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PJMLS OPEN ACCESS

Print ISSN: 2707-4471. Online ISSN: 2707-448X

Research Article	Pak-Euro Journal of Medical and Life Sciences
DOI: 10.31580/pjmls.v8i2.3265	Copyright © All rights are reserved by Corresponding Author
Vol. 8 No. 2, 2025: pp. 249-256	
www.readersinsight.net/pjmls	**Revised:** June 13, 2025 **Accepted:** June 17, 2025
Submission: February 28, 2025	**Published Online:** June 19, 2025

IRRIGATED WHEAT NITROGEN MANAGEMENT: IDENTIFYING OPTIMAL APPLICATION TIMING AND SPLITING

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Abstract

Bread wheat production in Punjab, Pakistan, is hindered by low available soil nitrogen (N) and reduced plant-use-efficiency. A well-balanced N supply is crucial for achieving higher grain yields, but accurately applying N fertilizer remains a challenge for wheat farmers in semiarid regions. This 2-year study (2023-24 and 2024-25) investigated the optimal timing and splits of N applications for maximizing wheat growth and grain yield in Attock and Gujrat, Pakistan. Our results showed that T3, where N was applied in three equal splits (at sowing, at first irrigation, and at second irrigation), significantly outperformed other N application splitting and timings, resulting in the highest wheat yield at both locations and growing seasons. Notably, this treatment also significantly improved the post-harvest soil fertility status, viz., soil organic matter (SOM), available phosphorus (P2O5), and extractable potassium (K2O), compared to pre-sowing soil fertility status at both locations and growing seasons. The findings of this study suggest that N fertilizer recommendations should consider the physiological processes of wheat that determine N uptake need and behavior. Therefore, based on the results of the current experiment, we recommend that N fertilizer application should be split into three equal episodes for improved wheat productivity in semi-arid regions. We further recommend the validation of these results in other climatic zones and variable soils.

Keywords: *Irrigated areas, Nitrogen fertilization, Pakistan, Split application, Yield response*

INTRODUCTION

Wheat (*Triticum aestivum* L.), is one of the most important cereal crop grown throughout the globe and Pakistan being a staple food to meet nutritional requirements with higher calories and protein of an average human diet (1). Wheat requires a balanced quantity of nutrient elements viz., macronutrients (nitrogen, phosphorus, potassium, sulfur) and micronutrients (iron, manganese, zinc, copper, boron, molybdenum) for optimal growth and yield. Therefore, proper soil nutrient management is crucial to obtain maximum crop yield and quality. The nutrient management require a careful strategy for adequate replenishment. Because specific nutrient requirements and deficiency symptoms can vary depending on the wheat variety, soil type, and growing conditions. Proper soil testing and plant tissue analysis can help determine the specific nutrient needs of a wheat crop (2).

Among 18 essential nutrient elements, N is the most crucial for optimal crop production and global food security. However, N is the most fragile element and subjected to numerous losses after application (3). In attempt to meet N deficiency, indiscriminate N use is creating many economic and environmental concerns. The excessive N fertilizer use leads to significant environmental issues, including soil acidification, groundwater pollution, and greenhouse gas emissions (GHGs). Furthermore, excessive N application poses significant economic burden to stimulate crop input cost (4). Similarly, lower N application becomes an obstacle to achieve yield goals. Therefore, optimizing N management is vital for sustainable agriculture, particularly for wheat, a staple crop providing 19% of global calories and 21% of protein (5). Wheat yield, grain protein content, and water productivity are significantly influenced by N addition (6). Previous studies have examined the individual impacts of N fertilizer management practices on wheat yield (7). However, the effects of N addition vary depending on soil conditions, climate variables, and crop management practices (8).

Traditionally, single N applications were recommended, but recent studies suggest that split applications can lead to better responses (9). However, changing climate patterns, particularly in Pakistan, are expected to continue until 2040 (10), posing challenges for wheat production. To mitigate N loss and optimize utilization, focusing on application timing and rates according to plant growth stages is essential. This approach can reduce input costs, increase nitrogen-use-efficiency (NUE), and improve grain quality (11). Split N applications can optimize growth, grain N content, protein, and baking quality (12). Research has shown that split N applications during growth stages can enhance grain yield, crude protein, and NUE (13). Nitrogen fertilization plays a vital role in yield and quality, and adjusting application rates according to crop growth stages can optimize N uptake and utilization (14). Proper N rates and application timings are crucial for good crop husbandry, grain quality, and increased NUE (15). Given the recent climate shift in Pakistan, optimizing N application timing is critical for addressing grain yield and quality (16). This study aims to i) investigate best N application timing and splitting of N recommended dose, ii) impact of N application timing and on wheat yield, in two different regions.

METHODOLOGY

DESCRIPTION OF SITE

Two years field experiments were conducted at farmers' field at Attock and Gujrat during 2023-24 and 2024-25. Attock has a humid subtropical climate characterized by hot, humid summers and cool to mild winters. Summer temperatures can reach 50 °C, while winter lows can drop to -2°C. The average rainfall is 783 mm. The soils of Attock district in Pakistan, predominantly found in the Potohar region, are characterized by being mostly medium (loam) to light (sandy loam) in texture. The majority of soils have a pH about 7.5-8.5, indicating normal and suitable conditions for nutrient uptake. However, many soils are deficient in organic matter and available phosphorus, and some areas show deficiencies in micronutrients like manganese and boron. While Gujrat has moderate climate, which is hot in summer and cold in winter. During peak summer, the day temperature rises up to 50 °C, but the hot spells are comparatively shorter due to proximity of Azad Kashmir Mountains. The winter months are very pleasant and the minimum temperature may fall below 2 °C. The average rainfall in Gujrat it is 522 mm. he soils of Gujrat, Pakistan are predominantly clayey, with significant portions classified as loam and sandy loam. A significant portion of the soils in Gujrat are saline, saline-sodic, or sodic. Additionally, a substantial number of samples show a low level of organic matter.

EXPERIMENT DESIGN AND TREATMENTS

To plant the crop, seedbed was prepared as recommended for wheat in the area. The experiment was laid out in randomized complete block design using four replications. The treatments of experiment were i)160-114-60 (1/2 N at sowing and 1/2 at 1st irrigation), ii) 160-114-60 (2/3 N at sowing and 1/3 at 1st irrigation), iii) 160-114-60 (1/3 N at sowing, 1/3 N at 1st irrigation, 1/3 N at 2nd irrigation), iv) 160-114-60 (1/4 N at sowing, 1/2 N at 1st irrigation, 1/4 N at 2nd irrigation). Pre-basic seeds of wheat (cv. Urooj-2022) recommended for both rain-fed and irrigated area were planted in first week of November every year using seed rate 120 kg ha^{-1}. Planting was made using mechanical drill. Phosphorus (114 kg ha^{-1}) and potassium (60 kg ha^{-1}) were applied as recommend at the time of the seedbed preparation using single super phosphate (18%) and Muriate of potash (60%). All management practices as per farmer practice were used at both locations.

CROP AND SOIL ANALYSES

At harvest of wheat crop samples of measurement 3 m × 3 m grid were harvested to determine wheat biomass and grain yield. Random composite soil samples 0-15 and 15-30 cm were collected from each experimental site before sowing and one composite soil sample 0-15 and 15-30 depths were collected at post-harvest. These collected soil samples were transported to the Soil and Water Testing Laboratory in Rawalpindi for subsequent physicochemical evaluations. The stored soil samples were then subjected to analyses for soil texture, soil reaction (pH), electrical conductivity (EC), soil organic matter (SOM), available phosphorus (P_2O_5), and extractable potassium (K_2O) at the aforementioned laboratory. Soil pH was determined using a soil-to-water ratio of 1:1, while EC was measured at a ratio of 1:10 soil to water, as outlined by Sajida Perveen et al. (17). SOM content was assessed via titration method (18), P_2O_5 was extracted using 0.5 M $NaHCO_3$ (19), and K_2O was extracted with 1 M CH_3COONH_4 (20). Samples prepared for P_2O_5 and K_2O were analyzed using a spectrometer and flame-photometry, respectively. Soil texture was determined according to the method described by Gee and Bauder (21).

Table I. Physicochemical characteristics of soils at before sowing of wheat

Year	2023-24				2024-25			
Location	Attock		Gujrat		Attock		Gujrat	
Depth	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30
pH	7.36	7.38	7.81	7.84	7.27	7.31	7.91	7.88
EC	0.49	0.46	1.02	0.89	0.52	0.56	1.11	1.02
OM	0.76	0.71	0.84	0.76	0.69	0.63	0.92	0.83
P_2O_5	3.1	2.3	7.2	6.9	3.9	3.4	7.9	7.4
K_2O	66	40	123	108	61	44	131	124

STATISTICAL ANALYSIS

The data were subjected to analysis of variance (ANOVA) using a randomized complete block design (22). Statistical analysis was performed using Statistics 8.1 software. Treatment means were compared using the least significant difference (LSD) test at a 5% probability level.

RESULTS & DISCUSSION

WHEAT GRAIN YIELD

In both growing seasons, N treatments significantly ($P < 0.05$) affected the grain yield of wheat (Fig. 1). Wheat grain yield at Attock in 2023-24 significantly increased by 29.43%, 35.96%, and 35.02%, respectively in T_2, T_3, and T_4, compared with T_1 (conventional timing and splitting) while in 2024-25 wheat grain yield increased by 16.53%, 18.93%, and 18.21% under same treatments plan. Similarly, in Gujrat in 2023-24 wheat grain yield with the same treatments increased by 3.61%, 9.97%, and 11.10% while 2024-25 increased by 7.53%, 15.30%, 18.21%. Overall at both locations and in both years T_4 showed most effective treatment plan with the highest grain yield except in Attock where T_3 performed statistically at par with T_4. The response N timings and splitting was more pronounced in Attock compared to Gujrat. We further observed that overall higher wheat grain yields were recorded in 2023-24 compared to 2024-25 season.

The splitting of N fertilizer application into basal and topdressing applications can increase grain yields and nitrogen recovery (23). In our experiment, in both years N fertilizer was applied to wheat as four treatments (base and topdressing to wheat). Although split N application is not new but the convention splitting in irrigated areas of Pakistan is not enhancing the N recovery instead it is declining. The splitting of N, on the other hand, considered one of the most efficient strategy to increase N use efficiency (24). Under climate change scenario posing GHGs emission and increasing fertilizer prices demands to revise the convention N application practices. In this experiment new timing and splitting of N showed a great potential to revise the N application program. Sustainable crop production depends on the continuous renewal of soil fertility through a balance between N demand and supply in cropping systems. Efficient N fertilizer management is essential for achieving economic yield and enhancing N use efficiency (25). In the present study, at the same N fertilizer rates (recommended), the timing and splitting of N modified. As a result, T_4 where N was divided in three splits 25% applied at sowing, 50% at first irrigation and 25% applied at second irrigation considering the nutrient uptake pattern of wheat as reported in literature, resulted in a higher total crop yield of wheat (26). The finding of this study are consistent with those of Li *et al.*, 1996, who found that delaying the topdressing fertilization time of wheat could boost crop productivity in the wheat (27). Thus, the nutrients released under the T_3 and T_4 treatment met the requirements of the crops, in turn promoting the transport of dry matter from vegetative organs to grain during yield formation and thereby increasing yield. The optimum time for nitrogen uptake by crops varies depending on the specific crop and its growth stage. Generally, N uptake is highest during the vegetative growth phase, when the plant's leaf and stem tissues are actively developing, and during the reproductive phase, when the plant is allocating resources to producing flowers, fruits, or seeds. Nitrogen uptake is also influenced by factors like soil moisture, temperature, and light availability. Mahfuzah *et al.*, 2007 indicated that the plant absorbed more N from fertilizer than from the available N in soil (28). The highest uptakes were at the 8^{th} and 9^{th} week after cropping with the values range from 50 to 60%.

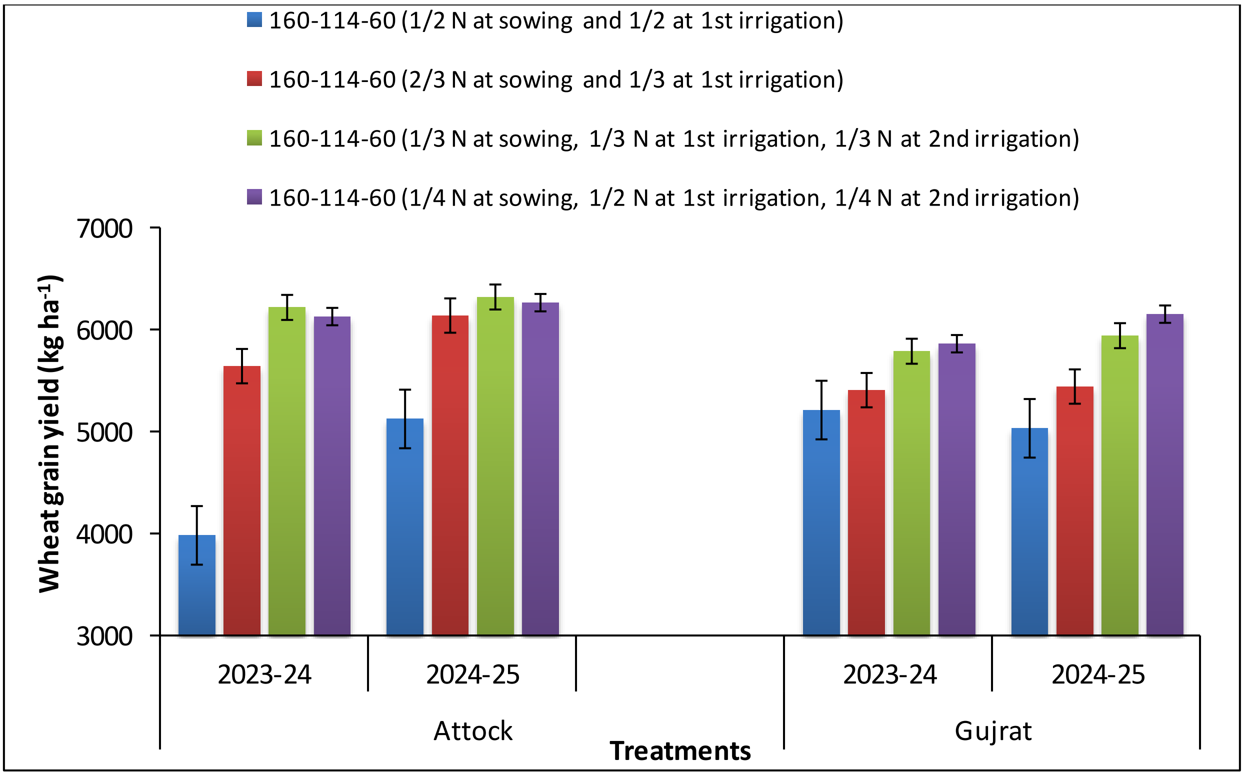

Fig. 1. Effect of nitrogen application timing and splitting on wheat grain yield

WHEAT BIOMASS YIELD

Biomass yield is an important parameter because farmers are also interested in straw in addition to grain. The analysis of variance indicated that the main effects timing and splitting of N application significantly ($P < 0.05$) enhanced wheat biomass yield. The maximum biomass yield was obtained in T_4 followed by T_3 at both Attock and Gujrat in both years (2023-24 and 2024-25). In T3 and T4 treatments N was splitted into three doses (Fig. 2). Whereas, the lowest biomass yield was recorded under T_1, the conventional two split application. The consistent supply of N due to three splits, vegetative growth was enhanced which resulted the higher biomass yield. Generally, biomass yields significantly increased when N applied in two splits compared with single N application. Under similar environmental conditions, maize straw yield was increased by 22% when N fertilizer was applied in splits compared with single N application (29). The authors explained that split application of N delayed phonological development, increased crop growth rate, leaf area per plant and plant height that resulted in higher straw / dry-matter yield. Because split application contributes to cell division, there may be a correlation between the rise in tillers and increased N availability during the tillering stage. The nitrate transporter is regulated by N availability, which in turn affects the tillering (30). Tiller bud outgrowth and tiller numbers increase when the N content of rice plants rises (31). Excessive rainfall or irrigation after planting often results in N loss through de-nitrification and leaching. Leaching also reduces nitrogen use efficiency in and, in turn, lower yields. Leaching of nitrate is economically and environmentally undesirable. Nitrate that leaches below the crop rooting zone represents the loss of a valuable plant nutrient, and hence an economic cost to agriculture. Given also the relatively high cost of fertilizer compared with produce, efficient use of N fertilizer is of both agro-economic and environmental importance (32). In the present investigation a yield increment was obtained N applications with three split for both locations under both years. This finding is in line with the findings of numerous authors who advised two split N applications for wheat production (33). Similar to the present finding, one third of the N rate should be applied at planting while the rest top dressed eight weeks after emergence (34). Most of the investigations on nitrogen fertilizer application management are in favor of split-applications to synchronize timing of fertilization according to the crop demand and increase grain yield (35).

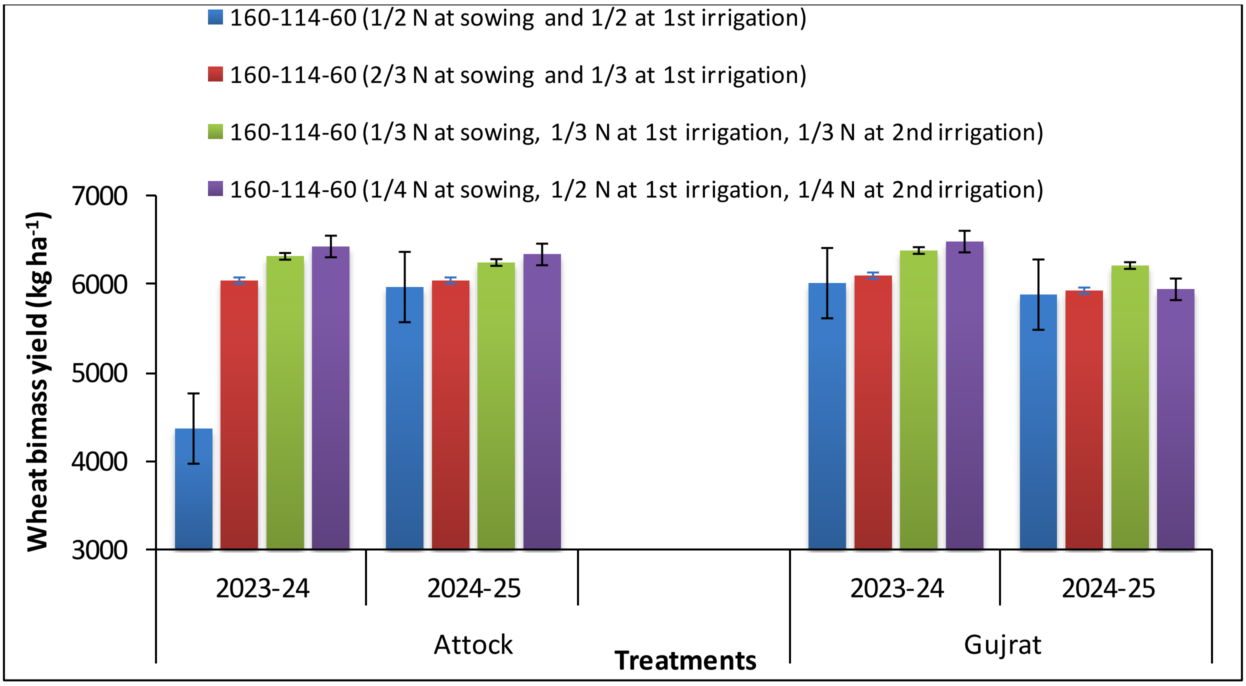

Fig. 2. Effect of nitrogen application timing and splitting on wheat biomass yield

SOIL FERTILITY

The data presented in Table 2 and 3 revealed the timing and splitting of N although showed statistically non-significant effect of soil fertility indicators but a considerable increasing trend of SOM, P_2O_5, and K_2O was noticed. We found that splitting the N into 3 doses, performed best as all fertility indicators showed higher concentration of SOM, P_2O_5, and K_2O in T_4 followed by T_3. The lowest soil fertility was observed in T_1 where traditional 2 split (½ + ½) was applied at both experimental locations and both years. It was further noticed that higher soil fertility at Gujrat compared to Attock was due indigenous soil fertility status but timing and splitting of N into 3 levels helped to improve soil fertility status at both locations.

The increase in SOM in T_3 and T_4 could due to consistent supply of N to crop plants which favored the root development and biomass production. Potentially, fertilizer N application can affect SOM in two ways: (i) it may increase SOM by promoting plant growth and increasing the amount of litter and root biomass added to soil compared with the soil not receiving fertilizer N; and (ii) it may accelerate SOM loss through decay or microbial transformation of litter (leaves, straw, manures) and indigenous forms of organic C already present in the soil. The first mechanism is widely accepted, but the second mechanism has not been demonstrated indisputably. Normally, SOM decreases with cultivation (36) when no N fertilizer is applied. Application of fertilizer N often increases SOM level and C sequestration in soils of intensively managed multiple cropping systems (37). Further, the increase P_2O_5 due to continuous N availability could be attributed to increase in root growth and foraging capacity for P_2O_5, potentially enhancing plant uptake. Additionally, N application can alter soil pH and affect phosphorus solubility, further impacting plant uptake (38). An ample N supply can impact soil potassium availability in both the short and long term, primarily through competition for soil sites and effects on plant uptake. In the short term, N fertilization, especially with ammonium, can temporarily increase K concentration in the soil solution. However, long-term high N, particularly with ammonium, may lead to depletion of both exchangeable and non-exchangeable K in the soil (39).

Table II. Soil physicochemical characteristics at harvest of wheat in 2023-24

Treatments	Attock					Gujrat				
	pH	EC (dS m^{-1})	OM (%)	P_2O_5 (mg kg^{-1})	K_2O (mg kg^{-1})	pH	EC (dS m^{-1})	OM (%)	P_2O_5 (mg kg^{-1})	K_2O (mg kg^{-1})
160-114-60 (1/2 N at sowing and 1/2 at 1st irrigation)	7.38	0.54	0.78	3.7	71	7.86	1.04	0.88	7.4	127
160-114-60 (2/3 N at sowing and 1/3 at 1st irrigation)	7.35	0.52	0.73	3.4	74	7.85	1.03	084	7.6	131
160-114-60 (1/3 N at sowing, 1/3 N at 1st irrigation, 1/3 N at 2nd irrigation)	7.37	0.47	0.75	3.6	78	7.91	1.01	0.85	7.5	141
160-114-60 (1/4 N at sowing, 1/2 N at 1st irrigation, 1/4 N at 2nd irrigation)	7.34	0.45	0.81	4.1	81	7.81	0.98	0.89	7.9	147

Table III. Soil physicochemical characteristics at harvest of wheat in 2024-25

Treatments	Attock					Gujrat				
	pH	EC (dS m^{-1})	OM (%)	P_2O_5 (mg kg^{-1})	K_2O (mg kg^{-1})	pH	EC (dS m^{-1})	OM (%)	P_2O_5 (mg kg^{-1})	K_2O (mg kg^{-1})
160-114-60 (1/2 N at sowing and 1/2 at 1st irrigation)	7.31	0.58	0.73	3.9	77	7.82	1.13	0.88	8.2	129
160-114-60 (2/3 N at sowing and 1/3 at 1st irrigation)	7.29	0.61	0.78	3.7	78	7.84	1.18	084	8.4	139
160-114-60 (1/3 N at sowing, 1/3 N at 1st irrigation, 1/3 N at 2nd irrigation)	7.32	0.63	0.74	3.8	82	7.88	1.11	0.85	8.3	147
160-114-60 (1/4 N at sowing, 1/2 N at 1st irrigation, 1/4 N at 2nd irrigation)	7.27	0.59	0.79	4.3	85	7.78	1.06	0.89	8.8	154

CONCLUSION

The fertile arable lands of Punjab, Pakistan, possess high yield potentials for wheat production, even with suboptimal fertilizer management. However, the inherently low soil organic matter content complicates N management due to temporal variability in soil N-releasing activities. Despite increasing fertilizer application, particularly N, wheat yields in Punjab have been stagnated over the years. We hypothesized that conventional N application strategies might be a significant impediment in achieving higher yield goals. Our two-year study across different locations revealed that splitting N application at three crop growth stages resulted in higher grain and biomass production compared to other N application timings and splitting levels. These findings suggest that a flexible approach to N fertilizer application, tailored to specific crop growth stages, is more effective than a rigid, one-size-fits-all approach. Adjusting N fertilizer timing can minimize N losses, making it a cost-effective strategy for large farms. Moreover, our study found that splitting N application has positive effects on soil properties and fertility. However, we recommend further field validation of these results across diverse soils and environments to ensure their broader applicability.

Authors' contribution:

AW, MR, and AGK Conceptualization and supervision; MR, MA, SA, and AR Conduction research, writing initial manuscript, and data acquisition; MTS, MUS, SA, SS, SA and RAR Data analysis, statistical analysis, and editing of manuscript.

Funding source:

This study did not receive any funding or financial support.

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