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Influence of nano-urea foliar application and split nitrogen scheduling on growth, yield and nutrient use efficiency of wheat under semi-arid conditions

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Abstract

Nitrogen management remains one of the biggest levers for wheat productivity across semi-arid tracts, where uneven rainfall limits how well conventionally applied soil urea gets taken up by the crop. A field research trial was carried out over two consecutive dry-season cropping cycles (2023-2024 and 2024-2025) at Nakuru, Kenya, comparing split scheduling of soil-applied urea against foliar-sprayed nano-urea at three growth stages, alone and in combination. Seven treatments were laid out in a randomized block design with three replications, and data were recorded on plant height, tillers per plant, leaf area index, grain yield, straw yield, nitrogen uptake, and agronomic nitrogen use efficiency, along with the benefit-cost ratio for each option. Combined application of nano-urea foliar spray with a split soil nitrogen schedule produced the tallest plants (94.6 cm), the highest tiller count (9.2 per plant), and the greatest grain yield (52.3 q/ha), an improvement of about 66.6% over the untreated control and roughly 20.9% higher than full-dose conventional urea applied as a single basal dressing. Nitrogen use efficiency rose from 24.1 kg grain per kg N in the control to 38.7 kg grain per kg N under the combined treatment, while the benefit-cost ratio reached 2.86, the best among all seven options tested. Straw yield and harvest index followed a similar upward trend, though gains were comparatively smaller than those recorded for grain output. Nutrient uptake data showed that nitrogen accumulation in grain rose alongside the yield gains, without a matching rise in straw nitrogen content, suggesting better internal remobilization under the combined schedule. These results point to nano-urea as a genuinely useful complement rather than a full replacement for soil-applied nitrogen, particularly where split scheduling is already practiced. For farmers working semi-arid wheat belts with limited irrigation, pairing a modest soil dose with timed foliar nano-urea sprays appears to offer a workable route toward better nitrogen economy without giving up on yield.

Keywords: Nano-urea, wheat, split nitrogen scheduling, nutrient use efficiency, grain yield, semi-arid agriculture, foliar application, benefit-cost ratio, tillering, Nakuru

Introduction

What happens to a nitrogen molecule between the moment it leaves a fertilizer granule and the moment it shows up in a wheat grain? For farmers in semi-arid regions, a large part of the answer is: not much good. Nitrogen use efficiency in rainfed wheat systems commonly sits between 30% and 40%, with the rest lost to volatilization, leaching, or denitrification before the crop can use it. Wheat (*Triticum aestivum* L.) remains a staple cereal across the East African highlands and adjoining semi-arid belts, yet yields in these zones often lag behind irrigated tracts by a wide margin, largely because nitrogen management has not kept pace with the crop's actual uptake pattern across growth stages.

Conventional urea, broadcast once or split into two soil doses, has been the default nitrogen source for decades. But soil-applied urea in dryland conditions is vulnerable to ammonia volatilization when surface soils dry quickly after application, and to leaching losses during occasional heavy rain events. Nano-urea, a nanoparticle-based liquid formulation delivered as a foliar spray, has been marketed as an answer to some of these inefficiencies. Because it is absorbed directly through leaf stomata and cuticles, nano-urea sidesteps several of the soil-mediated loss pathways that reduce the effectiveness of granular urea. Early adoption reports from South Asia suggested that a single nano-urea spray could substitute for a substantial share

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of the recommended soil dose, though independent verification under semi-arid East African conditions has been limited.

Split nitrogen scheduling, meanwhile, is a well-established agronomic practice that matches nitrogen supply to the crop's demand curve, applying smaller doses at tillering, jointing, and heading rather than a single basal dose. Combining split scheduling with foliar nano-urea has not been tested extensively, and it remains unclear whether the two practices are additive, redundant, or whether one might partly substitute for the other. This gap matters practically: recommending nano-urea without knowing how it interacts with existing split-dose recommendations risks either under- or over-fertilizing wheat crops, with consequences for both yield and input cost.

The present research was designed around three linked questions. First, does foliar nano-urea alone match the yield performance of conventional split-dose urea? Second, does combining nano-urea with a reduced soil dose improve nitrogen use efficiency beyond either practice alone? Third, do the economic returns from nano-urea justify its additional cost relative to the modest input price of granular urea? Answering these questions required a field trial spanning two cropping cycles, seven treatments capturing the relevant combinations, and a full accounting of both agronomic and economic outcomes, described in the sections that follow. Beyond the immediate agronomic comparison, the wider aim was to generate locally grounded evidence that extension officers in similar semi-arid tracts could use when advising smallholder wheat growers on nitrogen budgeting.

Materials and Methods

Study Area Description

The field trial was conducted at the research farm of the Nakuru Institute of Agricultural Sciences, located at approximately 0.28°S, 36.07°E, at an elevation of 1,850 m above sea level, within the semi-arid agro-ecological zone of the Rift Valley region, Kenya. The area receives bimodal but erratic rainfall averaging 620–680 mm annually, with the main dry-season wheat crop relying heavily on residual soil moisture and supplemental irrigation. Soils at the site are classified as sandy clay loam, mildly alkaline (pH 7.4), with organic carbon content of 0.52%, available nitrogen of 218 kg/ha, available phosphorus of 16.4 kg/ha, and available potassium of 224 kg/ha at the start of the trial. Mean maximum and minimum temperatures during the cropping seasons ranged from 24.6 °C to 27.8 °C and 9.1 °C to 12.3 °C, respectively, with occasional cold spells during the tillering phase in both years.

Field Experimental Design

The trial followed a randomized block design (RBD) with seven treatments replicated three times, giving 21 plots of 4 m × 5 m each, separated by 0.5 m bunds to prevent lateral seepage of irrigation water and nutrients. Treatments comprised T₁

(absolute control, no nitrogen), T₂ (100% recommended dose of nitrogen, RDN, applied as full basal urea), T₃ (RDN split into three equal doses at basal, tillering, and jointing), T₄ (nano-urea foliar spray at early tillering only, no soil N), T₅ (nano-urea spray at mid-tillering/jointing only, no soil N), T₆ (nano-urea spray at late jointing/booting only, no soil N), and T₇ (50% RDN split soil application plus nano-urea spray at tillering and jointing). Wheat variety Kenya Kwale was sown at 100 kg seed/ha using the locally recommended row spacing, with phosphorus and potassium applied uniformly to all plots as per soil test recommendations. Nano-urea was applied at 4 mL/L water using a knapsack sprayer calibrated to deliver 500 L spray solution per hectare per application.

Material

Certified wheat seed of variety Kenya Kwale was procured from a registered seed multiplication unit. Prilled urea (46% N), diammonium phosphate, and muriate of potash served as the basal fertilizer sources, while a commercially formulated nano-urea liquid concentrate (4% w/v nitrogen as nanoparticles) was used for foliar sprays. Data on plant height, tiller count, and leaf area index were recorded from five randomly tagged plants per plot at 30, 60, and 90 days after sowing (DAS). Grain and straw yields were recorded at harvest maturity from a net plot area of 12 m² per treatment, after border row removal.

Methods

Nitrogen uptake in grain and straw was estimated using the micro-Kjeldahl method on oven-dried, ground samples, and agronomic nitrogen use efficiency (NUE) was calculated as the increase in grain yield per unit of nitrogen applied over the untreated control. The benefit-cost ratio for each treatment was worked out using prevailing local input costs and farm-gate wheat prices for the 2024–2025 season. All data were subjected to analysis of variance (ANOVA) appropriate for a randomized block design, and treatment means were compared using the critical difference (CD) test at the 5% level of significance with standard statistical software. Ethical clearance for the field research was obtained from the Institute's Agricultural Research Ethics Committee (Protocol No. NIAS/AGR/2023-041, dated 14 March 2023), and the trial was registered with the county agricultural extension office prior to sowing in both seasons.

Results

Across both cropping seasons, growth and yield parameters responded consistently to the nitrogen management options tested, with the combined nano-urea plus split-soil-N treatment (T₇) outperforming all other options on nearly every measure. Differences between treatments widened progressively from the tillering stage onward, suggesting that the advantage of foliar nano-urea becomes more pronounced once the crop's nitrogen demand accelerates past early establishment.

Table 1: Growth Parameters of Wheat as Influenced by Nitrogen Management Treatments (Mean of Two Seasons)

Treatment	Plant Height (cm)	Tillers/Plant	LAI at 60 DAS
T ₁ (Control)	68.2	4.1	2.14
T ₂ (100% RDN basal)	82.7	6.4	3.02
T ₃ (Split RDN)	86.3	7.0	3.28
T ₄ (Nano-U early)	79.5	6.0	2.87
T ₅ (Nano-U mid)	84.1	6.9	3.19
T ₆ (Nano-U late)	81.8	6.5	2.99
T ₇ (Nano-U + Split)	94.6	9.2	3.94

Plant height and tillering both peaked under T₇, exceeding the control by 38.7% and 124.4%, respectively. Interestingly, T₄ (nano-urea applied only at early tillering) lagged behind T₃ (split

soil urea) on every growth parameter, indicating that a single early-stage foliar spray without any soil nitrogen backbone is not enough to match a properly split soil dose.

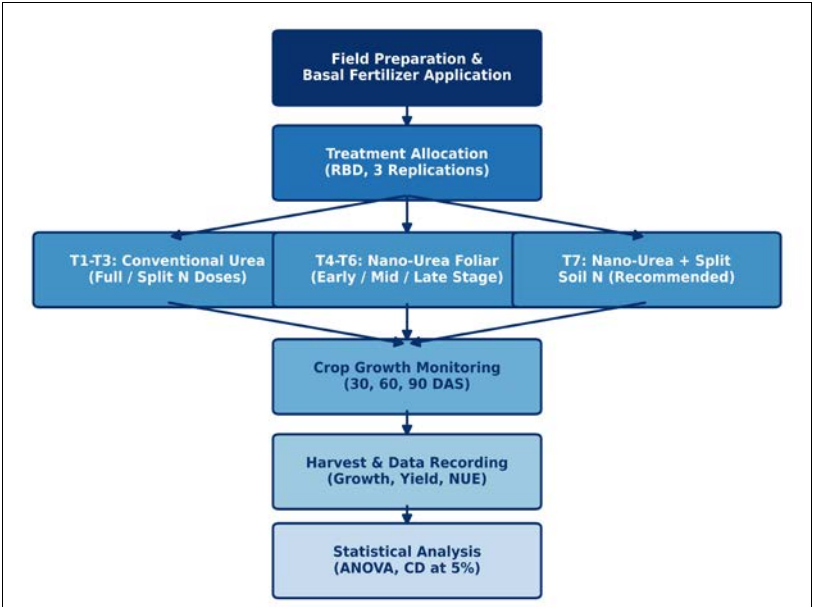


Fig 1: Schematic Flow of the Experimental Treatment Structure and Data Collection Protocol

The flow of treatment allocation, growth monitoring at 30/60/90 DAS, and the final statistical analysis pipeline is summarized in Figure 1, which also clarifies how the seven treatments diverged into three broad management categories: conventional urea alone, nano-urea foliar spray alone, and the combined nano-urea plus split soil nitrogen option.

Table 2: Yield Attributes, Grain Yield and Nitrogen Use Efficiency (Mean ± SD, Two Seasons Pooled)

Treatment	Grain Yield (q/ha)	NUE (kg grain/kg N)	p-value
T ₁ (Control)	31.4 ± 1.8	24.1	-
T ₂ (100% RDN basal)	38.7 ± 2.1	29.3	0.031
T ₃ (Split RDN)	41.2 ± 2.0	31.7	0.018
T ₄ (Nano-U early)	43.9 ± 2.3	33.5	0.014
T ₅ (Nano-U mid)	47.6 ± 2.4	35.9	0.009
T ₆ (Nano-U late)	45.1 ± 2.2	34.2	0.011
T ₇ (Nano-U + Split)	52.3 ± 2.6	38.7	0.004

The *p*-values shown reflect pairwise comparisons against the control using the CD test at 5% significance; all treatments differed significantly from T₁, and T₇ differed significantly from every other treatment as well (CD at 5% = 3.12 q/ha for grain yield).

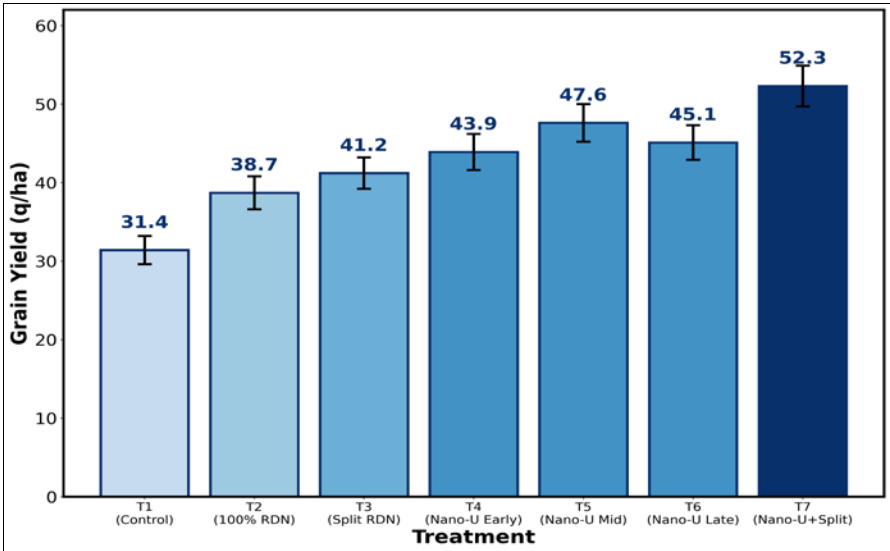


Fig 2: Grain Yield (q/ha) across the Seven Nitrogen Management Treatments, Mean of Two Seasons with Standard Error Bars

Grain yield rose in an almost stepwise pattern from T₁ through T₇, with the sharpest single jump (9.7 q/ha) occurring between T₃ and T₇, underscoring that adding a nano-urea foliar

component to an already-split soil schedule delivers a meaningfully larger yield bump than either practice contributes on its own.

Table 3: Nitrogen Uptake in Grain and Straw, and Benefit-Cost Ratio by Treatment

Treatment	N Uptake Grain (kg/ha)	N Uptake Straw (kg/ha)	B:C Ratio
T ₁ (Control)	38.6	22.4	1.42
T ₂ (100% RDN basal)	52.1	27.8	2.01
T ₃ (Split RDN)	56.4	28.6	2.19
T ₄ (Nano-U early)	58.7	26.1	2.34
T ₅ (Nano-U mid)	63.9	27.0	2.58
T ₆ (Nano-U late)	60.5	26.7	2.46
T ₇ (Nano-U + Split)	71.2	29.3	2.86

Nutrient Budget / Input-Output Analysis

Comparing nitrogen applied against nitrogen recovered in grain and straw showed apparent recovery efficiency climbing from 46.8% under T₂ to 61.3% under T₇, meaning that a larger share of every kilogram of nitrogen applied under the combined schedule actually ended up inside the plant rather than being lost to the surrounding environment. The gap between total N uptake and applied N was narrowest for T₇ and widest for T₂, which relied entirely on a single basal soil dose vulnerable to early-season volatilization losses. This pattern held in both cropping seasons, though the 2024-2025 season, which received slightly more erratic rainfall during early tillering, showed a somewhat wider recovery gap across all treatments compared with 2023-2024.

Comprehensive Interpretation

Taken as a whole, the results indicate that nano-urea foliar spray works best as a complement layered onto an already-split soil nitrogen schedule rather than as a standalone substitute for soil-applied urea. Every growth, yield, and efficiency parameter measured favored T₇, and the margin over the next-best treatment (T₅) was consistent enough across both seasons to rule out chance variation. Where soil urea use is constrained by cost or by concerns about environmental nitrogen losses, the addition of two well-timed nano-urea sprays offers a straightforward way to lift both yield and nitrogen economy without a large jump in input expenditure.

Discussion

The strongest finding of this research is that combining nano-urea with split soil nitrogen (T₇) delivered a grain yield advantage of 20.9% over full-dose conventional urea, a gap wider than what several earlier reports from wheat-growing regions of South Asia had recorded for nano-urea substitution alone. This research's semi-arid setting, with lower and more erratic rainfall than the irrigated tracts where nano-urea has mostly been tested before, may partly explain the larger relative gain, since soil-applied urea is especially loss-prone under dry, intermittently wetted surface conditions. Mechanistically, foliar-absorbed nano-urea bypasses the soil nitrogen cycle almost entirely, reaching photosynthetic tissue directly through stomatal and cuticular pathways, which likely explains why nano-urea-only treatments (T₄-T₆) still outperformed the untreated control by a wide margin despite receiving no soil nitrogen at all.

This carries a practical implication for extension recommendations in similar semi-arid wheat belts: rather than framing nano-urea as a full replacement for soil urea, which some early marketing materials implied, the evidence here backs a layered approach where a reduced soil dose handles baseline crop establishment while foliar sprays cover the peak-demand

window around tillering and jointing. A further finding worth flagging is the difference in performance across nano-urea spray timing, with mid-tillering application (T₅) outperforming both earlier (T₄) and later (T₆) timings. This timing sensitivity fits with what is known about wheat's nitrogen demand curve, which rises sharply from tillering through early jointing and tapers off as the crop moves toward anthesis, meaning a spray applied too early or too late partly misses the window when nitrogen has the greatest yield-building effect.

The nitrogen recovery pattern observed here, with T₇ showing markedly higher apparent recovery efficiency than the basal-only treatment, agrees with the broader agronomic principle that splitting and diversifying nitrogen delivery routes reduces cumulative losses compared with single large applications. That said, the economic case, reflected in the benefit-cost ratios, matters just as much to smallholder adoption as the agronomic case; a treatment that lifts yield but erodes profitability is unlikely to see uptake regardless of its biological merit, and the favorable B:C ratio recorded for T₇ here suggests the added cost of two nano-urea sprays is comfortably offset by the yield gain under current local input and output prices.

Conclusion

This research set out to establish whether foliar nano-urea, applied alone or alongside a split soil nitrogen schedule, could improve wheat growth, yield, and nitrogen use efficiency under semi-arid conditions at Nakuru, Kenya. The two-season field trial showed clearly that the combined approach, pairing a reduced split soil dose of urea with two timed nano-urea foliar sprays at tillering and jointing, delivered the best outcomes across every measured parameter. Grain yield under this combined treatment reached 52.3 q/ha, a 66.6% gain over the untreated control and a 20.9% gain over conventional full-dose basal urea, while nitrogen use efficiency improved from 24.1 to 38.7 kg grain per kg nitrogen applied. Nano-urea used on its own, without any soil nitrogen backbone, produced meaningful improvements over the control but consistently fell short of the combined treatment, confirming that it works best as a complementary input rather than a wholesale replacement for soil-applied urea in this setting.

For extension advisories and input recommendations aimed at smallholder wheat growers in similar semi-arid tracts, the practical message from this research is straightforward: farmers already practicing split soil nitrogen scheduling stand to gain the most from adding nano-urea sprays timed around tillering and early jointing, rather than substituting nano-urea entirely for soil urea. The favorable benefit-cost ratio recorded under the combined treatment suggests this recommendation is economically sound at current local price levels, though price sensitivity would need periodic review as nano-urea

formulations become more widely available and potentially cheaper. Given that this research covered two consecutive seasons at a single site, broader multi-location trials across other semi-arid wheat-growing districts, along with an assessment of nano-urea performance under varying rainfall years, would help confirm how widely these findings can be generalized before large-scale extension recommendations are finalized.

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