

BALANCING MINERAL FERTILIZATION FOR BOOSTING BIOMASS PRODUCTIVITY AND NUTRITIONAL ENRICHMENT OF FORAGE RICE BEAN

ASIF IQBAL¹, NILAY KAYIN^{2*}, JAMEEL M. AL-KHAYRI^{3*}, MUNEERA Q. AL-MSSALLEM⁴, FATIMA M. ALESSA⁵ AND MUHAMMAD AAMIR IQBAL⁶

¹Department of Agronomy, Faculty of Agriculture, University of Agriculture Faisalabad, Faisalabad 38040, Pakistan

²Graduate Education Institute, Bilecik Şeyh Edebali University, Türkiye

³Department of Agricultural Biotechnology, College of Agriculture and Food Sciences, King Faisal University, Al-Ahsa 31982, Saudi Arabia

⁴Department of Food Science and Nutrition, College of Agriculture and Food Sciences, King Faisal University, Al-Ahsa 31982, Saudi Arabia

⁵Department of Food Science and Nutrition, College of Agriculture and Food Sciences, King Faisal University, Al-Ahsa 31982, Saudi Arabia

⁶Department of Agronomy, Faculty of Agriculture, University of Poonch Rawalakot, Rawalakot 12350, Pakistan

*Corresponding author's email: nilay.kayin@bilecik.edu.tr, jkhayri@kfu.edu.sa

Abstract

In the changing climate of semi-arid regions, optimizing mineral fertilizer regimes is essential to minimize environmental degradation, support ecological recovery, and sustain biomass crop production. Significant research gaps remain regarding the macronutrient (nitrogen (N), phosphorus (P), and potassium (K)) requirements of untraditional and underutilized leguminous forage crops like rice bean (*Vigna umbellata*), especially in the low-fertility soils of semi-arid regions. To bridge this research gap, a two-year field experiment was conducted to study the growth, forage yield and nutritional quality of rice bean as affected by different fertilization regimes, including a single fertilization regimen (N 150 kg ha⁻¹), double fertilization regime (N 150 kg ha⁻¹ and P 100 kg ha⁻¹), and triple fertilization (N 150 kg ha⁻¹, P 100 kg ha⁻¹, and K 100 kg ha⁻¹), along with a control (no fertilization) treatment. The results showed that the triple fertilization remained superior by producing the highest plant density, plant height, and leaf area index, along with fresh and dry weight of rice bean during both seasons. Additionally, this fertilization treatment recorded its supremacy by producing the highest green forage yield (179% greater than control) and dry matter biomass. Concerning the nutritional quality of forage rice bean, the triple fertilization regime gave the greatest contents of crude protein, ether extractable fats, and total ash, whereas fiber content was significantly decreased. Double fertilization followed it, which in turn was followed by a single fertilization, underscoring the need for integrated and balanced supplementation of macronutrients for forage rice bean production in semi-arid regions. Moreover, correlation analysis revealed a highly significant association of plant height ($R^2=0.987^{***}$), leaf area index ($R^2=0.977^{***}$), and fresh weight per plant ($R^2=0.977^{***}$) with green forage yield of rice bean. However, further research is needed to examine the impact of these fertilizer regimes on nitrogen fixation rate in rice bean root nodules, along with the estimation of nutrient losses in the form of leaching and volatilization.

Key words: Biological nitrogen fixation, Correlation analysis, Mineral fertilizers, Non-traditional forages, *Vigna umbellata*.

Introduction

Globally, the integration of crop-livestock mixed farming has evolved into a quintessential, irreplaceable, and crucial element within contemporary, profit-driven, and economically oriented supply chains of food production (Kaçan & Aydemir, 2026; Ben Abdallah *et al.*, 2024; Kumar *et al.*, 2022). The economic fabric of South Asian countries, most notably India, Pakistan, and Bangladesh, relies substantially on the livestock sector as a fundamental pillar for ensuring food security amidst a rapidly expanding populace, while simultaneously facilitating the sustainable generation of revenue streams (Iqbal *et al.*, 2019). In the current era, the economic performance of dairy farms is intricately linked to the year-round availability of forage, as this is a critical determinant of meeting short- and long-term milk and meat productivity benchmarks (Jamil *et al.*, 2026; Aguerre *et al.*, 2023). The productivity and financial viability of dairy livestock are

profoundly determined by the nutritional quality of green forages, particularly during hot summers when their availability is drastically constrained (Akdeniz *et al.*, 2019). In addition, demand for nutritionally superior forage resources is persistently escalating to sustain the growing populations of dairy animals and livestock-based enterprises (Lauriault *et al.*, 2023).

Cereal forages such as sorghum, maize, oats, and millets can yield substantial quantities of biomass; they are often deemed nutritionally subpar, primarily due to their high fiber content (Iqbal *et al.*, 2019). In contrast, forage legumes such as rice bean (*Vigna umbellata*) present a promising alternative owing to their superior nutritional qualities, particularly high protein content compared to major cereals (Sabagh *et al.*, 2022; Islam *et al.*, 2023). *Vigna umbellata* belongs to the tribe Phaseoleae, Faboideae subfamily, and Fabaceae family. It is commonly known as red bean, oriental bean, climbing mountain bean, bamboo bean, etc., and is closely related to mung beans

(Iqbal *et al.*, 2006; Ayub *et al.*, 2004). It is traditionally cultivated as a protein-rich pulse crop (Langrai *et al.*, 2025) and could enrich soil with nitrogen (Migaya *et al.*, 2025; Thakur *et al.*, 2023; Katoch, 2013). It is a fast-growing crop that has the potential to produce abundant vegetative biomass through multiple harvests and is highly suitable for cut-and-carry forage systems of South Asia (Kujur *et al.*, 2017; Bepary *et al.*, 2016). Despite being a warm-season and dual-purpose legume crop, it remained neglected and underutilized with limited genetic improvement, despite its potential to adapt well to marginal soils under suboptimal environmental conditions and provide enough biomass with high nutritional value (Ariharasutharsan *et al.*, 2024; Katoch *et al.*, 2023; Sarkar & Bhattacharyya, 2023; Dhillon & Tanwar, 2018). The commercial potential has been constrained by prolonged maturity (over 180 days), sensitivity to saline ecosystems (Nengparmou *et al.*, 2025; Pattanayak *et al.*, 2019), and lower forage yield owing to outdated agronomic management systems (suboptimal nutrition and irrigation practices, etc.). Moreover, prolonged time taken for maturity deteriorates forage quality by causing an increase in fiber content (particularly in older leaves) at the cost of protein content (Katoch, 2011), whereas optimal use of mineral fertilization may address these challenges.

For non-traditional forage crops like *V. umbellata* (rice bean), optimization of mineral fertilization is vital to ensure nutrient supply and demand synchronization, leading to an increase in biomass productivity, superior nutritive quality, improved nitrogen fixation, abiotic stress resilience, and soil fertility, ultimately imparting sustainability to forage-livestock-based production systems. The nitrogen (N) fertilizers trigger vegetative growth (plant height, leaf area, and overall canopy development) of leguminous forages by enhancing the biosynthesis of chlorophyll and accelerating the photosynthesis rate. Likewise, phosphorus (P) tends to assist in developing stronger roots, which reduces lodging, and provides the required ATP for biological N fixation (BNF). Moreover, K fertilization regulates stomatal activity, improves water and nutrient use efficiency, and increases assimilate (carbohydrate) synthesis, thereby improving the palatability and digestibility of forage crops by reducing fiber content. Previously, Nanda *et al.*, (2025) suggested the application of 50% of the recommended dose of N in conjunction with farmyard manure (FYM) for boosting forage yield, soil fertility, and energy efficiency of rice bean, whereas Rachel *et al.*, (2022) suggested the application of organic manures (5 tons ha⁻¹) for achieving the potential yield of rice bean. Contrastingly, a full dose of inorganic N with FYM (0.7 tons ha⁻¹) was recommended for rice bean (Solo *et al.*, 2023). In another study, the provision of NPK (40:80:40 kg ha⁻¹, respectively) through mineral fertilizers was found superior for rice bean (Yadav *et al.*, 2022). Moreover, in a recent study by Gadi *et al.*, (2025), it was inferred that mineral NPK (20, 40, and 30 kg ha⁻¹ of NPK) applied in combination with poultry manure and biochar significantly enhanced rice bean yield and soil fertility, whereas mineral P (60 kg ha⁻¹) along with boron (0.03%) has also been recommended for rice bean (Sanskriti & Umesha, 2023). These findings are limited in scope for addressing rice bean fertilization using organo-

mineral fertilizers and specific soil and agroecosystems, underscoring the need to conduct further in-depth studies.

Therefore, the research hypothesis of this study entailed that different fertilization treatments (macronutrients applied in various combinations) may enhance forage yield and quality attributes of forage rice bean grown under irrigated conditions by triggering canopy development and may also increase protein content at the cost of fiber content through balanced growth. Thus, a two-consecutive-season field study was performed with the prime aim of finding out the most balanced and superior NPK fertilization for achieving the potential forage yield of rice bean, along with higher nutritional quality (higher protein, fat, and ash contents, while low fiber content).

Materials and Methods

Experimental locality description: This multi-season field investigation was carried out at the University of Agriculture, Faisalabad, Pakistan (Agronomy Department's research area) (31°25'0"N 73°5'28"E, and an altitude of 184 m), during two consecutive years of 2021 (first season) and 2022 (second season). Before sowing the crop, soil samples from the experimental block were taken at a depth of 15-30 cm from five spots, including four corners and the middle. After thorough manual mixing of these soil samples, testing was conducted in the lab. The soil was found to be alkaline (pH 8.3) with low organic matter (0.61%) and deficient in macronutrients (NPK content of 314, 6.80, 168.3 mg kg⁻¹ of soil, respectively). Higher fertilizer amounts than recommended doses were chosen for testing. The meteorological features of the experimental site (temperature and rainfall) were collected from the meteorological observatory (about 200 meters away from the experimental block) during the crop growing seasons of 2021 and 2022 and are presented in Fig. 1.

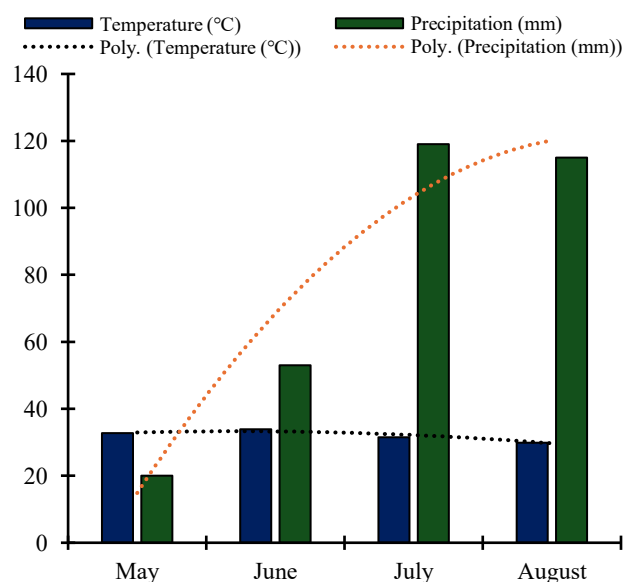


Fig. 1. Meteorological features of the experimental locality (Faisalabad, Punjab, Pakistan) during the crop growth period (2-year mean values). Polynomial trend lines depict a non-linear pattern (best-fit curved change).

Details of field experiments and treatments: The trial aimed to evaluate a single fertilization regimen (N 150 kg ha⁻¹), a double fertilization regimen (N 150 kg ha⁻¹ and P 100 kg ha⁻¹), and a triple fertilization (N 150 kg ha⁻¹, P 100 kg ha⁻¹, and K 100 kg ha⁻¹) for forage rice bean. A control (no fertilization) treatment was maintained for comparison. The sources of fertilizers were urea (46% N), diammonium phosphate (18% N and 46% P₂O₅), and sulphate of potash (50% K₂O). Urea was applied in two equal splits (half as a basal dose and the remaining half was applied with the second irrigation), whereas other fertilizers were applied as a basal dose. All the fertilizers were applied as a broadcast in the experimental block with the utmost uniform distribution. The study was conducted using a randomized complete block design (RCBD) with four replicates. The net area of the experimental plot was 3.6 m × 9 m in size (12 rows of rice bean in each plot).

After harvesting wheat, the experimental block was plowed twice using a tractor-driven common cultivator, each followed by planking with a wooden plank to crush soil clods and prepare a fine seedbed. The sowing of rice bean was performed in the first week of May during both years, using a seed rate of 25 kg ha⁻¹ with the help of a single-row hand drill, while 30 cm spacing was maintained between rows. The maintenance of spacing among plants was not ensured as per the recommendation because forage rice bean was grown for biomass rather than reproductive yield. However, the recommended seed rate regulates the stand density of forage rice bean, ensuring field-level realism (Iqbal *et al.*, 2024). The crop received four irrigations of 7.5 cm each as per the needs of the crop and weather conditions.

Response variables recordings: The crop was harvested after 90 days during the first week of August in both years, and all response variables were recorded. The estimation of stand density was done by counting rice bean plants in a 1 m² area, randomly selecting 5 plants from the inner rows of each experimental unit, and then computing their average. Likewise, the plant height of rice bean plants was determined from the base to the tip of the topmost leaf with the help of a tailor's measuring tape. Additionally, leaf area index (LAI) was measured as suggested by Iqbal *et al.*, (2019).

$$LAI = \frac{\text{Leaf area}}{\text{Land area}} \times 100 \quad (1)$$

Fresh weight of rice bean plants was recorded immediately after harvesting, using a digital scale. For fresh forage yield estimation, rice bean plants in each plot were harvested using a sickle and weighed using a spring balance (tripod-supported type). The dry matter yield (DMY) was recorded using the methodology of Iqbal *et al.*, (2016). Nutritional quality traits (crude protein, crude fiber, ether extractable fat, and total ash) were determined following AOAC methods (Anon., 1990). The Kjeldahl N determination method was used to estimate N, which was multiplied by the nitrogen-to-protein conversion factor of 6.25 for estimation of crude protein. Likewise, the acid-alkali digestion method and the Soxhlet extraction technique were employed for the determination of crude

fiber and fat contents of forage rice bean. Moreover, for estimation of total ash, the muffle furnace method, also called the dry ashing technique, was used.

Statistical analysis

Firstly, Bartlett's test was employed for the recorded data of response variables of irrigated rice bean for year significance estimation (Iqbal *et al.*, 2021). Subsequently, treatment effects were evaluated with the help of Fisher's one-way analysis of variance, implemented in IBM SPSS (Statistical Package for the Social Sciences). Finally, to estimate the significance among treatment means, the least significant difference (LSD) test at the 5% probability level was employed. Moreover, correlation analysis was performed for the estimation of linear or reverse association among yield-contributing traits and green forage yield as well as dry matter biomass of rice bean using the Microsoft Excel program (non-significant = R² ≤ 0.50, significant = R² between 0.50-0.80, and highly significant = R² ≥ 0.80) (Aydemir *et al.*, 2026).

Results

Plant population density, height of plants, and their leaf area index: Concerning the population density of forage rice bean, treatments had no significant difference in the first season; the triple fertilization method remained effective in recording the maximum population density during the second season (Table 1). However, it was statistically at par with the double fertilization method, whereas the control recorded the minimum plant population of rice bean grown under irrigated conditions. As far as the plant height of rice bean was concerned, the triple fertilization surpassed the rest of the treatments during both seasons. Whereas the double fertilization treatment performed statistically equal to triple fertilization during the second season and followed it during the first season. The triple fertilization treatment proved its efficacy by recording the maximum leaf area index of rice bean plant, while it remained at par with the double fertilization treatment during both seasons. However, in the control, the minimum leaf area index was recorded during both seasons (Table 1). Overall, the second season recorded taller plants and a higher leaf area index of forage rice bean compared to the preceding season. Moreover, the single fertilization performed better than the control, but it could perform at par with the double and triple fertilization treatments.

Plants' fresh and dry weights, and yields (green and dry matter): The results of this study exhibited that the triple fertilization technique remained superior by producing the maximum plant weight (fresh and dry) of forage rice bean grown under irrigated conditions during both seasons (Table 2). Double fertilization followed the triple fertilization during the first season, whereas double and triple fertilization did not differ significantly for fresh and dry weights of rice bean during the second season. For green forage yield and dry matter productivity of rice bean, the triple fertilization was recorded to be superior during both seasons. This fertilization treatment was followed by the double fertilization treatment during the first season,

whereas it remained statistically non-significant with a double fertilization regime during the second season. Overall, the solo fertilization also produced significantly higher production of green and dry biomass compared to the control treatment; however, it performed subpar to other fertilization treatment under investigation. Interestingly, lower green forage yield and dry matter productivity were recorded during the second season than in the preceding year.

Quality attributes: As per recorded data, seasonal variations were pronounced as far as different quality traits of forage rice bean were concerned, as the second season recorded relatively higher (13.43%) protein than the preceding season (Table 3). Likewise, fertilization regimes also recorded differential responses of forage rice bean in terms of crude protein content. During the first season of crop growth, the double fertilization treatment produced the maximum crude protein, while it was on par with the triple fertilization treatment. However, the triple fertilization exhibited its superior efficacy by recording the maximum crude protein of forage rice bean during the second season,

and the double fertilization treatment followed the triple fertilization treatment. Likewise, the solo fertilization regimen also performed better than the control treatment; it could not compete with other fertilization treatments. In contrast to the crude protein content of rice bean, the triple fertilization treatment produced the lowest crude fiber content during the first season, followed by double fertilization, whereas the control treatment recorded the greatest fiber content. During the preceding season of crop growth, the triple fertilization regime was the most effective treatment combination by recording the minimum fiber content, followed by the double fertilization regime, which was statistically similar to the solo fertilization regimen. Moreover, the triple fertilization regime displayed its supremacy, producing the maximum quality traits, including extractable fat and ash contents of rice bean during both seasons, except for the double fertilization regime, which produced the maximum extractable fat during the first growth season of forage rice bean. Overall, the second season outperformed the preceding one by giving greater values of both extractable fat and total ash content of rice bean grown under irrigated conditions (Table 3).

Table 1. Plant population density, height of plants, and leaf area index of rice bean in response to different mineral fertilization regimes under semi-arid conditions.

Treatments	Plant population			Plant height (cm)			Leaf area index (cm ²)		
	Season-1	Season-2	Mean	Season-1	Season-2	Mean	Season-1	Season-2	Mean
Control (no fertilization)	25.00	21.25c	23.12C	77d	82c	79.5D	0.48c	0.41c	0.45C
Single fertilization regimen (N 150 kg ha ⁻¹)	25.33	24.66b	24.99B	80c	88b	84.0C	0.53b	0.55b	0.54B
Double fertilization regime (N 150 kg ha ⁻¹ and P 100 kg ha ⁻¹)	26.25	28.00a	27.12A	84b	91a	87.5B	0.62a	0.73a	0.67A
Triple fertilization regime (N 150 kg ha ⁻¹ , P 100 kg ha ⁻¹ , and K 100 kg ha ⁻¹)	26.00	28.13a	27.06A	86a	91a	88.5A	0.64a	0.74a	0.69A
LSD (0.05)	0.70	3.11	0.35	0.43	0.44	0.28	0.021	0.03	

Values having different letters within a column differ significantly at P = 0.05. Small letters within columns indicate the significance of year-wise data, whereas capital letters within columns depict the significance of mean data

Table 2. Biomass accumulation of rice bean in response to different mineral fertilization regimes under semi-arid conditions.

Treatments	Fresh weight plant ⁻¹ (g)			Dry weight plant ⁻¹ (g)			Yield (green forage) (t ha ⁻¹)			Yield (dry matter) (t ha ⁻¹)		
	Season-1	Season-2	Mean	Season-1	Season-2	Mean	Season-1	Season-2	Mean	Season-1	Season-2	Mean
Control (no fertilization)	331d	309c	320D	43.4d	40.0c	41.7D	1.52d	1.75c	1.64D	0.43d	0.400c	0.417D
Single fertilization regimen (N 150 kg ha ⁻¹)	382c	417b	399C	52.5c	55.5b	54.0C	2.83c	2.64b	2.74C	0.52c	0.555b	0.540C
Double fertilization regime (N 150 kg ha ⁻¹ and P 100 kg ha ⁻¹)	436b	568a	502B	62.2b	74.9a	68.5B	3.42b	3.95a	3.68B	0.62b	0.748a	0.685B
Triple fertilization regime (N 150 kg ha ⁻¹ , P 100 kg ha ⁻¹ , and K 100 kg ha ⁻¹)	448a	582a	515A	65.5a	77.1a	71.3A	4.24a	4.21a	4.23A	0.65a	0.771a	0.713A
LSD (0.05)	5.3	17.9	8.5	2.0	2.3	1.5	0.05	0.357	0.166	0.02	0.022	0.014

Values having different letters within a column differ significantly at P = 0.05. Small letters within columns indicate the significance of year-wise data, whereas capital letters within columns depict the significance of mean data

Table 3. Nutritional quality attributes of rice bean in response to different mineral fertilization regimes under semi-arid conditions.

Treatments	Protein (%)			Fibre (%)			Fat (%)			Ash (%)		
	Season-1	Season-2	Mean	Season-1	Season-2	Mean	Season-1	Season-2	Mean	Season-1	Season-2	Mean
Control (no fertilization)	11.3c	11.5d	11.4C	31.96a	31.05a		1.43 d	1.48 c	1.46 C	10.1c	10.36 c	10.2C
Single fertilization regimen (N 150 kg ha ⁻¹)	13.4b	13.8c	13.6B	31.52b	29.16b		1.45 c	1.47 d	1.46 C	10.1c	10.34 d	10.2C
Double fertilization regime (N 150 kg ha ⁻¹ and P 100 kg ha ⁻¹)	13.6a	14.0b	13.8A	30.89c	29.11b		1.53 b	1.55 b	1.54 B	10.9a	10.37 b	10.6A
Triple fertilization regime (N 150 kg ha ⁻¹ , P 100 kg ha ⁻¹ , and K 100 kg ha ⁻¹)	13.5ab	14.3a	13.9A	29.03d	28.00c		1.54 a	1.57 a	1.55 A	10.9b	10.41 a	10.6B
LSD (0.05)	0.189	0.151	0.115	0.10	0.05	0.046	0.009	0.010	0.002	0.02	0.014	0.01

Values having different letters within a column differ significantly at P = 0.05. Small letters within columns indicate the significance of year-wise data, whereas capital letters within columns depict the significance of mean data

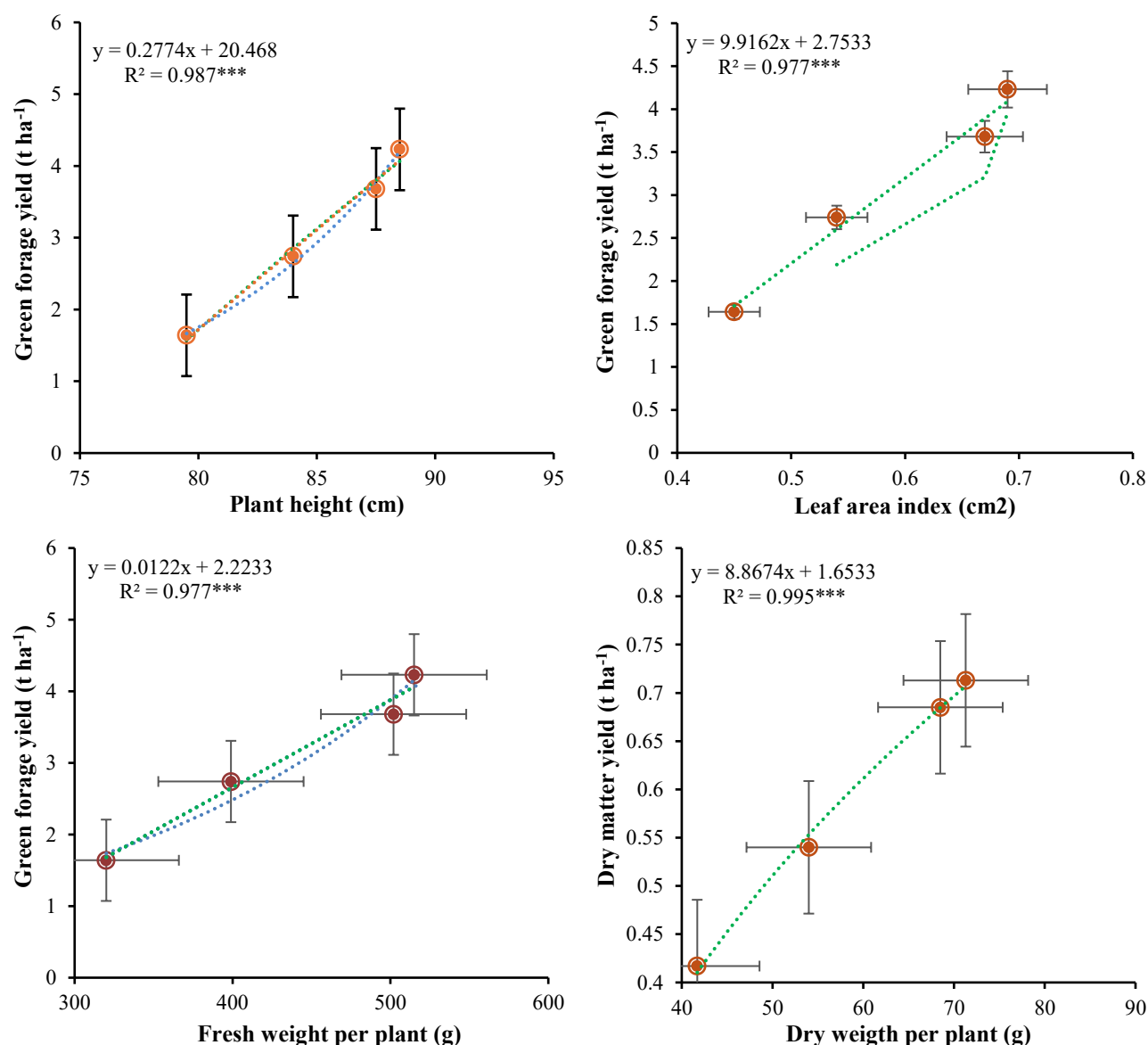


Fig. 2. Correlation analysis of yield-contributing traits of rice bean with green forage yield and dry matter biomass. *** depict highly significant association.

Correlation analysis: To determine the nature of association (positive or negative), the correlation analysis was performed (Fig. 2). The results showed that plant height was significantly associated ($R^2 = 0.987^{***}$) with green forage yield of rice bean. In addition, leaf area index of rice bean was also found to be positively correlated ($R^2 = 0.977^{***}$) with green forage yield. Moreover, Fresh weight per plant of rice bean was also linearly associated ($R^2 = 0.977^{***}$) with green forage yield, whereas dry weight per plant had a highly significant relationship ($R^2 = 0.995^{***}$) with dry matter yield of rice bean grown under irrigated conditions.

Discussion

In this study, no treatment effect on the plant density of forage rice bean during the first growth season may be ascribed to uniform seed germination rate and absence or equal scale of plant lodging during the crop growth cycle. However, the triple fertilization regime (N 150 kg ha⁻¹, P 100 kg ha⁻¹, and K 100 kg ha⁻¹) maximized population density during the second season, and these results agreed with

Ahlawat and Saraf (2009), who inferred that mineral fertilizers, especially P, help crops grow strong roots, reducing lodging and leading to a greater number of plants at harvest. Likewise, taller plants in response to the triple fertilization regime may be attributed to higher availability of N and P, which likely supported more cell division and led to taller plants. It may also be inferred that P and K improved root nodulation and enabled rice bean plants to cope better under moisture-deficient conditions through an increase in growth rate. Previously, it was reported that N remained instrumental in boosting vegetative growth (plant height, leaf area, and overall canopy development) of leguminous forages by enhancing the biosynthesis of chlorophyll and accelerating the photosynthesis rate at early stages before nodules become fully functional to fix atmospheric N (Iqbal *et al.*, 2024). However, suboptimal N doses tend to suppress the functioning of root nodules, leading to underperformance of the BNF process, along with causing a reduction in leaf area (Devi *et al.*, 2021). Ali *et al.* (2019) concluded that macronutrients, particularly N, improved the interception of photosynthetically active

radiation, which enhanced the rate of photosynthesis and promoted plant height. In concurrence with our findings, N was reported to improve leaf area expansion, causing a significant increment in leaf area index (Katoch, 2010). Contrastingly, suboptimal N produces fewer leaves with smaller leaf area, resulting in a drastic reduction in leaf area index under dry conditions (Luo *et al.*, 2021). These findings align with those of Iqbal *et al.*, (2019), who recommended the optimal use of mineral fertilization for enhancing plant height, canopy cover, and vegetative growth of forage legumes like soybean. Moreover, N supplementation directly promotes meristematic activity, leading to taller plants with greater leaf area expansion (Kundu *et al.*, 2015). It has been inferred that optimum P doses applied before sowing stimulate root growth of forage legumes, which promotes nodulation and enhances the rate of the BNF process. Furthermore, the exogenous P application provides the required ATP for the BNF process, which is an energy-intensive process required for producing taller plants, vigorous canopies, and significantly higher leaf area (Megur *et al.*, 2025; Morab *et al.*, 2021).

The triple fertilization regime (N 150 kg ha⁻¹, P 100 kg ha⁻¹, and K 100 kg ha⁻¹) produced the highest fresh and dry weight per plant of rice bean, which led to the maximum green forage yield and dry matter biomass in this study. Combining optimal doses of mineral fertilizers improves the BNF process, leading to better vegetative growth and yield of blackgram (Sadiq *et al.*, 2023). The optimal dose of N tends to enhance the biosynthesis of various viral enzymes such as Rubisco, which accelerates the fixation of CO₂, leading to higher biomass production on a per unit area basis. P supplemented through organic or mineral sources facilitates the transport of photosynthate from leaves to root nodules and tissues, causing growth promotion and biomass enhancement of rice bean sustainably (Megur *et al.*, 2025; Katoch, 2010). K fertilization regulates the activity of stomata and improves water use efficiency in leguminous forages under water-deficit conditions, leading to higher biomass production (Iqbal *et al.*, 2024). In addition, K has been reported to enhance the tolerance of crop plants against temperature fluctuations and moisture scarcity. Moreover, it is reported that K regulates energy metabolism, which results in the generation of more ATP (adenosine triphosphate) and ultimately, biomass yield increases owing to better functioning of the BNF process and photosynthesis (Susilowati *et al.*, 2016; Kundu *et al.*, 2015). Moreover, K effectively maintains the osmotic balance within cells, which enables plants to continue vegetative growth and produce biomass as per varietal potential under mild periods of abiotic stress. It has been inferred that P plays a critical role in driving N fixation through the BNF process, which in turn supports the vegetative growth and canopy development, whereas K safeguards the potential biomass yield of forage legumes through superior water and nutrient use efficiency (Swathi *et al.*, 2021). The optimal doses of NPK synchronize carbon and N metabolism, resulting in superior forage yield. The optimum P concentration within plants promotes the biosynthesis of root exudates (flavonoids and lectins), which serve as signals for rhizobia to cause infection and initiate the BNF process (Megur *et al.*, 2025; Katoch, 2010). Furthermore, P is a vital constituent of phospholipids and phosphoproteins; therefore, optimum P content strengthens the integrity and vital functions of membranes, which ensures higher

biomass and dry matter yield of forages (Saithala *et al.*, 2024; Rundun *et al.*, 2023). Furthermore, correlation analysis indicated a strong linear association of plant height, leaf area index, and fresh weight per plant with green forage yield of rice bean in our study. In addition, we also recorded that dry weight per plant had a strong direct relationship with dry matter yield of rice bean, indicating that agro-botanical traits of leguminous crops may serve as a reliable indicator to forecast forage yield. Previously, Aydemir *et al.*, (2026) reported that correlation analysis assisted in identifying morphological and botanical traits of legumes that could be improved to achieve the yield of field crops as their genetic potential. Similar to our findings, Reza *et al.*, (2018) found a positive correlation between yield attributes and the yield of rice bean, indicating the need for breeding new cultivars with improved potential for canopy development, plant height, and fresh weight accumulation for bolstering the productivity of this underutilized dual-purpose crop in changing climatic scenarios.

The protein content of forage crops has been regarded as one of the most crucial nutritional quality attributes that play a vital role in boosting milk and meat productivity of animals (Aydemir *et al.*, 2026). It may be inferred that the triple fertilization regime entailing NPK fertilizers together effectively increases amino acid production, which raises crude protein content in rice bean. Being a constituent of amino acids, exogenous N application (NH₄⁺ or NO₃⁻) improves protein content of leguminous forages under varying agroecological systems (Iqbal *et al.*, 2024). The deficiency of P restricts the biosynthesis of protein and promotes N accumulation as nitrates (referred to as the non-protein form of N) (Shehata *et al.*, 2026; Megur *et al.*, 2025). Likewise, P provides ATP for nitrogenase synthesis and activity and thus indirectly affects the protein content of forage crops. Moreover, K facilitates nitrate reduction and conversion of inorganic N into protein and also maintains an appropriate C:N ratio (Saithala *et al.*, 2024). Higher fiber content in ruminant feed has been associated with dairy animals' underperformance in the long run (Iqbal *et al.*, 2019). However, our findings contradict with those of Ndiaye *et al.*, (2023), who found that higher protein levels lead to lower fiber content. This may suggest that optimized NPK fertilizer doses promote rice bean plant growth, especially in terms of plant height (stem length), leading to increased fiber content. The lower fiber content in the control group might be due to the shorter plants that grew without fertilizers, as stem length contributes most of the fiber in rice bean (Solo *et al.*, 2025; Iqbal *et al.*, 2021). Potassium supplementation improves the synthesis of assimilates (carbohydrates), which results in enhanced palatability and digestibility of forages by reducing the fiber content (both neutral detergent fiber and acid detergent fiber). Interestingly, K serves as a competitor of lignin precursors and delays lignification, which reduces fiber content (Al-Furtuse *et al.*, 2019). The underlying mechanism is balanced N concentration produced by parenchyma cells with thin walls and delayed lignification, and ultimately, fiber content gets reduced. Contrastingly, supra-optimal doses of N increase lignification, which increases fiber content (Awasthi *et al.*, 2011). Moreover, P deficiency impairs the division of meristematic cells and results in stunted growth and significantly higher fiber content (Mounika *et al.*, 2024).

The extractable fat in animals' feed is vital for improving forage palatability, microbial activity, digestion of fiber, and body insulation of dairy animals, along with providing instant energy to large ruminants (Konuskan *et al.*, 2025; Iqbal *et al.*, 2021). As per our results, the triple fertilization regime effectively increased fat content, and these results aligned with those of Iqbal *et al.*, (2019), who inferred that a significant increment in fat content of forage crops might be achieved through optimization of mineral fertilizer doses. Fats have been recognized as the energy-concentrated, carbon-rich compounds that tend to decline in response to suboptimal doses of N owing to dilution of lipids (Aydemir *et al.*, 2026; Iqbal *et al.*, 2016). Likewise, P has been regarded as a structural component of phospholipids and triggers the biosynthesis of fatty acids, leading to improvement in the fat content of forage crops. Besides other quality traits, total ash represents the mineral constituents of forages that support numerous vital metabolic functions in large ruminants. A well-balanced ash content in forage contributes to animal health by strengthening bones and skeleton, maintaining electrolyte balance, activating key enzymes, and supporting the immune system and tissues (Iqbal *et al.*, 2021). The optimum concentration of P within the plant ensures mineral balance, leading to higher dry matter production and total ash content of forage crops. Moreover, P triggers root growth (branching and rebranching), and plants tend to take up significantly higher amounts of minerals from the soil solution; ultimately, total ash content gets remarkably elevated. Furthermore, K applied in a balanced quantity has been reported to enhance the uptake of anions (particularly NO_3^- and Cl^-) and influence the composition of ash in forage crops (Saithala *et al.*, 2024; Paul *et al.*, 2023).

Conclusions

The recorded findings of this multi-season study supported the research hypothesis because different fertilization regimes significantly improved the yield attributes, biomass productivity, and nutritional quality of forage rice bean grown in a semi-arid climate. The triple fertilization regime remained superior by recording the maximum forage productivity, probably owing to a better biological nitrogen fixation process, which resulted in a higher rate of photosynthesis and, ultimately, increased biomass accumulation. This fertilizer regime also improved the nutritional quality of rice bean, particularly by increasing crude protein, ether extractable fat, and total ash content, whereas fiber content was significantly decreased. These benefits are likely to be due to the combined effect of balanced macronutrient supply, which promoted biosynthesis of amino acids and resulted in parenchyma cells with thin walls, leading to higher protein and lower fiber content. Based on the results from this multi-season study, the triple fertilization regime may be recommended for rice bean growers in semi-arid regions and similar agro-climatic zones to boost both yield and nutritional quality attributes. However, rice bean may respond differently in rainfed areas, so further research is needed to evaluate the impacts of triple fertilization regimes under rainfed conditions. Moreover, future studies may also need to examine the effect of these doses of mineral fertilizers on the amount of N fixed through the

biological N fixation process, N buildup in the soil solution after crop harvest, and estimation of greenhouse gas emissions to promote environmentally sustainable practices under the scenarios of abiotic stressors (drought, heat, and salinity). Furthermore, rhizobia inoculation may also be tested to promote the N fixation process and reduce the requirement of mineral fertilizers for rice bean (*Vigna umbellata*) cultivation in arid and semi-arid regions.

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