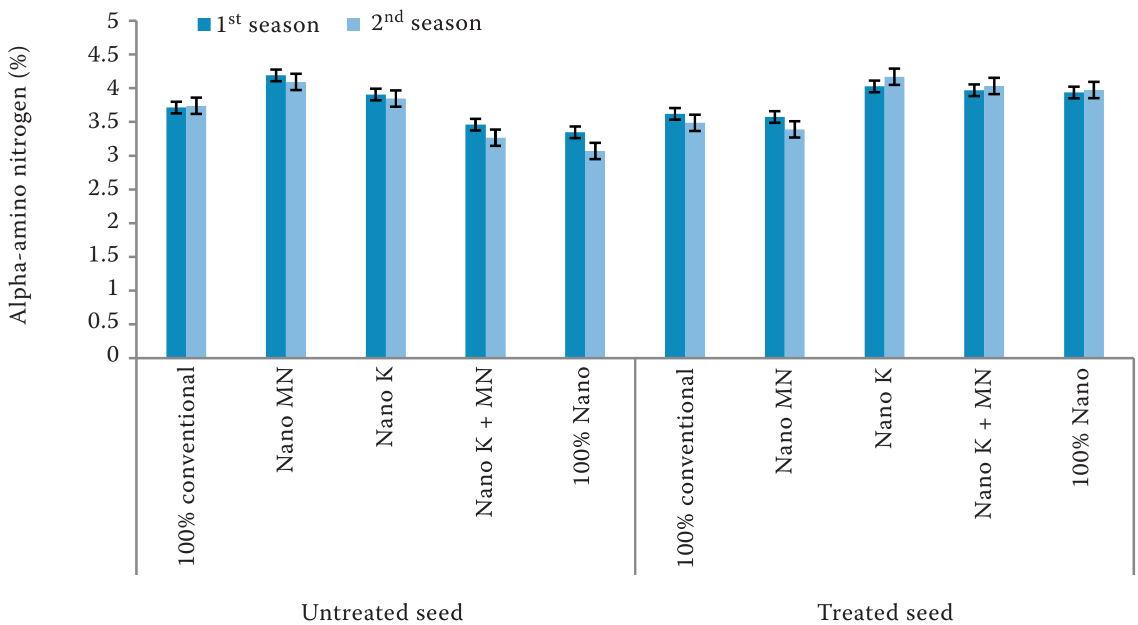

Figure 3. Effect of seed and fertiliser treatments on alpha-amino nitrogen in sugar beet roots during two seasons

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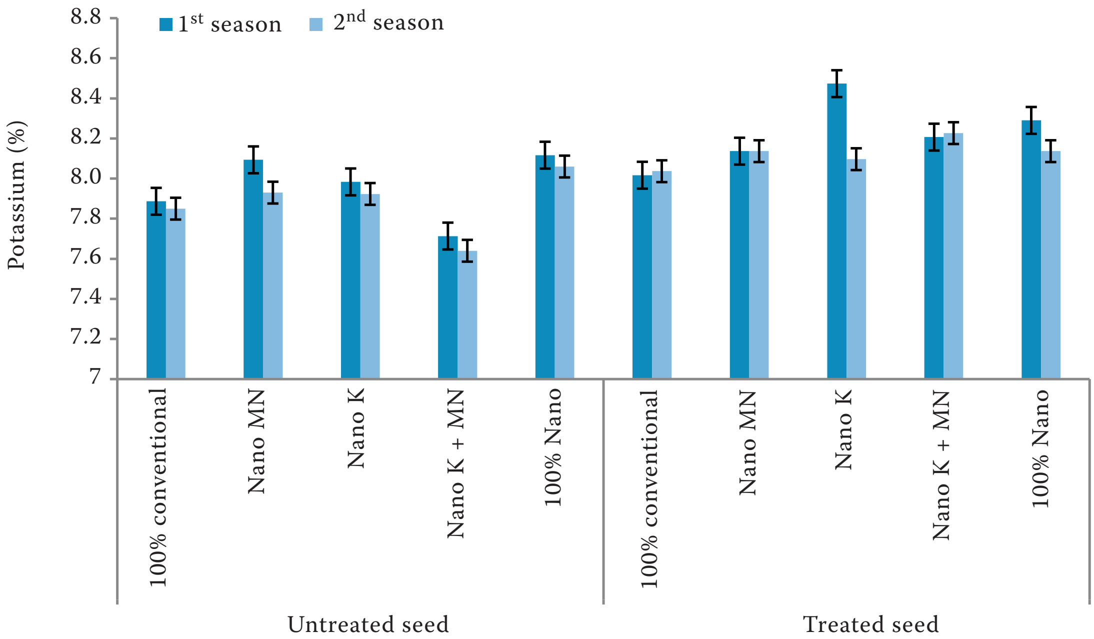

Figure 4. Potassium in sugar beet roots as influenced by seed priming and fertiliser formulations over two seasons

consistently yielding comparatively higher concentrations under both seed conditions. In untreated seeds, sucrose reached 20.65% (2023–2024) and 20.04% (2024–2025), averaging 20.35%. Intermediate levels (~19.3–19.4%) were observed under nano K and 100% conventional conditions, whereas nano MN recorded the lowest level (~18.8%), particularly in untreated seeds. Seed treatment further enhanced sucrose accumulation, most notably under nano-K and nano-K + MN (Tables 4 and 5).

Impurity percentage (%). Juice impurities, a key determinant of processing quality, were lowest under 100% nano and nano K + MN (~0.96–0.97%), especially with treated seeds. By comparison, nano K and nano MN showed slightly higher impurity levels (~1.02%), particularly in untreated seeds. Overall, seed treatment contributed to reduced impurity levels, with results stable across both seasons.

Sucrose loss to molasses (%). Sucrose loss to molasses followed a similar trend to impurities. The

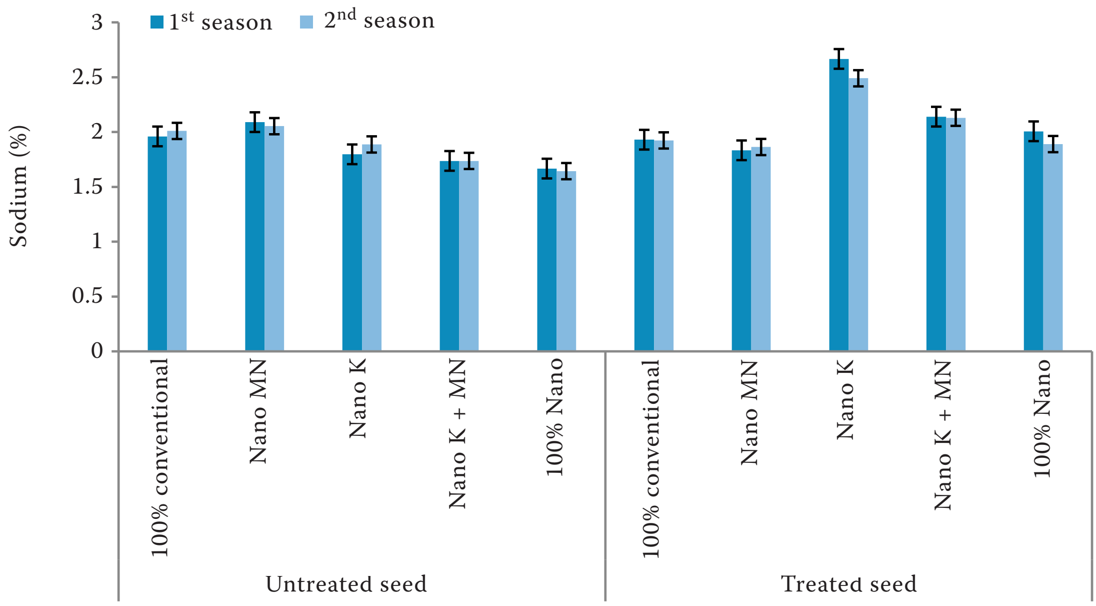

Figure 5. Sodium in sugar beet roots under different seed and fertiliser treatments across two growing seasons

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Table 4. Effect of different fertiliser treatments on sucrose content, impurities, and sucrose loss to molasses of sugar beet during two seasons

Fertiliser	Sucrose (%)		Mean	Impurities (%)		Mean	Sucrose loss to molasses		Mean
	2023–2024	2024–2025		2023–2024	2024–2025		2023–2024	2024–2025	
100% conventional	19.48 ± 0.12	19.36 ± 0.11	19.42	0.97 ± 0.20	0.97 ± 0.11	0.97	3.43 ± 0.09	3.43 ± 0.20	3.43
Nano MN	18.92 ± 0.22	18.84 ± 0.13	18.88	1.00 ± 0.15	0.98 ± 0.17	0.99	3.51 ± 0.17	3.47 ± 0.38	3.49
Nano K	19.40 ± 0.15	19.20 ± 0.12	19.30	1.02 ± 0.22	1.02 ± 0.15	1.02	3.65 ± 0.12	3.56 ± 0.47	3.61
Nano K + MN	19.19 ± 0.23	19.05 ± 0.23	19.12	0.98 ± 0.25	0.97 ± 0.24	0.98	3.43 ± 0.10	3.42 ± 0.94	3.43
100% Nano	20.65 ± 0.50	20.04 ± 0.19	20.35	0.98 ± 0.30	0.96 ± 0.23	0.97	3.48 ± 0.10	3.40 ± 0.68	3.44
$LSD_{0.05}$	0.70	0.35		ns	0.04		ns	0.10	

ns – not significant; ± SE – standard error; *LSD* – least significant difference

lowest losses were measured under 100% conventional and nano K + MN (~3.42–3.43%), while nano K showed comparatively higher losses (~3.65%). Seed treatment helped to reduce losses, particularly with nano K + MN and 100% nano (Table 5).

Root and sugar yields (t/ha). Root and sugar yields were strongly affected by the fertiliser regime and seed priming. The 100% nano treatment achieved comparatively higher yields, averaging 36.12 t/ha across both seasons (37.07 t/ha in 2023–2024 and 35.16 t/ha in 2024–2025). Corresponding sugar yields mirrored this pattern, with the 100% nano treatment producing 36.12 t/ha under untreated seeds. Nano K + MN and nano K followed with yields of 31.56 and 28.12 t/ha, respectively, whereas nano MN and 100% conventional showed markedly lower performance. Seed treatment slightly reduced absolute yield values across treatments but maintained similar treatment ranking (Tables 6 and 7).

Post-harvest soil nutrient availability

Table 8 presents the post-harvest assessment of soil nutrient status, indicating that the form of fertiliser and seed treatment had significant effects on the availability of nitrogen, phosphorus, and potassium across both cropping seasons. The data revealed that integrated application of nano-fertilisers, particularly in combination with seed soaking, improved nutrient retention in the soil compared to conventional fertilisation.

Post-harvest analysis indicated that soil nutrient availability was notably influenced by fertiliser formulation and seed treatment.

Available nitrogen levels ranged from 17.9 to 21.7 mg/kg, with the T2-soaked treatment exhibiting comparatively higher concentrations (21.7 and 21.2 mg/kg in the 2023 and 2025 seasons, respectively). Other nano-based treatments, such as T5-soaked and T3-soaked, also resulted in improved

Table 5. Effect of seed priming on sucrose content, impurities, and sucrose loss to molasses of sugar beet during two seasons

Seed treatment	Sucrose (%)		Mean	Impurities (%)		Mean	Sucrose loss to molasses (%)		Mean
	2023–2024	2024–2025		2023–2024	2024–2025		2023–2024	2024–2025	
Untreated	19.28 ± 0.18	19.13 ± 0.14	19.21	0.98 ± 0.22	0.96 ± 0.12	0.97	3.40 ± 0.24	3.37 ± 0.29	3.39
Treated	19.77 ± 0.25	19.46 ± 0.13	19.62	1.00 ± 0.31	1.00 ± 0.14	1.00	3.60 ± 0.16	3.54 ± 0.36	3.57
$LSD_{0.05}$	0.46	0.22		0.02	0.02		0.15	0.06	

± SE – standard error; *LSD* – least significant difference

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Table 6. Impact of fertiliser treatments on sugar recovery and yields of sugar beet in both growing seasons

Fertiliser	Root yield (t/ha)		Mean	Sugar yield (t/ha)		Mean
	2023–2024	2024–2025		2023–2024	2024–2025	
100% conventional	100.80 ± 7.98	98.79 ± 5.68	99.79	19.64 ± 1.62	19.13 ± 1.02	19.38
Nano MN	123.47 ± 3.84	122.01 ± 8.31	122.74	23.35 ± 0.75	22.98 ± 1.68	23.17
Nano K	140.58 ± 4.70	150.94 ± 5.90	145.76	27.27 ± 1.00	28.98 ± 1.07	28.12
Nano K + MN	162.74 ± 3.20	167.47 ± 3.24	165.10	31.23 ± 0.51	31.89 ± 0.76	31.56
100% Nano	179.53 ± 10.75	175.43 ± 8.34	177.48	37.07 ± 1.62	35.16 ± 1.02	36.12
$LSD_{0.05}$	24.93	21.86		3.25	2.89	

± SE – standard error; *LSD* – least significant difference

nitrogen availability compared to the conventional control (T1), which recorded lower values (18.4 and 17.9 mg/kg).

Similarly, soil potassium availability was enhanced in treatments involving nano potassium, with T2-soaked registering 71.0 and 70.3 mg/kg, substantially improved relative to T1 (63.5 and 62.7 mg/kg). Treatments incorporating nano K, including T4 and T5, also showed promising increases in residual potassium concentrations.

Phosphorus availability ranged from 3.1 to 3.7 mg/kg, with T5-soaked and T2-soaked treatments showing comparatively greater retention (3.7 and 3.6 mg/kg), while the T1-unsoaked treatment exhibited the lowest levels (3.2 and 3.1 mg/kg). Notably, nano phosphorus application, even at 30% of the conventional dose, contributed to sustained post-harvest phosphorus availability. The differences across nitrogen, potassium, and phosphorus availability were statistically significant at the 5% level (*LSD* values: 1.54 and 1.56 for N; 3.75 and 3.67 for K; and 0.24 and 0.26 for P, respectively). These outcomes suggest that nano-fertiliser applications, particularly when integrated with seed soaking, may contribute to improved nutrient retention and enhanced soil fertility under sandy soil conditions.

Nitrogen use efficiency. Nitrogen use efficiency was significantly enhanced by nano-fertiliser application and seed soaking across both seasons. The T_2-soaked treatment (conventional NPK + nano K) achieved comparatively higher NUE values, 55.1 and 52.8 kg sugar/kg N, in the 2023–2025 seasons, respectively. This was followed by T_5-soaked (100% nano), with NUE values of 51.4 and 49.3, indicating the strong efficiency of nano formulations. Seed soaking improved NUE across all treatments, while the lowest values were recorded in the T_1 (conventional) unsoaked plots (37.9 and 35.4) (Table 9).

However, while the results across both seasons were consistently positive, these outcomes are likely influenced by specific environmental conditions, such as sandy soils. Validation in different agroecological zones is necessary to confirm generalisability.

DISCUSSION

The findings of this study provide robust evidence that the combined use of nano-fertilisers and seed priming significantly enhances sugar beet quality, yield performance, and post-harvest soil nutrient status. Alpha amino nitrogen (α-N) concentrations were notably influenced by both fertiliser form and seed treatment. Elevated α-N levels observed in nano-micronutrient treatments applied to unprimed seeds may reflect enhanced amino acid biosynthesis driven by improved micronutrient availability. In contrast,

Table 7. Effect of seed priming on sugar recovery and yields of sugar beet in 2023–2025

Seed treatment	Root yield (t/ha)		Mean	Sugar yield (t/ha)		Mean
	2023–2024	2023–2024		2023–2024	2023–2024	
Untreated	80.12 ± 8.24	80.84 ± 8.62	80.48	15.45 ± 1.68	15.46 ± 1.66	15.46
Treated	79.14 ± 8.15	80.54 ± 7.86	79.84	15.65 ± 1.94	15.68 ± 1.70	15.66
$LSD_{0.05}$	24.93	21.86		3.25	2.89	

± SE – standard error; *LSD* – least significant difference

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Table 8. Post-harvest soil nitrogen (N), phosphorus (P), and potasium (K) availability as affected by seed treatment and fertiliser form in two seasons

Treatment		N (mg/kg)		K (mg/kg)		P (mg/kg)	
		2023–2024	2024–2025	2023–2024	2024–2025	2023–2024	2024–2025
Unsoaked	T_1	18.4	17.9	63.5	62.7	3.2	3.1
	T_2	21.2	20.7	70.1	69.4	3.6	3.5
	T_3	20.1	19.6	67.8	66.8	3.5	3.4
	T_4	19.8	19.2	66.5	65.6	3.4	3.3
	T_5	20.9	20.4	69.3	68.2	3.6	3.5
Soaked	T_1	18.9	18.4	64.0	63.2	3.3	3.2
	T_2	21.7	21.2	71.0	70.3	3.7	3.6
	T_3	20.6	20.2	68.5	67.6	3.6	3.5
	T_4	20.3	19.8	67.0	66.3	3.5	3.4
	T_5	21.4	20.9	70.5	69.1	3.7	3.6

Least significant difference $(LSD)_{0.05}$ is 1.54 and 1.56 for available N, 3.75 and 3.67 for available K and 0.24 and 0.26 for available P in 2023–2025, respectively

lower α-N levels in the 100% nano and nano K + MN treatments suggest more efficient nitrogen assimilation into structural and enzymatic proteins, thereby reducing residual nitrogen content in the juice. The application of seed priming further contributed to α-N regulation, indicating a beneficial role in optimising early nitrogen metabolism, particularly when integrated with nano-nutrient delivery systems. These observations are consistent with the findings of Ramesh et al. (2018), who reported that nano-urea formulations improved nitrogen assimilation and reduced nitrogen losses in field crops.

Potassium uptake was substantially improved in treatments receiving nano-K, with primed seeds exhibiting substantially improved K concentrations. This enhancement aligns with the results of Demirkıran and Sohrabi (2024), who reported increased K uptake efficiency and physiological regulation under nano-potassium application. Moreover, an inverse relationship between K and Na concentrations was observed, particularly in the nano K + MN and 100% nano treatments, where sodium levels were significantly reduced. This supports the hypothesis of ionic antagonism and improved K^+/Na^+ selectivity, even under non-saline conditions, a mechanism supported by Bhardwaj et al. (2022), who highlighted the role of nano-fertilisers in promoting ionic balance.

Root yield varied significantly in response to both fertiliser regimes and seed priming treatments. The most notable performance was observed with the 100% nano-fertiliser treatment (T_5), which consistently outperformed all other treatments across the growing seasons. This enhancement is primarily attributed to the slow-release and high-efficiency characteristics of nano-formulations, which optimise nutrient delivery and minimise environmental losses (Bhardwaj et al. 2022, Ammar et al. 2025).

Treatments involving partial nano-formulations, such as T_4 (conventional NP + nano K + micronutrients) and T_3 (conventional NP + nano K), also showed elevated yields (31.56 and 30.04 t/ha, respectively). Meanwhile, T_1 (100% conventional) and T_2 (conventional NPK + nano micronutrients) yielded

Table 9. Nitrogen use efficiency (NUE, kg sugar/kg N applied) under different fertiliser and seed treatments during two seasons

NUE	T_1		T_2		T_3		T_4		T_5	
	unsoaked	soaked	unsoaked	soaked	unsoaked	soaked	unsoaked	soaked	unsoaked	soaked
2023–2024	37.9^{ghij}	39.2^{efgi}	52.6^{ab}	55.1^{a}	46.2^{bcdef}	48.5^{abcde}	43.8^{bcdefh}	45.6^{bcdefg}	49.0^{abcd}	51.4^{abc}
2024–2025	35.4^{ghij}	36.8^{fghi}	50.3^{ab}	52.8^{a}	44.1^{bcdef}	46.4^{abcde}	41.9^{cdefgh}	44.0^{bcdefg}	47.2^{abcd}	49.3^{abc}

Least significant difference $(LSD)_{0.05}$ is 8.0 and 8.2 for 2023–2025, respectively

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lower outputs, particularly when seeds were not primed, indicating suboptimal nutrient efficiency and possible leaching.

While seed priming generally contributed to yield improvement, its effects were modest compared to fertiliser treatments. These findings are in line with previous research suggesting that nano-fertiliser applications play a more direct role in root development and biomass production (Sathiyabama 2019).

Interestingly, a slight reduction in yield was recorded in primed seeds under T_5, potentially due to nutrient overavailability or altered resource allocation within the plant. This indicates that the impact of priming is highly dependent on treatment conditions (Abdel-Hakim et al. 2023).

Overall, the study reinforces the effectiveness of nano-fertiliser technologies as sustainable alternatives to conventional practices, particularly in low-fertility sandy soils. These strategies have been associated with substantial yield gains, consistent with previous studies that reported improvements through nano-based nutrient management (Bhardwaj et al. 2022).

Sucrose content and juice quality traits were also markedly improved by nano-fertilisation. The comparatively higher sucrose percentages were recorded under the 100% nano treatment, likely due to enhanced nutrient availability and improved translocation of photosynthates. This finding is consistent with Hamed et al. (2025a), who observed similar improvements in sucrose content and juice purity following nano-Zn and nano-K foliar applications in sugar beet. Additionally, reductions in impurities and sucrose loss to molasses in the nano K + MN and 100% nano treatments indicate a greater proportion of processable sugar, in line with observations by Abbas et al. (2022), who linked the use of nano-nutrients to enhanced sugar recovery efficiency and a reduction in non-sugar constituents.

The overall improvements in juice quality were reflected in significantly higher sugar recovery and sugar yield. The 100% nano treatment consistently surpassed conventional fertiliser application, with yield increases exceeding 50% in unprimed seed conditions. Furthermore, the nano K + MN treatment showed a balanced impact on both biochemical and agronomic performance, suggesting its potential as a sustainable strategy for maximising sugar yield and juice quality simultaneously (Aberathna et al. 2024).

Post-harvest soil analysis revealed that nano-fertiliser applications, especially when combined with seed soaking, significantly improved the residual availability of nitrogen, phosphorus, and potassium. Treatments such as T_2-soaked and T_5-soaked outperformed conventional treatments in maintaining soil fertility post-harvest. These improvements may be attributed to the controlled release and high surface area characteristics of nano-fertilisers, which minimise nutrient losses *via* leaching and volatilisation, a phenomenon particularly beneficial in sandy soils with low nutrient retention capacity, as highlighted by Bhardwaj et al. (2022). Increased soil potassium levels under nano-treated conditions align with the findings of Singh et al. (2024), who demonstrated that nano-chelated potassium formulations enhance both potassium mobility and uptake. Similarly, the higher phosphorus retention under nano-fertilisation aligns with the findings of Zhao et al. (2020), who reported improved phosphorus solubility in low-retentive soils following nano-hydroxyapatite application.

The T_5-primed treatment consistently outperformed all others, while the T_2-soaked combination (conventional NP + nano K) also proved highly effective in enhancing soil nutrient retention and nitrogen use efficiency.

Nitrogen use efficiency was significantly improved in plots treated with nano-fertilisers, particularly T_2 and T_5, and was further enhanced under seed priming conditions. These results are in agreement with Singh et al. (2024), who reported that nano-nitrogen fertilisers synchronise nutrient release with plant uptake, leading to higher utilisation efficiency. Similarly, Hamed et al. (2025a) observed comparable increases in NUE in sugar beet under nano-urea application. Seed priming appeared to promote early nutrient assimilation and physiological readiness, contributing to consistent NUE performance across both seasons. The integration of nano-fertilisation with seed priming demonstrated synergistic effects on both NUE and soil nutrient retention, attributed to the dual action of precise nano-nutrient delivery and enhanced metabolic activity initiated by priming. This finding is consistent with the results of Hamed et al. (2025a), who emphasised that nano-fertilisers combined with priming enhanced nutrient uptake and plant responses in sugar beet. Furthermore, Sathiyabama (2019) highlighted the role of nano-seed priming in enhancing plant metabolic activity and nutrient uptake, particularly important in nutrient-poor, sandy soils vulnerable to leaching. These treatments promote sustainable nutrient management, reducing fertiliser inputs and minimising environmental losses. The controlled release and high bioavailability of nano-fertilisers support efficient nutrient uptake, improve

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soil nutrient retention, and limit nitrogen leaching critical in mitigating environmental degradation and promoting long-term soil health.

Collectively, these results suggest that nano-fertiliser and seed priming integration offers a promising strategy for boosting NUE and sustaining soil fertility under challenging agroecological conditions.

Importantly, these strategies align with climate-smart agriculture by lowering reactive nitrogen emissions, improving resource use efficiency, and enhancing the resilience of cropping systems to climate variability. As such, nano-fertilisers and seed priming offer a dual benefit: boosting productivity and supporting environmental conservation.

To build on these promising results, future research should investigate the long-term ecological impacts, nanoparticle behavior in soil systems, and cost-effectiveness of nano-fertilisers under diverse crops and agroecological conditions.

One limitation of the current study is the lack of multi-location trials and long-term environmental impact data on nanoparticle accumulation. Additionally, cost-benefit analysis for farmers remains to be evaluated.

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