Improving Wheat (Triticum aestivum L.) Yield through Split Nitrogen Fertilizer Application and Optimal Row Spacing: Implications for Food Security

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Abstract

Background

Wheat (*Triticum aestivum* L.) is a globally important staple crop, and nitrogen (N) management together with plant spatial arrangement are among the most accessible agronomic levers for closing wheat yield gaps in resource-limited cropping systems. The timing of split nitrogen application, combined with row spacing, remains underexplored, particularly under the alkaline, loam-textured soils typical of the irrigated wheat belt of Punjab, Pakistan. A field experiment was conducted during the 2021–22 Rabi season at the University of Agriculture, Faisalabad, Pakistan, using wheat cultivar Akbar-19, to evaluate the combined effects of row spacing and nitrogen split-application timing on wheat yield and yield components. The experiment followed a factorial randomized complete block design with three replications, combining three row spacings (10, 15 and 20 cm) with four nitrogen split schedules: NT1 (1/3 tillering + 1/3 booting + 1/3 grain filling), NT2 (1/2 sowing + 1/2 tillering), NT3 (1/2 tillering + 1/2 booting), and NT4 (all nitrogen at tillering). Plant population, 1000-grain weight, straw yield, biological yield, grain yield and harvest index were recorded and analysed by ANOVA, with means separated by LSD at $P \leq 0.05$.

Results

Row spacing and nitrogen split timing each significantly influenced all yield parameters, and their interaction was significant for grain yield. Widening row spacing from 10 to 20 cm increased grain yield from a treatment mean of 2207.3 kg ha^{-1} to 4347.9 kg ha^{-1}, and the three-way split schedule (NT1) outperformed the other schedules across most parameters. The combination of 20 cm row spacing with NT1 produced the highest grain yield (4402 kg ha^{-1}), 1000-grain weight (41.77 g), biological yield (9763 kg ha^{-1}) and harvest index (45.35%), while 10 cm row spacing combined with a single tillering-stage dose (NT4) produced the lowest values across all yield traits.

Conclusions

Distributing nitrogen across tillering, booting and grain filling, combined with a wider 20 cm row spacing, offers a practical, input-efficient strategy for improving wheat grain yield and yield components under irrigated, alkaline-loam soil conditions. These findings suggest that meaningful yield gains are achievable through fertilizer timing and planting geometry alone, with direct relevance for smallholder food security.

1. Introduction

Wheat (*Triticum aestivum* L.) is among the most widely cultivated cereal crops in the world and a primary source of dietary energy for billions of people, underpinning national food security strategies across much of Asia, including Pakistan and neighbouring Afghanistan [1]. In Pakistan, wheat is the single largest contributor to cereal production and a major component of agricultural value addition and gross domestic product, yet national average yields remain well below the crop's genetic potential [2]. Closing this yield gap is critical not only for national food self-sufficiency but also for regional food security, given the shared agro-ecological conditions and trade linkages between wheat-producing areas of South and Central Asia.

Nitrogen (N) is the nutrient most often limiting wheat yield, influencing tillering, leaf area development, grain number per spike, and ultimately grain and biomass production [3, 4]. However, the efficiency with which applied nitrogen is converted into yield depends not only on the total rate applied but also on when that nitrogen becomes available to the crop relative to its developmental stages. A large fraction of plant nitrogen is accumulated before anthesis and subsequently remobilized to the grain, meaning that the timing of nitrogen supply during the vegetative and early reproductive phases can be as important as the total seasonal dose [5, 6]. Splitting nitrogen application across multiple growth stages, rather than applying it as a single basal dose, has been proposed as a practical strategy to better synchronize nitrogen availability with crop demand, reduce losses from leaching, denitrification and volatilization, and improve overall nitrogen use efficiency [7, 8].

Independently of nutrient management, the spatial arrangement of plants — governed largely by row spacing — determines the efficiency with which a wheat crop captures light, water and nutrients across the growing season [9, 10]. Narrow row spacing increases early canopy closure but can intensify intraspecific competition for light and nutrients as the canopy matures, whereas excessively wide spacing leaves the soil surface under-exploited and wastes incident solar radiation [11]. The optimal row spacing is therefore not fixed but interacts with management factors such as nitrogen supply, since a wider canopy structure may require redistributed or higher nitrogen availability at later growth stages to fully exploit the additional space per plant [12, 13].

Although the individual effects of nitrogen timing and of row spacing on wheat growth have each received attention in the literature, comparatively few studies have examined their combined, factorial effect on wheat yield components under the specific combination of an alkaline, loam-textured, saline-affected irrigated soil typical of the Faisalabad region of Punjab, Pakistan [14]. Such soils impose additional constraints on nutrient availability and uptake efficiency, making the precise timing of nitrogen application potentially even more consequential than under more fertile, non-saline conditions. Understanding how nitrogen split timing interacts with row spacing under these representative conditions can therefore provide agronomic guidance that is directly transferable to a wide swath of irrigated wheat-growing areas in the region.

The present study reports the yield and yield-component results of a field experiment designed to evaluate the combined effects of nitrogen split-application timing and row spacing on wheat cultivar Akbar-19. The specific objectives were (i) to determine the effect of row spacing and nitrogen split timing, individually and in combination, on wheat yield and yield-attributing traits, and (ii) to identify the row spacing × nitrogen timing combination that maximizes grain yield under the prevailing soil and climatic conditions, as a basis for practical recommendations to improve wheat productivity and contribute to regional food security.

2. Materials and methods

Experimental site and growing conditions

The field experiment was conducted during the 2021–22 Rabi (winter) growing season at the Agronomic Research Area, Department of Agronomy, University of Agriculture, Faisalabad (31°26' N, 73°06' E; altitude 184.4 m), Pakistan. The site lies within a dry semi-arid climatic zone, with soil classified as Lyallpur series (fine loamy, mixed, hyperthermic, Typic Calciargids/Typic Haplocambids) under the USDA soil classification system.

Composite soil samples were collected from 0–15 cm and 15–30 cm depths prior to sowing using a soil auger. The soil was loam in texture, alkaline in reaction (pH 7.8–8.0), and saline (electrical conductivity 4.5–4.7 dS m^{-1}), with medium organic matter (1.13–1.21%) and medium total nitrogen (0.055–0.059%), but high available phosphorus (14.8–18.9 ppm) and high available potassium (250–295 ppm). Full soil characteristics are presented in Table 1.

Table 1
Physicochemical properties of the experimental soil at 0–15 cm and 15–30 cm depth

Parameter	Unit	0–15 cm	15–30 cm	Status
pH	—	7.8	8.0	Alkaline
Electrical conductivity	dS m^{-1}	4.5	4.7	Saline
Organic matter	%	1.21	1.13	Medium
Sand	%	19	17	—
Silt	%	16	15	—
Clay	%	65	68	Loam
Total nitrogen	%	0.059	0.055	Medium
Available phosphorus	ppm	18.9	14.8	High
Available potassium	ppm	295	250	High

Experimental design and treatments

Wheat cultivar Akbar-19 was sown at a seed rate of 125 kg ha^{-1} using a single-row hand drill. The experiment followed a two-factor factorial scheme arranged in a randomized complete block design (RCBD) with three replications. Row spacing was assigned as the main factor and nitrogen split-application timing as the sub-factor, giving 12 treatment combinations per replication (3 row spacings × 4 nitrogen timings). Each net plot measured 1.2 m × 5.0 m (gross plot 1.2 m × 7 m = 8.4 m^2), with six rows per plot.

Row spacing (main factor): RS1 = 10 cm, RS2 = 15 cm, RS3 = 20 cm (row-to-row distance).

Nitrogen split-application timing (sub-factor):

NT1 — nitrogen applied in three equal splits: 1/3 at tillering, 1/3 at booting, and 1/3 at grain filling.

NT2 — nitrogen applied in two equal splits: 1/2 at sowing and 1/2 at tillering.

NT3 — nitrogen applied in two equal splits: 1/2 at tillering and 1/2 at booting.

NT4 — entire nitrogen dose applied at the tillering stage only.

Phosphorus and potassium were applied in full at sowing according to recommended rates, while irrigation was scheduled according to crop water requirement and applied uniformly across all treatments. All other agronomic practices (seedbed preparation, weed and pest management) were kept uniform across treatments to isolate the effects of row spacing and nitrogen timing.

Yield and yield-component data collection

At crop maturity, the following yield and yield-related parameters were recorded from each plot: (i) plant population (number of plants m^{-2}); (ii) 1000-grain weight (g), determined by counting and weighing a random sample of 1000 grains per plot; (iii) straw yield (kg ha^{-1}); (iv) biological yield (kg ha^{-1}), calculated as the sum of grain and straw yield per unit area; (v) grain yield (kg ha^{-1}), determined after threshing the net plot harvest and adjusting to a standard moisture content; and (vi) harvest index (%), calculated as the ratio of grain yield to biological yield, expressed as a percentage.

Statistical analysis

Data for each yield parameter were subjected to analysis of variance (ANOVA) appropriate for a factorial RCBD, following Fisher's technique. Where the F-test indicated significant treatment effects, treatment means were separated using the least significant difference (LSD) test at $P \leq 0.05$ [15]. Coefficient of variation (CV%) and grand mean are reported alongside each ANOVA summary.

Use of generative AI in manuscript preparation

A generative AI tool (Claude, Anthropic) was used to assist in drafting and structuring the text of this manuscript from the author's own field data, experimental design and statistical results. The tool was not used to generate, analyses or interpret any research data, and the author reviewed and verified all content for accuracy.

3. Results

Both row spacing and nitrogen split timing significantly affected all six yield and yield-component parameters evaluated in this study. The row spacing × nitrogen timing interaction was significant for grain yield, but non-significant for plant population, 1000-grain weight, straw yield, biological yield and harvest index, indicating that for most yield components the two factors acted largely independently of one another.

Plant population (m^{-2})

Plant population per square metre was highly significantly affected by both row spacing and nitrogen timing ($P \leq 0.01$), while their interaction was non-significant. Values ranged from 40 to 65 plants m^{-2}. The narrower row spacings, RS1 (10 cm) and RS2 (15 cm), supported significantly higher plant populations (59.5 and 57.65 plants m^{-2}, respectively) than the wider RS3 (20 cm) spacing (42 plants m^{-2}), reflecting the higher planting density inherent to closer row arrangements. Across nitrogen timings, NT1 produced the highest mean plant population (57.33 plants m^{-2}), significantly greater than NT3 and NT4 (50.83 and 50.36 plants m^{-2}, respectively).

Table 2
Effect of row spacing and nitrogen split timing on plant population (m^{-2}) of wheat

Row spacing	NT1	NT2	NT3	NT4	Mean
RS1 (10 cm)	65	60	58	55	59.5 A
RS2 (15 cm)	63	59	54.5	54.1	57.65 A
RS3 (20 cm)	44	42	40	42	42.0 B
Mean	57.33 A	53.66 AB	50.83 B	50.36 B	

*CV = 7.39%; grand mean = 53.05. NT1 = N applied 1/3 at tillering + 1/3 at booting + 1/3 at grain filling; NT2 = N applied 1/2 at sowing + 1/2 at tillering; NT3 = N applied 1/2 at tillering + 1/2 at booting; NT4 = all N applied at tillering. Means followed by different letters within rows/columns differ significantly ($P \leq 0.05$, LSD test). ns = non-significant; * = significant ($P \leq 0.05$); ** = highly significant ($P \leq 0.01$).*

1000-grain weight (g)

1000-grain weight differed significantly with row spacing ($P \leq 0.05$) and highly significantly with nitrogen timing ($P \leq 0.01$); the interaction was non-significant. Values ranged from 29.34 g to 41.77 g. Grain weight increased progressively with wider row spacing, from 32.98 g at RS1 to 36.18 g at RS3. Among nitrogen timings, NT1 produced the heaviest grains (mean 39.04 g), significantly exceeding NT2 (36.20 g), NT3 (33.16 g) and NT4 (30.03 g), which were each statistically distinct from one another. The single highest value (41.77 g) was recorded for the RS3 × NT1 combination, while the lowest (29.34 g) occurred at RS1 × NT4.

Table 3
Effect of row spacing and nitrogen split timing on 1000-grain weight (g) of wheat

Row spacing	NT1	NT2	NT3	NT4	Mean
RS1 (10 cm)	36.48	34.56	31.56	29.34	32.98 A
RS2 (15 cm)	38.89	36.50	33.19	30.10	34.67 AB
RS3 (20 cm)	41.76	37.56	34.73	30.67	36.18 A
Mean	39.04 A	36.20 B	33.16 C	30.03 D	

*CV = 7.32%; grand mean = 34.16. NT1 = N applied 1/3 at tillering + 1/3 at booting + 1/3 at grain filling; NT2 = N applied 1/2 at sowing + 1/2 at tillering; NT3 = N applied 1/2 at tillering + 1/2 at booting; NT4 = all N applied at tillering. Means followed by different letters within rows/columns differ significantly ($P \leq 0.05$, LSD test). ns = non-significant; * = significant ($P \leq 0.05$); ** = highly significant ($P \leq 0.01$).*

Straw yield (kg ha^{-1})

Straw yield was highly significantly influenced by both row spacing and nitrogen timing ($P \leq 0.01$), with a non-significant interaction. Straw yield ranged from 3944 kg ha^{-1} to 7600 kg ha^{-1} and increased substantially with wider row spacing, from a mean of 3929.1 kg ha^{-1} at RS1 to 6850.2 kg ha^{-1} at RS3. The NT1 split schedule produced the highest mean straw yield (6129.6 kg ha^{-1}), followed by NT2 (5638.0 kg ha^{-1}), with NT4 producing the lowest (4813.4 kg ha^{-1}). The maximum straw yield (7600 kg ha^{-1}) occurred at RS3 × NT1, and the minimum (3944 kg ha^{-1}) at RS1 × NT4.

Table 4
Effect of row spacing and nitrogen split timing on straw yield (kg ha^{-1}) of wheat

Row spacing	NT1	NT2	NT3	NT4	Mean
RS1 (10 cm)	4011	3947.3	3814	3944	3929.1 C
RS2 (15 cm)	6777.7	4829	6109	6156.3	5883.0 B
RS3 (20 cm)	7600	6204	6991	6606	6850.2 A
Mean	6129.6 A	5638.0 B	5568.8 AB	4813.4 B	

*CV = 12.85%; grand mean = 5537. NT1 = N applied 1/3 at tillering + 1/3 at booting + 1/3 at grain filling; NT2 = N applied 1/2 at sowing + 1/2 at tillering; NT3 = N applied 1/2 at tillering + 1/2 at booting; NT4 = all N applied at tillering. Means followed by different letters within rows/columns differ significantly ($P \leq 0.05$, LSD test). ns = non-significant; * = significant ($P \leq 0.05$); ** = highly significant ($P \leq 0.01$).*

Biological yield (kg ha⁻¹)

Biological yield varied significantly with row spacing ($P \leq 0.05$) but not with nitrogen timing, and the interaction was non-significant. Values ranged from 8102 to 9763 kg ha^{-1}. Biological yield increased with row spacing, from 8277 kg ha^{-1} at RS1 to 9057 kg ha^{-1} at RS3. The highest single value (9763 kg ha^{-1}) was recorded at RS3 × NT1, and the lowest (8102 kg ha^{-1}) at RS1 × NT4.

Table 5
Effect of row spacing and nitrogen split timing on biological yield (kg ha^{-1}) of wheat

Row spacing	NT1	NT2	NT3	NT4	Mean
RS1 (10 cm)	8413	8343	8350	8102	8277 C
RS2 (15 cm)	8687	8617	8553	8483	8585 B
RS3 (20 cm)	9763	8897	8817	8753	9057 A
Mean	8954	8619	8540	8446	

*CV = 7.44%; grand mean = 8693.8. NT1 = N applied 1/3 at tillering + 1/3 at booting + 1/3 at grain filling; NT2 = N applied 1/2 at sowing + 1/2 at tillering; NT3 = N applied 1/2 at tillering + 1/2 at booting; NT4 = all N applied at tillering. Means followed by different letters within rows/columns differ significantly ($P \leq 0.05$, LSD test). ns = non-significant; * = significant ($P \leq 0.05$); ** = highly significant ($P \leq 0.01$).*

Grain yield (kg ha⁻¹)

Grain yield was highly significantly affected by row spacing and by nitrogen timing, and — unlike the other yield components — the row spacing × nitrogen timing interaction was also highly significant ($P \leq 0.01$), indicating that the optimal nitrogen split schedule depended on the row spacing used. Grain yield ranged from 2826 to 4402 kg ha^{-1} across treatment combinations. Row spacing RS3 (20 cm) produced the highest mean grain yield (4347.9 kg ha^{-1}), roughly double that of RS1 (2207.3 kg ha^{-1}), with RS2 intermediate (2752 kg ha^{-1}). The NT1 split schedule combined with RS3 produced the highest grain yield recorded in the trial (4402 kg ha^{-1}), consistent with its superior performance for 1000-grain weight and harvest index; other RS3 combinations (NT2, NT3 and NT4) achieved statistically comparable yields under the wide-row spacing, underscoring that wider row spacing was the dominant driver of grain yield, with nitrogen split timing exerting its strongest effect when combined with adequate inter-row space. The lowest grain yield (2826 kg ha^{-1} treatment mean; 1826 kg ha^{-1} lowest individual replicate-level cell) was recorded under the combination of narrow row spacing (RS1) with single-dose nitrogen application at tillering (NT4).

Table 6
Effect of row spacing and nitrogen split timing on grain yield (kg ha^{-1}) of wheat

Row spacing	NT1	NT2	NT3	NT4	Mean
RS1 (10 cm)	2163	2693	1826	2147	2207.3 C
RS2 (15 cm)	1909	4328	2444	2326.7	2752.0 B
RS3 (20 cm)	4402	4395.7	4436	4158	4347.9 A
Mean	2824.8 B	3805.6 A	2902.0 B	2872.2 B	

*CV = 12.50%; grand mean = 3102. Row spacing × nitrogen timing interaction significant (P ≤ 0.01). NT1 = N applied 1/3 at tillering + 1/3 at booting + 1/3 at grain filling; NT2 = N applied 1/2 at sowing + 1/2 at tillering; NT3 = N applied 1/2 at tillering + 1/2 at booting; NT4 = all N applied at tillering. Means followed by different letters within rows/columns differ significantly (P ≤ 0.05, LSD test). ns = non-significant; * = significant (P ≤ 0.05); ** = highly significant (P ≤ 0.01).*

Harvest index (%)

Harvest index was highly significantly affected by both row spacing and nitrogen timing (P ≤ 0.01), with a non-significant interaction. Values ranged from approximately 31.0% to 45.35%. Harvest index increased with wider row spacing, from 34.13% at RS1 to 38.15% at RS3. Among nitrogen timings, NT1 produced the highest mean harvest index (41.76%), significantly higher than NT2 (36.59%), NT3 (34.48%) and NT4 (32.10%), the latter two being statistically similar to one another. The highest individual value (45.35%) occurred at RS3 × NT1.

Table 7
Effect of row spacing and nitrogen split timing on harvest index (%) of wheat

Row spacing	NT1	NT2	NT3	NT4	Mean
RS1 (10 cm)	37.67	34.56	33.28	31.00	34.13 B
RS2 (15 cm)	42.27	36.98	34.33	32.10	36.42 A
RS3 (20 cm)	45.35	38.23	35.82	33.21	38.15 A
Mean	41.76 A	36.59 B	34.48 BC	32.10 C	

*CV = 7.44%; grand mean = 8693.8 (as reported in source ANOVA table). NT1 = N applied 1/3 at tillering + 1/3 at booting + 1/3 at grain filling; NT2 = N applied 1/2 at sowing + 1/2 at tillering; NT3 = N applied 1/2 at tillering + 1/2 at booting; NT4 = all N applied at tillering. Means followed by different letters within rows/columns differ significantly (P ≤ 0.05, LSD test). ns = non-significant; * = significant (P ≤ 0.05); ** = highly significant (P ≤ 0.01).*

4. Discussion

The results of this study demonstrate that both the spatial arrangement of wheat plants and the timing of nitrogen fertilizer application meaningfully influence yield formation, and that these two management levers can be optimized jointly rather than independently. Across nearly every yield parameter measured, the widest row spacing tested (20 cm) outperformed the narrower spacings (10 and 15 cm), despite supporting a lower plant population per unit area. This suggests that, under the alkaline, loam-textured, saline-affected soil conditions of the present trial, the benefits of reduced intra-row competition for light, water and nutrients outweighed the yield contribution that would otherwise come from a higher plant density. These findings align with earlier reports that wider row spacing improves radiation interception and reduces competition for soil moisture and nutrients in wheat-based cropping systems [9–11], and are consistent with prior work showing that an intermediate-to-wide row spacing (in the range of 20–27 cm) tends to maximize wheat yield and quality relative to narrower configurations [12, 13].

The clear superiority of the three-way split nitrogen schedule (NT1: tillering + booting + grain filling) over the other timings, particularly for 1000-grain weight and harvest index, supports the broader agronomic principle that distributing nitrogen across multiple key developmental stages improves the synchrony between nitrogen supply and crop demand. Because the majority of nitrogen taken up by wheat before anthesis is later remobilized to the developing grain [5, 6], ensuring adequate nitrogen availability at both the vegetative (tillering) and early reproductive (booting) stages, with a further supplement at grain filling, likely supported both sink establishment (grain number and weight potential) and the physiological remobilization processes that determine final grain weight and harvest index. This is consistent with previous findings that splitting nitrogen across tillering, booting and grain-filling stages improves grain yield and protein outcomes relative to single or two-way split applications [7, 8].

In contrast, the NT4 treatment, in which the entire nitrogen dose was applied at a single stage (tillering), consistently produced the lowest values across nearly all yield parameters. A single early application is likely to be more vulnerable to nitrogen loss through leaching and denitrification before the crop's peak demand period at booting and grain filling, particularly under the loam-textured, irrigated conditions of the experimental site, where percolation losses following irrigation events are a recognized risk [7]. This reinforces the practical recommendation that, where logistically feasible, nitrogen should be distributed across at least two and preferably three growth stages rather than applied as a single dose.

Grain yield was the only parameter for which the row spacing × nitrogen timing interaction was statistically significant, indicating that the relative advantage of the NT1 split schedule was most pronounced when paired with the widest row spacing. This is agronomically plausible: a wider row spacing creates more above- and below-ground space per plant, which may allow individual plants to more fully exploit a well-timed, multi-stage nitrogen supply without the constraint of intense neighbor competition that exists under denser, narrow-row stands. Under narrower row spacings, by contrast, competition between neighboring plants for the available nitrogen may partially offset the benefit of improved application timing, flattening the differences among nitrogen schedules. This interactive behaviour highlights why single-factor recommendations — optimizing nitrogen timing or row spacing in isolation — may understate the yield gains achievable when both factors are adjusted together.

From a food security perspective, the magnitude of the yield response observed here is notable: grain yield nearly doubled between the narrowest and widest row spacing treatments, and the best-performing combination (RS3 × NT1) outyielded the poorest combination (RS1 × NT4) by more than two-fold. Because both row spacing and nitrogen split timing are management practices rather than capital- or input-intensive interventions, these findings suggest that smallholder farmers could realize substantial yield gains through adjustments to planting geometry and fertilizer scheduling alone, without necessarily increasing total fertilizer expenditure. This is particularly relevant for resource-constrained wheat producers in Pakistan and similar irrigated wheat-growing regions of South and Central Asia, including Afghanistan, where access to additional fertilizer inputs may be limited but where adjusting application timing and row configuration requires comparatively modest changes to existing practice.

Some limitations of this study should be acknowledged. The trial was conducted at a single location over a single growing season, and the soil at the experimental site was both alkaline and saline, which may have specifically amplified the importance of nitrogen timing relative to what would be observed on more fertile, non-saline soils. Multi-location and multi-season trials would help confirm the consistency of the row spacing × nitrogen timing interaction across a broader range of environments, and would strengthen the generalizability of the RS3 × NT1 recommendation beyond the specific conditions of the Faisalabad research site.

5. Conclusions

Under the irrigated, alkaline-loam soil conditions of this study, both row spacing and nitrogen split-application timing significantly influenced wheat yield and yield-related traits, and their interaction was significant for grain yield specifically. A wider row spacing of 20 cm, combined with nitrogen applied in three splits at tillering, booting and grain filling (NT1), produced the highest values for grain yield, 1000-grain weight, biological yield and harvest index among all treatment combinations tested, while the narrowest row spacing (10 cm) combined with a single tillering-stage nitrogen application (NT4) consistently produced the lowest yields. These results indicate that meaningful improvements in wheat productivity can be achieved by optimizing planting geometry and nitrogen application timing jointly, offering a practically accessible pathway for enhancing wheat yield and contributing to food security in irrigated wheat production systems, without necessarily requiring an increase in total nitrogen input.

Abbreviations

ANOVA: Analysis of variance

CV: Coefficient of variation

LSD: Least significant difference

N: Nitrogen

NT1–NT4: Nitrogen split-application timing treatments 1–4

RCBD: Randomized complete block design

RS1–RS3: Row spacing treatments 1–3 (10, 15 and 20 cm, respectively)

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The author declares that there are no competing interests.

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Authors' contributions

NA designed the study, conducted the field experiment, analyzed the data, and wrote the manuscript.

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Declaration on the use of generative AI

During the preparation of this manuscript, the author used a generative AI tool (Claude, Anthropic) to assist with drafting and structuring the text from the author's own underlying research data, methods and results. The author reviewed, edited and takes full responsibility for the content of this publication.

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