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## Improving Nitrogen Use Efficiency in Dual-Purpose Maize Production through Optimized Nutrient Scheduling

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### ABSTRACT

Timely and effective rate of nitrogen (N) and application is essential in enhancing the maize productivity and nitrogen use efficiency (NUE) in semi-arid areas of Pakistan. To determine the impacts of five N-rates, N<sub>0</sub>-N<sub>4</sub> (0, 80, 120, 160, and 200 kg N ha<sup>-1</sup>) and three split applications S<sub>1</sub> (whole sowing), S<sub>2</sub> (two splits - 1/2 at sowing + 1/2 at tasseling) and S<sub>3</sub> (three splits - 1/3 at sowing + 1/3 knee height, and 1/3 at tasseling) on maize were applied. The findings indicated that there was a significant increase in growth and yield characteristics with increasing N rate and in split application. The highest performance shown in N<sub>4</sub> and S<sub>3</sub> as, plant height (232.60 and 210.80 cm), cob length (23.27 and 21.8 cm), cob diameter (6.63 and 5.97 cm), grain rows per cob (15.78 and 14.93 cm), grains per cob (574 and 502), and hundred grain weight (32.96 and 29.25 g) was measured. Similarly, the highest grain yield (8.14 and 7.69 t ha<sup>-1</sup>), and biological yield (27.75 and 25.72 t ha<sup>-1</sup>) was observed under N<sub>4</sub> and S<sub>3</sub> which was (32.3 and 13.1 %), and (60.6 and 23.0%) higher than the lowest control treatments as N<sub>0</sub> and S<sub>1</sub>. The forage performance also increased as the green fodder yield was improved to 43.56 t ha<sup>-1</sup> (42.5%), dry matter yield 18.39 t ha<sup>-1</sup>, crude protein content was raised to 10.26% and crude protein yield (202.03 kg ha<sup>-1</sup> in S<sub>1</sub> and N<sub>0</sub>) was upgraded 194%. As NUE was highest at the moderate rates of N, whereas the largest Partial Factor Productivity (PFP) (74.71 kg kg<sup>-1</sup>), Agronomic Efficiency (AE) (48.59 kg kg<sup>-1</sup>), Recovery Efficiency (RE) (61.68%), and Physiological Efficiency (PE) (84.09 kg kg<sup>-1</sup>) were obtained at S<sub>3</sub> and 80 kg N ha<sup>-1</sup>. In general, three-split N application at a moderate and higher N rate maximized the productivity of maize and the efficiency of nitrogen utilization.

**KEYWORDS:** maize production; nitrogen scheduling; nitrogen use efficiency; yield components; forage quality; nutrient recovery; split fertilization strategy

### INTRODUCTION

Maize productivity is strongly constrained by nitrogen availability; however, excessive and inefficient nitrogen application reduces yield response and nitrogen use efficiency, underscoring the need for optimized nitrogen management in intensive agricultural systems (Yuan *et al.*, 2021). Certain limitations to maize productivity include low soil fertility, poor nutrient management, among others (Zhang *et al.*, 2022). The exploitation of increased yields in most swine systems of growing maize has commonly depended on super application of chemical fertilizer that will later cause low nutrient use efficiency and prolonged deterioration of soil and ecosystem operation. These activities lead to soil acidification, nutrient disproportion, low nutrient levels, and pollution of the environment (Guo *et al.*,

2022; Li *et al.*, 2020; Zhang *et al.*, 2016). There is a need to develop effective strategies in managing nutrients thus to maintain the crop productivity and also ensure that the soil is healthy and environmentally friendly (Fan *et al.*, 2020). Excessive use of chemical fertilizers does not invariably translate to greater yields; it usually reduces the effectiveness of nitrogen use. It has been demonstrated that crop response to nutrients over an optimum range is nonlinear: yield improvement is observed on a range of nutrient input, but at significantly higher levels, nutrient input fails to give the same yield result as the input (Irmak *et al.*, 2016; Wang *et al.*, 2021).

Excess use of nutrients may also increase the loss of nutrients, decrease nutrient use efficiency, and have an adverse effect on the productivity of the soil (Dou *et al.*, 2022; Yan *et al.*, 2021). Therefore, it has been

determined that nutrient scheduling is an important method of careful planning of the application rates and time of nutrients to maximize maize productivity and enhance the efficiency of nitrogen use. It is known that organic fertilizers are sustainable agronomic practice because it has many positive impacts on the physicochemical properties of the soil and biological activity (Zhai *et al.*, 2022). However, the use of only organic fertilizers might not be suitable due to the needs of crops since the nutrients have to undergo mineralization before reaching the plants (Cheng *et al.*, 2023; Diaz-Perez *et al.*, 2021). A combined approach to nutrient management that encompasses both inorganic and organic fertilizer has thus emerged as a more popular approach to enhancing soil fertility, nutrient levels and crop production (Liu *et al.*, 2021). Several studies have shown that the combined application of inorganic and organic to fertilizer is more effective than the use of chemical fertilizers in terms of improving soil quality and fertility, in addition to lowering the environmental risk (Han *et al.*, 2021; Sheoran *et al.*, 2017). The integrated nutrient plans enhance crop productivity, efficiency in using nitrogen as well, leading to a more sustainable cropping system (Quemada and Gabriel, 2016). Besides the fact that organic fertilizers have been commonly used, biofertilizers have also become important tools in minimizing the utilization of chemical fertilizers yet ensuring crop productiveness. These contributions depend on positive rhizosphere microorganisms, which enhance plant development by solubilizing nutrients, inducing hormones, and resistance to adverse circumstances (Chauhan *et al.*, 2015). Species of *Bacillus* have become highly popular as biofertilizers due to their capacity to increase soil fertility, help plants grow, and that of plants to resist against environmental stresses (Ali and Khan, 2021; Li *et al.*, 2021).

It is consistently known that nutrient supply is closely related to plant physiologic demand, and the optimization of the fertilizer rates is frequently insufficient to obtain high nitrogen use efficiency (Li *et al.*, 2020). There might also be the problem of excess fertilizer usage that leads to the environment problems concentrated on nitrate leaching and greenhouse gas emission, and this is why it is important to create management approaches that must prioritize efficiency over quantity (Quemada and Gabriel, 2016). Applying fertilizer at the right time and in the right form according to crop nutrient demand is an effective way to improve nitrogen use efficiency and reduce nutrient losses (Li *et al.*, 2019). Proper nitrogen management is especially important for maize in semi-arid regions, as the time of application strongly affects growth, yield, and nutrient use efficiency (Ali and Khan, 2021). It is also true that the soil processes regulate the effectiveness of fertilizers and the mineralization of nutrients and the activities of the microorganisms that eventually impact the nutrient availability of crops and their

uptake (Diaz-Perez *et al.*, 2021; Li *et al.*, 2010). The past researches reveal that an application of bio-fertilizer has an interrelation with the nutrient dynamics of the soil, which has a great impact on the yield of crops and the efficiency of nutrient utilization (Nadeem *et al.*, 2014).

Maize productivity is often limited by low nitrogen use efficiency due to excessive or poorly timed fertilizer application, which can reduce yields and harm soil and the environment. Optimized nutrient scheduling, offers a way to enhance nitrogen use efficiency, improve crop growth, and maintain soil health. Therefore, this study aims to improve nitrogen use efficiency in dual-purpose maize production through optimized nutrient management, with the specific objectives to (a) evaluate the effects of nitrogen rates and application timing on growth, yield, and nitrogen use efficiency, (b) assess the role of integrated nutrient management in enhancing soil fertility and crop performance, and (c) develop practical nutrient scheduling strategies for semi-arid environments.

## MATERIALS AND METHODS

**Experimental Site:** The experiment was conducted in the spring of 2025 at the Agronomic Research Area, Institute of Agronomy, Bahauddin Zakariya University, Multan, Pakistan. The experimental site is situated at an altitude of 184 meters above sea level, with latitude of 31°25'N and a longitude of 73°09'E. The region falls within the hot semi-arid climate of southern Punjab, characterized by long, hot, dry summers, mild winters, low annual rainfall predominantly during the monsoon period, and generally high temperatures, conditions that are typical of semi-arid environments and influence crop growth and water availability. Figure 1 indicates the physio-chemical properties of the soils, which were of great significance before planting, while Figure 2 presents the weather conditions during the crop season. The climate of the area is semi-arid, with hot temperatures in summer and moderate temperatures in winter.

**Experimental Design and Treatments:** The experiment was laid out in a Randomized Complete Block Design (RCBD) with split plot arrangement having three replications. Nitrogen levels of 0 (control), 80 (low), 120 (normal), 160 (high), and 200 (excess) kg ha<sup>-1</sup> constituted the main plot factor. Three nitrogen application methods were used as the sub-plot factor: S<sub>1</sub>, where the full nitrogen dose was applied at sowing; S<sub>2</sub>, with half applied at sowing and half at tasseling; and S<sub>3</sub>, with one-third applied at sowing, one-third at knee height, and one-third at tasseling. The experiment comprised a total (net plot size 3 × 5 m) of 45 plots.

**Agronomic Practices:** A fine seedbed was prepared for the experiment by means of tractor mounted cultivator followed by two planking. A maize hybrid cultivar (P1419) was sown on 15<sup>th</sup> February 2025 by

maintaining 75 cm row-to-row and 25 cm plant-to-plant spacing with seed rate of 25 kg ha<sup>-1</sup>. At the time of planting, 100 kg ha<sup>-1</sup> of single superphosphate (SSP) and 100 kg ha<sup>-1</sup> of muriate of potash (MOP) were applied to increase soil fertility. Nitrogen in the form of urea, was applied at different rates according to treatment plan. During the growing phase of the crop, a total of five irrigations were carried out: the first irrigation was done fifteen days after planting, the remaining irrigation was timed according to the crop's needs, and the last one was conducted one week before harvest. To manage weeds, two hoeing's were done by hand, and to reduce stem borer infestation, 18 kg ha<sup>-1</sup> of carbofuran granules were applied. The crop was harvested at physiological maturity, after which the grains were mechanically shelled and dried to determine grain yield.

#### Parameters Recorded:

##### Growth and Yield Parameters:

**Plant Height (cm):** Ten plants were selected randomly from each plot and their height was measured from ground surface to tip of plant by using measuring tape and then average height was taken in cm.

**Cob Length (cm):** Ten cobs of maize were randomly selected from each plot and their length was measured by means of measuring tape and means value was recorded for statistical analysis.

**Cob Diameter (cm):** The diameter of 10 randomly selected cobs from each plot was recorded by using Vernier caliper and the cob diameter average was calculated.

**Number of Grain Rows per Cob:** The ten randomly selected cobs from each plot were used to count grains rows per cobs by manually and the average was recorded by standard method.

**Number of Grains per Cob:** Numbers of grains per cobs were determined by shelling the 10 randomly selected cobs from each treatment the grains were counted by means of electric grain counter and average was recorded.

**Hundred Grain Weight (gm):** A sample of 100 grain was taken from each seed lot of each plot, weighed was calculated in gram by means of electrical balance and then average was worked out.

**Grain Yield (t ha<sup>-1</sup>):** After harvesting and shelling of whole plot, their grains yield plot<sup>-1</sup> was recorded by means of electrical field balance in kilogram. The actual maize yield was taken at grain moisture content of 14%. Then the grain yield converted kg per plot to tons per hectare.

**Biological Yield (t ha<sup>-1</sup>):** The biological yield was calculated by tallying the summation of the above-ground dry biomass (that is stalks, leaves and cobs), of individual plots after being dried in the sun and then converted to tons per hectare.

**Harvest Index (%):** Harvest index was calculated to assess the partitioning efficiency of biomass into economic yield using the formula (Donald and Hamblin, 1976):

$$\text{Harvest Index (\%)} = (\text{Grain yield} / \text{Biological yield}) \times 100$$

##### Fodder-Related Parameters

**Green Fodder Yield (t ha<sup>-1</sup>):** Green fodder harvest yield was measured to determine the mass of fresh above ground biomass that was harvested at vegetative mature stage from each plot.

**Dry Matter Yield (t ha<sup>-1</sup>):** The representative sample of green fodder was taken from each plot, after drying at room temperature then put into oven 65 °C for the period of 48 hours and then weighed. Then drive the total dry matter yield per hectare.

**Crude Protein Content (%):** Crude protein content of fodder was calculated from nitrogen concentration using a conversion factor of 6.25, based on nitrogen constitutes about 16% of protein (Silva *et al.*, 2005). Formula given below:

$$\text{Crude Protein (\%)} = \text{Nitrogen content (\%)} \times 6.25$$

**Crude Protein Yield (kg ha<sup>-1</sup>):** Crude protein yield was calculated as (Silva *et al.*, 2005):

$$\text{Crude Protein Yield} = \text{Dry matter yield} \times \text{Crude protein content} / 100$$

##### Nitrogen Use Efficiency Parameters

##### Partial Factor Productivity of Nitrogen (PFP<sub>n</sub>):

**This** parameter represents the productivity of applied nitrogen in terms of grain yield and was calculated as (Sarkar *et al.*, 2021):

$$\text{PFP}_n (\text{kg grain kg}^{-1} \text{ N}) = \text{Grain yield (kg ha}^{-1}) / \text{Nitrogen applied (kg ha}^{-1})$$

**Agronomic Efficiency of Nitrogen (AE<sub>n</sub>):** Agronomic efficiency indicates the increase in yield per unit of nitrogen applied and was calculated using the formula (Dobermann, 2007):

$$\text{AE}_n (\text{kg kg}^{-1}) = (\text{Grain yield in N-treated plot} - \text{Grain yield in control}) / \text{Nitrogen applied}$$

**Recovery Efficiency of Nitrogen (RE<sub>n</sub>):** Recovery efficiency reflects the proportion of applied nitrogen taken up by the crop and was calculated as (Liu *et al.*, 2011):

$$\text{RE}_n (\%) = [(\text{Total N uptake in fertilized plot} - \text{Total N uptake in control}) / \text{Nitrogen applied}] \times 100$$

##### Physiological Efficiency of Nitrogen (PE<sub>n</sub>):

Physiological efficiency expresses the efficiency of converting absorbed nitrogen into yield and was calculated as (Dobermann, 2007):

$$\text{PE}_n (\text{kg kg}^{-1}) = (\text{Grain yield in fertilized plot} - \text{Grain yield in control}) / (\text{N uptake in fertilized plot} - \text{N uptake in control})$$

**Statistical Analysis:** The composed data were collected to analyze statistically by using Fisher's analysis of variance technique by using Statistix 8.1

computer software. The least significant difference (LSD) test was used for mean comparison at 0.05 (5%) probability levels (Steel *et al.*, 1997).

## RESULTS

**Maize Growth and Yield:** The effect of nitrogen application rate and split application timing on maize growth and yield components was significant. According to Table 1, increasing nitrogen doses from 0 to 200 kg ha<sup>-1</sup> progressively enhanced plant growth and yield traits. The highest plant height (232.60 cm), cob length (23.27 cm), cob diameter (6.63 cm), grain rows per cob (15.78), grains per cob (574.00), and hundred-grain weight (32.96 g) were recorded under 200 kg ha<sup>-1</sup> nitrogen (N<sub>4</sub>), representing increases of 56.2%, 54.4%, 61.5%, 32.7%, 47.2%, and 53.4%, respectively, compared to the lowest values observed under 0 kg ha<sup>-1</sup> nitrogen (N<sub>0</sub>), which recorded plant height 148.90 cm, cob length 15.07 cm, cob diameter 4.10 cm, grain rows per cob 11.89, grains per cob 390.00, and hundred-grain weight 21.50 g. Similarly, nitrogen application timing significantly influenced maize growth and yield. The split application of one-third N at sowing, one-third at knee-height, and one-third at tasseling (S<sub>3</sub>) produced the highest plant height (210.80 cm), cob length (21.80 cm), cob diameter (5.97 cm), grain rows per cob (14.93), grains per cob (501.90), and hundred-grain weight (29.25 g), which were 17.0%, 23.2%, 17.2%, 11.9%, 8.8%, and 16.3% higher, respectively, than the lowest values recorded under full nitrogen at sowing (S<sub>1</sub>) (180.10 cm, 17.70 cm, 5.09 cm, 13.33, 461.30, and 25.15 g). These results indicate that both higher nitrogen rates and optimized split applications substantially improve maize growth and yield, while omission of nitrogen or single-time application limits plant performance.

The effect of nitrogen application rate and split application timing on maize grain yield, biological

yield, and harvest index was significant (Table 2). Increasing nitrogen doses from 0 to 200 kg ha<sup>-1</sup> progressively improved both grain and biological yields. The highest grain yield (8.14 t ha<sup>-1</sup>) and biological yield (27.75 t ha<sup>-1</sup>) were recorded under 200 kg ha<sup>-1</sup> nitrogen (N<sub>4</sub>), representing increases of 32.3% and 60.6%, respectively, compared to the lowest values under 0 kg ha<sup>-1</sup> nitrogen (N<sub>0</sub>), which produced 6.15 t ha<sup>-1</sup> grain yield and 17.28 t ha<sup>-1</sup> biological yield. In contrast, the harvest index (%) decreased with increasing nitrogen rates, with N<sub>4</sub> (29.46%) recording the lowest value, whereas the highest harvest index (35.73%) was observed under N<sub>0</sub>, indicating that nitrogen application favored total biomass production more than the proportion allocated to grain. Similarly, nitrogen application timing significantly influenced maize yield and harvest index. The split application of one-third N at sowing, one-third at knee-height, and one-third at tasseling (S<sub>3</sub>) produced the highest grain yield (7.69 t ha<sup>-1</sup>) and biological yield (25.72 t ha<sup>-1</sup>), which were 13.1% and 23.0% higher, respectively, than the lowest values obtained under full nitrogen at sowing (S<sub>1</sub>) (6.80 t ha<sup>-1</sup> grain yield and 20.91 t ha<sup>-1</sup> biological yield). The harvest index decreased slightly with split application, with S<sub>3</sub> (30.43%) being lower than S<sub>1</sub> (32.93%), suggesting that while optimized split doses increase total biomass and grain yield, the proportion of biomass allocated to grain slightly decreases. These results indicate that both higher nitrogen rates and optimized split applications substantially improve maize productivity, whereas omission of nitrogen or single-time application

**Table 1.** Effect of Nitrogen Dose through Optimized Scheduling on Plant Height (cm), Cob Length (cm), Cob Diameter (cm), Grain Rows per Cob, Grains per Cob, and Hundred Grain Weight (g) in Maize.

|                                        |                                                          |                | Plant Height (cm) | Cob Length (cm) | Cob Diameter (cm) | Grain Rows per Cob | Grains per Cob | 100 Grain Weight (g) |
|----------------------------------------|----------------------------------------------------------|----------------|-------------------|-----------------|-------------------|--------------------|----------------|----------------------|
| <b>Nitrogen Application Rate</b>       | <b>0 kg ha<sup>-1</sup></b>                              | N <sub>0</sub> | 148.9e            | 15.07d          | 4.10e             | 11.89d             | 390.0e         | 21.50e               |
|                                        | <b>80 kg ha<sup>-1</sup></b>                             | N <sub>1</sub> | 185.4d            | 18.59c          | 5.19d             | 13.56c             | 432.0d         | 24.18d               |
|                                        | <b>120 kg ha<sup>-1</sup></b>                            | N <sub>2</sub> | 203.0c            | 20.43b          | 5.60c             | 14.44bc            | 479.6c         | 26.88c               |
|                                        | <b>160 kg ha<sup>-1</sup></b>                            | N <sub>3</sub> | 212.3b            | 22.21a          | 6.25b             | 15.22ab            | 525.4b         | 29.89b               |
|                                        | <b>200 kg ha<sup>-1</sup></b>                            | N <sub>4</sub> | 232.6a            | 23.27a          | 6.63a             | 15.78a             | 574.0a         | 32.96a               |
| <b>Standard Error (SE)</b>             |                                                          |                | 3.87              | 0.54            | 0.13              | 0.45               | 4.97           | 0.44                 |
| <b>Critical Value (CV)</b>             |                                                          |                | 7.89              | 1.09            | 0.28              | 0.91               | 10.13          | 0.90                 |
| <b>Application Times (Split Doses)</b> | <b>Full at Sowing</b>                                    | S <sub>1</sub> | 180.1c            | 17.70c          | 5.09c             | 13.33b             | 461.3c         | 25.15c               |
|                                        | <b>½ at Sowing and ½ at Tasseling</b>                    | S <sub>2</sub> | 198.4b            | 20.22b          | 5.61b             | 14.27a             | 477.3b         | 26.83b               |
|                                        | <b>⅓ N at Sowing + ⅓ at Knee-height + ⅓ at Tasseling</b> | S <sub>3</sub> | 210.8a            | 21.80a          | 5.97a             | 14.93a             | 501.9a         | 29.25a               |
|                                        | <b>Standard Error (SE)</b>                               |                | 3.01              | 0.42            | 0.11              | 0.35               | 3.85           | 0.34                 |
|                                        | <b>Critical Value (CV)</b>                               |                | 6.11              | 0.85            | 0.22              | 0.70               | 7.85           | 0.69                 |

**Table 2.** Effect of Nitrogen Dose through Optimized Scheduling on Grain Yield (t ha<sup>-1</sup>), Biological Yield (t ha<sup>-1</sup>), and Harvest Index (%) in Maize. n limits yield potential.

|  | Grain Yield | Biological Yield | Harvest Index |
|--|-------------|------------------|---------------|
|--|-------------|------------------|---------------|

|                            |                               |                      | (t ha <sup>-1</sup> ) | (t ha <sup>-1</sup> ) | (%)     |
|----------------------------|-------------------------------|----------------------|-----------------------|-----------------------|---------|
| <b>Nitrogen</b>            | <b>0 kg ha<sup>-1</sup></b>   | <b>N<sub>0</sub></b> | 6.15e                 | 17.28d                | 35.73a  |
| <b>Application Rate</b>    | <b>80 kg ha<sup>-1</sup></b>  | <b>N<sub>1</sub></b> | 6.88d                 | 21.35c                | 32.47b  |
|                            | <b>120 kg ha<sup>-1</sup></b> | <b>N<sub>2</sub></b> | 7.38c                 | 24.27b                | 30.58c  |
|                            | <b>160 kg ha<sup>-1</sup></b> | <b>N<sub>3</sub></b> | 7.68b                 | 24.93b                | 30.97bc |
|                            | <b>200 kg ha<sup>-1</sup></b> | <b>N<sub>4</sub></b> | 8.14a                 | 27.75a                | 29.46c  |
| <b>Standard Error (SE)</b> |                               |                      | 0.14                  | 0.81                  | 0.76    |
| <b>Critical Value (CV)</b> |                               |                      | 0.29                  | 1.54                  | 1.55    |
| <b>Application Times</b>   | <b>Full at Sowing</b>         | <b>S<sub>1</sub></b> | 6.80c                 | 20.91c                | 32.93a  |
| <b>(Split Doses)</b>       | <b>½ at Sowing and ½ at</b>   | <b>S<sub>2</sub></b> | 7.25b                 | 22.72b                | 32.17a  |
|                            | <b>Tasseling</b>              |                      |                       |                       |         |
|                            | <b>⅓ N at Sowing + ⅓ at</b>   | <b>S<sub>3</sub></b> | 7.69a                 | 25.72a                | 30.43b  |
|                            | <b>Knee-height + ⅓ at</b>     |                      |                       |                       |         |
|                            | <b>Tasseling</b>              |                      |                       |                       |         |
| <b>Standard Error (SE)</b> |                               |                      | 0.11                  | 0.63                  | 0.59    |
| <b>Critical Value (CV)</b> |                               |                      | 0.22                  | 1.27                  | 1.20    |

**Maize Forage Production:** Nitrogen rate and split application had great effects on maize forage production. According to Figure 3, application of nitrogen and in split applications led to a maximum fodder production of 43.56 t ha<sup>-1</sup> with three splits at 200 kg N ha<sup>-1</sup> which is a 42.5% improvement over the 30.57 t ha<sup>-1</sup> in the control (S<sub>1</sub>N<sub>0</sub>) condition (Figure 3a). There was also a positive response of dry matter yield having maximum yield of 18.39 t ha<sup>-1</sup> was recorded with three splits with 200 kg N ha<sup>-1</sup> compared to 13.21 t ha<sup>-1</sup> at the control treatment (Figure 3b). On the same lines, the yields of crude protein went up by 202.03 kg ha<sup>-1</sup> (S<sub>1</sub>N<sub>0</sub>) in control condition. However, 595.42 kg ha<sup>-1</sup> crude protein was recorded at three splits at 200 kg N ha<sup>-1</sup> indicating a growth of almost 194 % (Figure 3c), whereas crude protein content (percent) rise to 10.26% (Figure 3d). Collectively, split applications, especially three splits, and increased nitrogen levels maximized the quantity and quality of forage in maize, increasing the biomass accretion and animal feed in protein content.

**Fertilizer Use Efficiency:** Nitrogen rate sensitivity and split sensitivity were also found to have a significant effect on the nitrogen use efficiency parameters. According to Figure 4, the partial factor

productivity (PFP) declined as the levels of nitrogen increased. PFP was highest (74.70 kg kg<sup>-1</sup> N) at N<sub>1</sub> (80 kg N ha<sup>-1</sup>) with three splits application dose S<sub>3</sub>, and lowest (31.49 kg kg<sup>-1</sup> N) was observed under N<sub>4</sub> (200 kg N ha<sup>-1</sup>) with full application dose at sowing S<sub>1</sub> (Figure 4a). While, the agronomic efficiency (AE) was similar in nature with the highest efficiency (48.59 kg kg<sup>-1</sup> N) at N<sub>1</sub> (80 kg N ha<sup>-1</sup>) with three split application dose S<sub>3</sub>, and lowest by increasing the nitrogen application (21.57 kg kg<sup>-1</sup> N) at N<sub>4</sub> (200 kg N ha<sup>-1</sup>) with full application dose at sowing S<sub>1</sub> (Figure 4b). The recovery efficiency (RE) was also different across splits with the highest values at lower to medium rates of nitrogen. Highest RE was recorded at (65.95%) N<sub>3</sub> (160 kg N ha<sup>-1</sup>) with full application of nitrogen at time of sowing while, lowest (46.46%) was at N<sub>4</sub> (200 kg N ha<sup>-1</sup>) under application of N in two splits S<sub>2</sub> (Figure 4c). The physiological efficiency (PE) remains high (84.09 kg kg<sup>-1</sup> N) at N<sub>1</sub> (80 kg N ha<sup>-1</sup>) under three splits S<sub>3</sub>, and lower (37.69 kg N ha<sup>-1</sup>) at N<sub>4</sub> (200 kg N ha<sup>-1</sup>) with full application at sowing S<sub>1</sub> (Figure 4d). In general, split nitrogen application, especially three splits, improved the nitrogen use efficiency

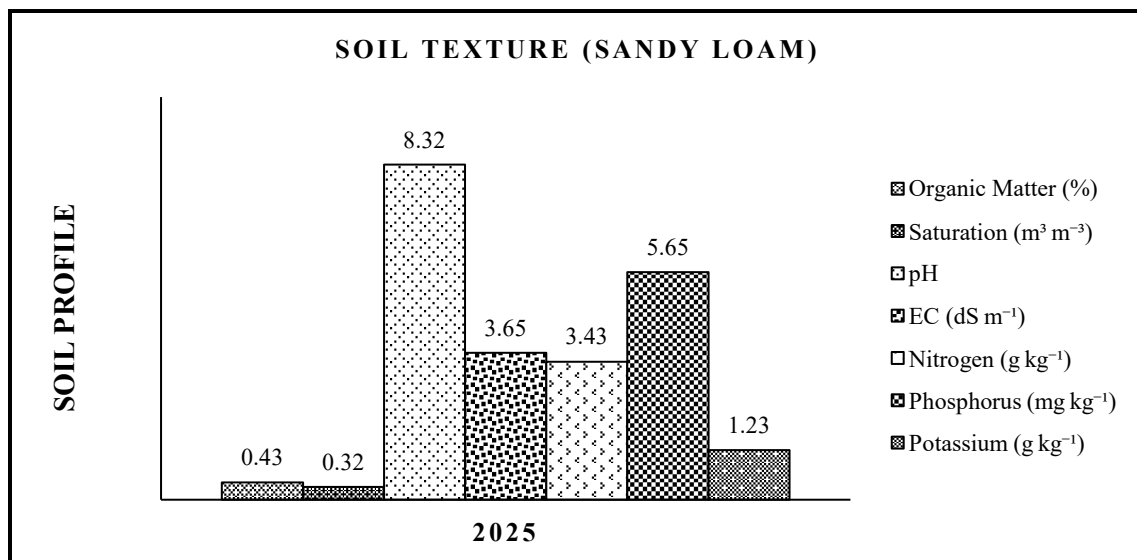


Figure 1. Physio-Chemical Properties of Soil

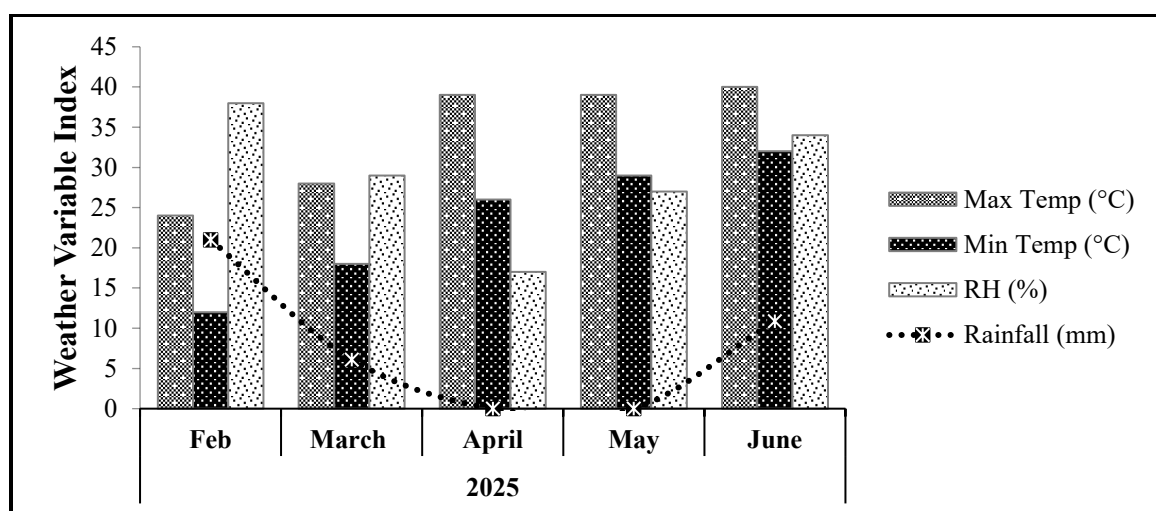
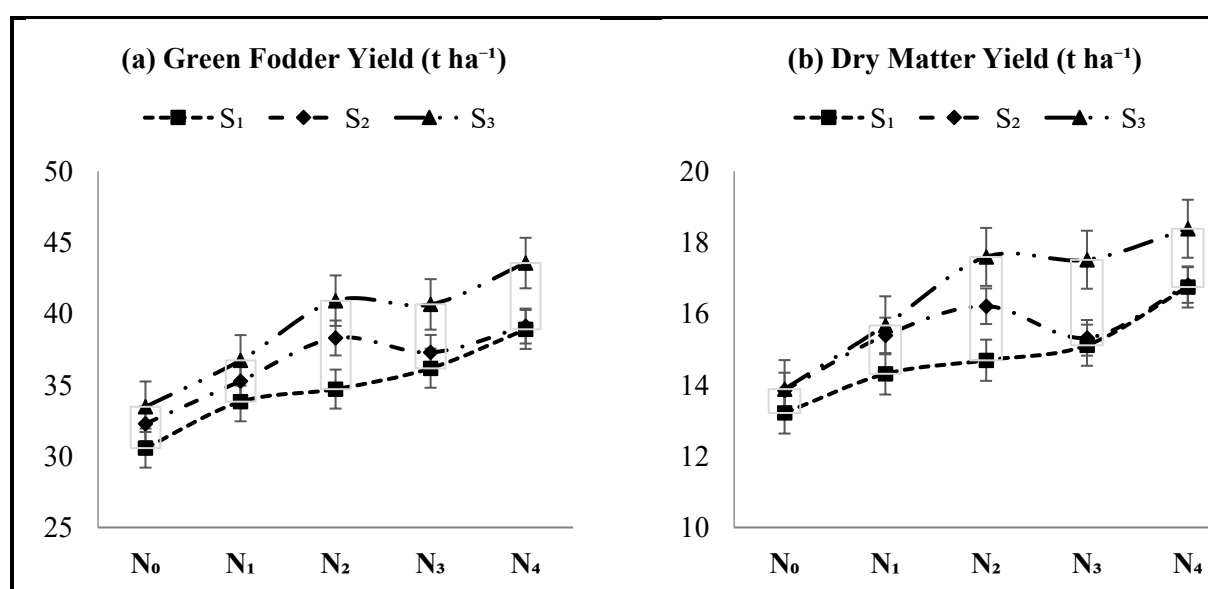


Figure 2. Agro-meteorological Data of Bahauddin Zakariya University, Multan, Punjab, Pakistan, 2025



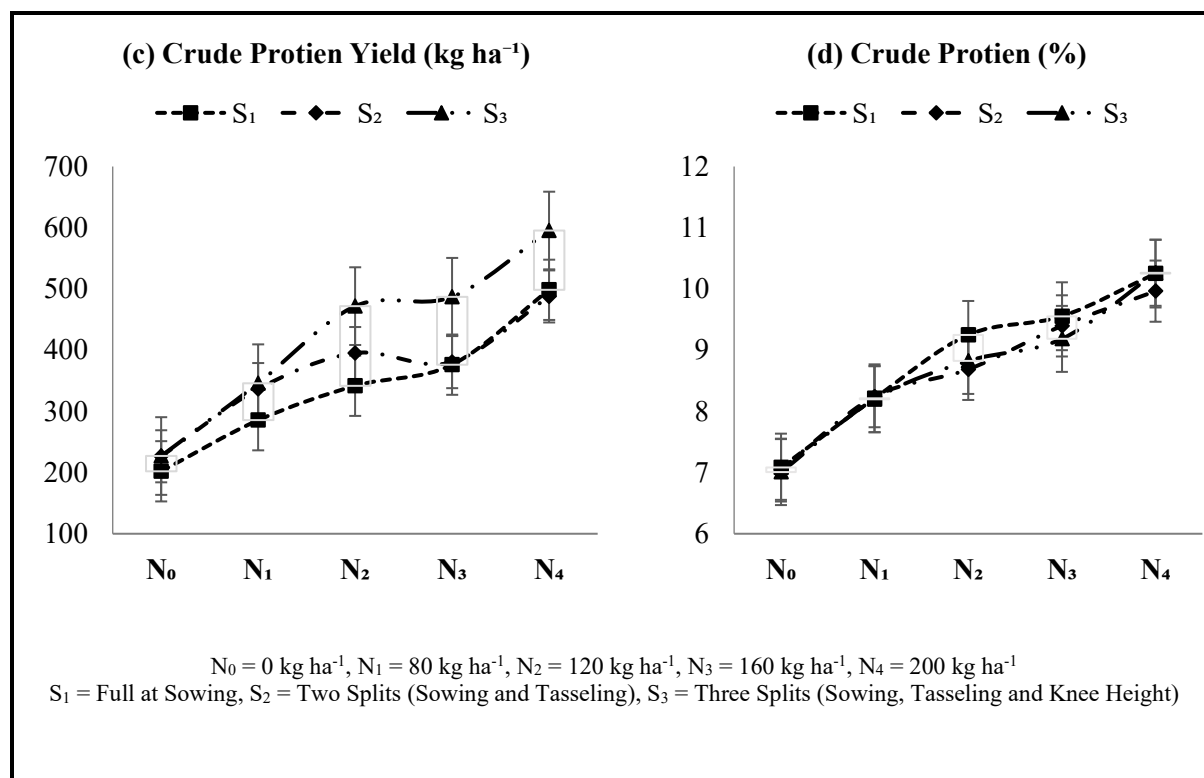
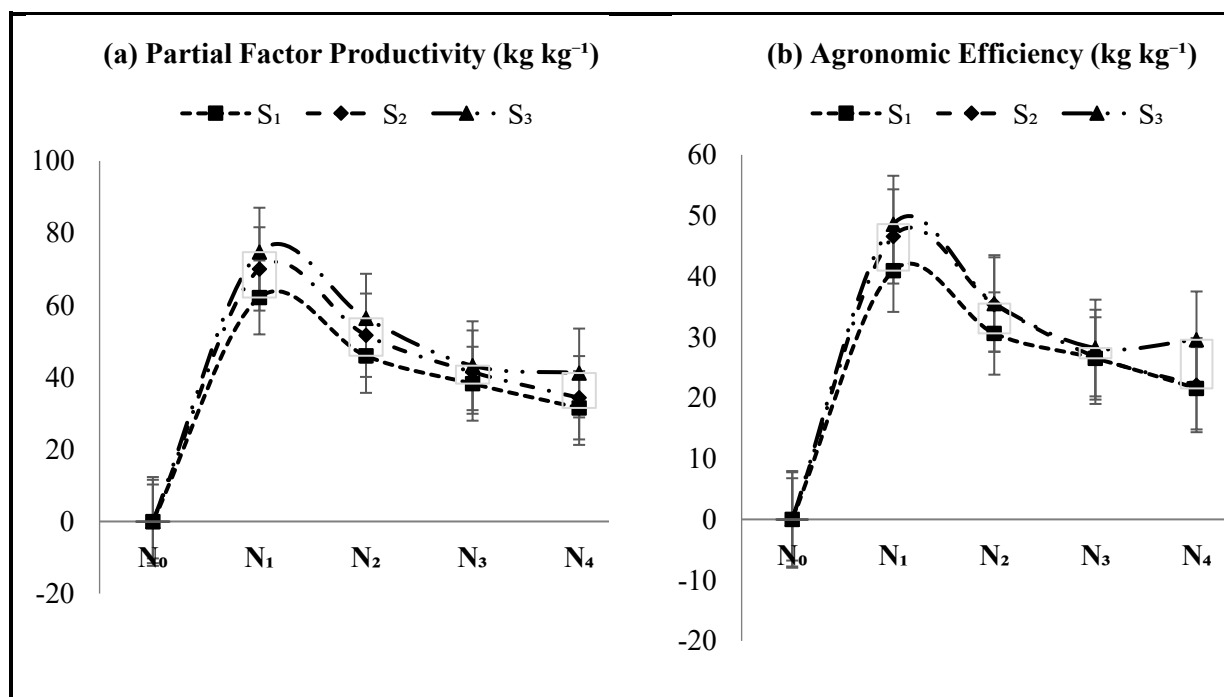


**Figure 3.** Effect of Nitrogen Dose through Optimized Scheduling on (a) Grain Fodder Yield (t ha<sup>-1</sup>), (b) Dry Matter Yield (t ha<sup>-1</sup>), (c) Crude Protein (%), and (d) Crude Protein Yield (kg ha<sup>-1</sup>) in Maize.



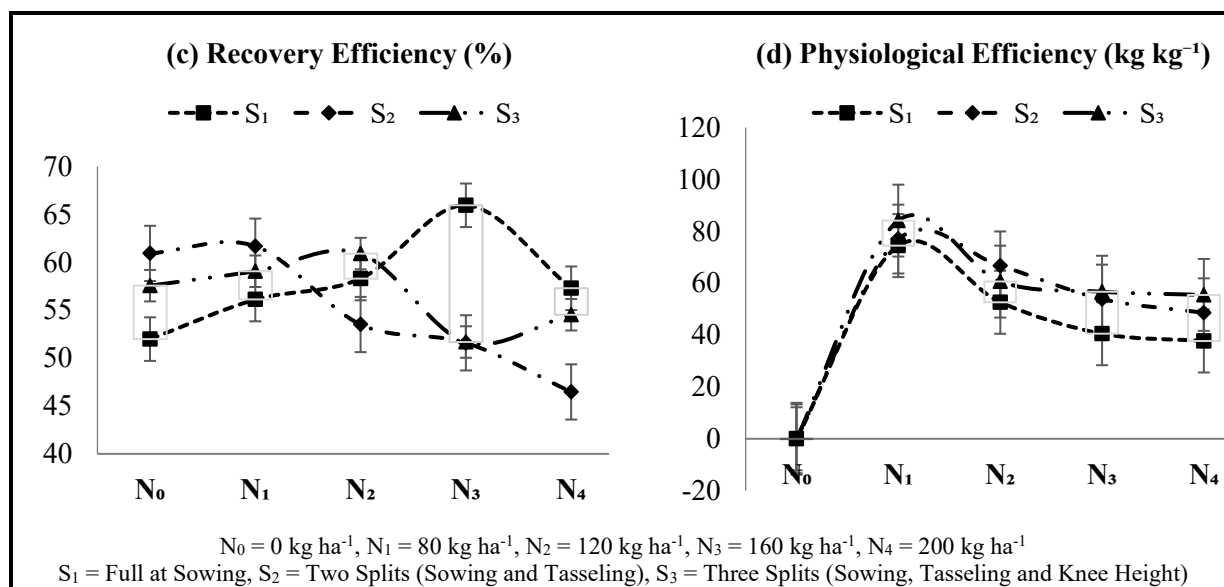


**Figure 4.** Effect of Nitrogen Dose through Optimized Scheduling on (a) Partial Factor Productivity (PFP<sub>n</sub>), (b) Agronomic Efficiency (AE<sub>n</sub>), (c) Recovery Efficiency (RE<sub>n</sub>), and (d) Physiological Efficiency (PE<sub>n</sub>) in Maize.

## DISCUSSION

**Growth and Yield Parameters:** Common indicators of the maize growth and yield potential include plant height, cob length, cob diameter, the number grain rows per cob, the quantity of grains per cob and hundred-grain weight. In the current study, these parameters were found to go up with the increase in rates of nitrogen and split application of nitrogen which showed improved crop growth and yield. Likewise, the height of plants has been improved in the presence of supplemented nitrogen; this increase is also attributed to enhanced vegetative growth resulting from improved nitrogen availability (Sarker *et al.*, 2020; Li *et al.*, 2021). The anticipated growth of cob length and diameter of the cob at the time of nitrogen application are indicative of the enhanced cob growth as well as sink strength, which is conducive to grain formation and ultimate production (Zhai *et al.*, 2022). Similarly, the number of grain rows per cob and grains per cob was higher with higher nitrogen rates and split applications, which confirms that sufficient supply of nitrogen at reproductive stages promotes the initiation of the kernel and minimizes the percentage of its abortion (Guo *et al.*, 2022). Increasing hundred-grain weight also indicates the increased filling of the grain with its optimized nitrogen management, which is in line with other past studies that show the higher availability of nitrogen during grain formation augments the kernel mass (Fan *et al.*, 2020). The rate and split application of nitrogen greatly enhanced grain yield which proved that it was effective to match the nitrogen supply with the crop demand. The higher the biological yield under the high nitrogen rates, the more is the total biomass yield, but reduction in slight in the harvest index implies that vegetative biomass production at the higher nitrogen levels was proportionately less than the increase in grain yield. The same trends were

observed in maize where increased nitrogen rates did not only favor higher vegetative gains but also minimally decreased biomass partitioning to grain (Sadras *et al.*, 2012; Sarker *et al.*, 2020).

**Fodder-Related Parameters:** The yield of green fodder and dry matter increases with the rate of nitrogen and split application which indicated better vegetative growth and the article of fodder biomass. High nitrogen supply has been well recognized to elevate the fodder production due to better leaf and stem growth (Zhao *et al.*, 2021; Han *et al.*, 2021). This further proves the notion by the increase in dry matter yield as more indication of the effectiveness of nitrogen availability in the promotion of structural biomass accumulation in maize. The amount of crude protein percentage and the crude protein yield reacted positively to the application of nitrogen because nitrogen is one of the essential constituents of plant proteins. Increased rates of nitrogen enhance the nitrogen concentration in plant tissues resulting to better crude protein content and significant increase in yield of crude protein. Previous studies have also made similar observations to improve the quality of maize fodder with a rising rate of nitrogen (Fan *et al.*, 2020; Zhao *et al.*, 2021).

**Nitrogen Use Efficiency Parameters:** Nitrogen rate and split application had a considerable effect on partial factor productivity (PFP<sub>n</sub>), agronomic efficiency (AE<sub>n</sub>), recovery efficiency (RE<sub>n</sub>), and physiological efficiency (PE<sub>n</sub>). When PFP<sub>n</sub> and AE<sub>n</sub> increase with a reduction in nitrogen rates, it demonstrates more efficient utilization of administered nitrogen whereas increase in these indices with increase in the nitrogen level indicates diminishing returns with excessive application of nitrogen. The concluding has been extensively evident in maize because higher nitrogen application rates produced greater yield of maize, but when efficiency

is measured, the outcomes decrease with increase rates of nitrogen (Timsina, 2018; Wang *et al.*, 2021). Split nitrogen application enhanced the RE<sub>n</sub> by improving the ratio between the availability of nitrogen and plant uptake, lowering the losses of nitrogen to soil and raising the amount of nitrogen recovered by the plant (Guo *et al.*, 2022). An increase in PE<sub>n</sub> under split application depicts a higher efficiency of absorbed nitrogen to grain yield and shows that better nitrogen management leads to greater internal nitrogen use efficiency (Ciampitti and Vyn, 2012; Sarker *et al.*, 2020). All in all, optimized nitrogen rate and split fertilization enhanced the growth, yield, fodder production and nitrogen use efficiency of maize, and thus the strategies of managing nitrogen usage should help to synchronize the rate of nitrogen supply and demand by crops.

## CONCLUSION

Present study concluded that the nitrogen rate and in split application of nitrogen was significant affect the maize growth and yield, fodder and N-use efficiency. Two of the applications (S<sub>3</sub>: 33% N by sowing and 33% N by knee-height and 33% N by tasselling) altered the nitrogen concentration and yielded the best plant height, cob length, cob diameter, grain rows per cob, grains per cob, hundred-grain weight, grain yield, and biological yield, suggesting the best crop growth and yield process. The parameters met under S<sub>3</sub>N<sub>4</sub> like the presence of fodder-related parameters such as green fodder yield, dry matter yield, crude protein content, and crude protein yield also showed increased forage quantity and quality. Maximum nitrogen use efficiency indices (PFP<sub>n</sub>, AE<sub>n</sub>, and PE<sub>n</sub>) were observed at lowest rate of nitrogen (80 kg N ha<sup>-1</sup>) at three splits application, but the high RE<sub>n</sub> (%) was under 160 kg N ha<sup>-1</sup> with application of nitrogen at sowing time. High nitrogen rates maximized yield but decreased the efficiency. In general, splitting of nitrogen in maize crop, particularly S<sub>3</sub> that was highest in the moderate to high N rates, maximized maize yield and nitrogen use efficiency (NUE) that can be proposed as a sustainable management of N in maize production.

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## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

## AUTHOR CONTRIBUTIONS

H.S.H. and M.S. performed experiments and data analysis. A.U.R. provided supervision. M.H. handled statistics and visualization. M.N.S. provided

guidance and manuscript review. A.H. and A.S. assisted in literature review and manuscript formatting.

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