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Potential Production of mombasa grass planted at varying plant spacing and sowing methods in Punjab province, Pakistan

Producción potencial de pasto mombasa plantado con diferentes distancias entre plantas y métodos de siembra en la provincia de Punjab, Pakistán

Produção potencial do capim mombaça plantado com diferentes espaçamentos entre plantas e métodos de semeadura na província de Punjab, Paquistão

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Abstract
Fodder scarcity during lean periods in Pakistan is a major concern of the farmers to feed their animals which can be reduced by sowing the potential perennial grasses like mombasa grass. Therefore, an experiment was carried out at University of Agriculture, Faisalabad in a Randomized Complete Block Design (RCBD) with spilt plot arrangement using sowing methods (ridge sowing, bed sowing and line sowing) in main plots while, plant spacing (30 cm, 60 cm and 90 cm) in sub-plots. Collected data was analyzed statistically and difference in treatment means was determined by using LSD test at 5 % probability level. The maximum fresh forage yield (43.2 t ha^{-1}) and dry matter yield (12.85 t ha^{-1}) were recorded when crop was planted at 30 cm plant-plant distance on ridges (S1P1). However, highest crude protein (19.0 %) were observed with ridge sowing method and plant spacing 90 cm (S1P3), while plant space 60 cm provided a balance of fresh weight and crude protein. It is recommended from the observations that mombasa grass should be planted on ridges rather than beds and flat surfaces. Plant space of 60 cm may be adopted as practical compromise between yield and forage quality.

Keywords: perennial pasture; production; quality

Resumen
La escasez de forraje durante los períodos de escasez en Pakistán constituye una preocupación importante para los agricultores en la alimentación de sus animales, que se puede resolver mediante la siembra de gramíneas perennes de alto potencial como el pasto Mombasa. Por lo tanto, se llevó a cabo un experimento en la Universidad de Agricultura de Faisalabad, utilizando un Diseño de Bloques Completos al Azar (DBCA) con arreglo de parcelas divididas, donde los métodos de siembra (siembra en camellones o surcos, en camas y en líneas) se asignaron a las parcelas principales, mientras que el espaciamiento entre plantas (30 cm, 60 cm y 90 cm) se asignó a las subparcelas. Los datos obtenidos se analizaron estadísticamente y las diferencias entre medias de tratamientos se determinaron mediante la prueba LSD al nivel de probabilidad del 5 %. El mayor rendimiento de forraje fresco (43,2 t ha^{-1}) y de materia seca (12,85 t ha^{-1}) se obtuvo con un espaciamiento de 30 cm entre plantas en camellones (S1P1). Sin embargo, el mayor contenido de proteína cruda (19,0 %) se observó con el método de siembra en camellones y espaciamiento de 90 cm (S1P3), mientras que el espaciamiento de 60 cm proporcionó un equilibrio entre rendimiento de forraje fresco y contenido de proteína cruda. Se recomienda, en base a los resultados obtenidos, que el pasto Mombasa se establezca en camellones o surcos en lugar de camas o superficies planas. Asimismo, se sugiere un espaciamiento de 60 cm para lograr un mejor equilibrio entre rendimiento y calidad del pasto Mombasa para la alimentación del ganado.

Palabras clave: pasto perenne; producción; calidad

Resumo
A escassez de forragem durante os períodos críticos no Paquistão é uma grande preocupação para os produtores no que diz respeito à alimentação de seus animais, um problema que pode ser resolvido por meio do cultivo de gramíneas perenes de alto potencial, como o capim Mombaça. Assim, foi conduzido um experimento na Universidade de Agricultura de Faisalabad, utilizando um Delineamento de Blocos Completos Casualizados (DBC), com arranjo de parcelas divididas, no qual os métodos de semeadura (em camalhões ou sulcos, em canteiros e em linhas) foram atribuídos às parcelas principais, enquanto o espaçamento entre plantas (30 cm, 60 cm e 90 cm) foi atribuído às subparcelas. Os dados coletados foram analisados estatisticamente e as diferenças entre as médias dos tratamentos foram determinadas pelo teste LSD ao nível de 5 % de probabilidade. O maior rendimento de forragem fresca (43,2 t ha^{-1}) e de matéria seca (12,85 t ha^{-1}) foi obtido quando a cultura foi estabelecida com espaçamento de 30 cm entre plantas em camalhões (S1P1). No entanto, o maior teor de proteína bruta (19,0 %) foi observado no método de semeadura em camalhões com espaçamento de 90 cm (S1P3), enquanto o espaçamento de 60 cm proporcionou um equilíbrio entre o rendimento de forragem fresca e o teor de proteína bruta. Com base nos resultados obtidos, recomenda-se que o capim Mombasa seja cultivado em camalhões ou sulcos, em vez de canteiros ou superfícies planas. Além disso, sugere-se um espaçamento de 60 cm para alcançar um melhor equilíbrio entre rendimento e qualidade do capim Mombaça para a alimentação do gado.

Palavras-chave: pasto perene; produção; qualidade

Introduction

Livestock needs sufficient nutrition to maintain good health, reproduction and ideal growth rate. But the less accessibility of feed and fodder resources causes a problem for livestock growth and reproductivity. Perennial grasses hold remarkable promise for sustainable biomass production and require less intensive management and chemical inputs to achieve a commercially acceptable yield (Zahorec *et al.*, 2022). In tropical and subtropical areas, these grasses provide vital elements that are necessary for the health and productivity of livestock, including vitamins, protein, and carbs (Vendramini *et al.*, 2023, Saleem *et al.*, 2025).
Mombasa grass (*Megathyrsus maximus* (Jacq.) B.K.Simon & S.W.L.Jacobs (≡*Panicum maximum* Jacq.)) is a perennial grass in *Poaceae* family, originated in Africa and widely extend to the all-tropical regions because of its high quality (Benabderrahim and Elfalleh, 2021). It is a major grass species that is marketed as feed for cattle and is well known for its large biomass of forage and superior nutritional quality (Pereira *et al.*, 2021, Saleem *et al.*, 2026). Its high diversity and adaptability make it particularly important in regions experiencing water stress (Oliveira *et al.*, 2022). It is extremely valued as multi cut forage grass due to its efficiency of propagation and quick growth, i.e., it grows very rapidly after cutting and capable of providing 6-8 cutting annually. It sustains its palatability for a prolonged period and thus is suitable for hay and silage production (Pankhaniya *et al.*, 2023). It shows remarkable resilience to trampling and could produce quality forage yield that is both highly palatable and digestible for livestock (Romero Delgado *et al.*, 2020).
Mombasa grass has been evaluated in grasslands but there is lack of literature on its evaluation in croplands especially under cut and carry system (Saleem *et al.*, 2026). There are many factors which affect crop production directly or indirectly, including sowing methods and plant spacing. Changing sowing method has been reported to affect different crops in arid to semiarid regions (Sher *et al.*, 2018). Flat sowing is the easy and cost effect methods but provides wet conditions leading to more disease attach (Asif *et al.*, 2019) and weed infestation (Nadeem *et al.*, 2013). The ridge system is rapidly gaining importance in fields across the regions with inadequate irrigation and low soil temperature during spring (Gan *et al.*, 2013) because it provides suitable conditions for root penetration and expansion (Nawaz *et al.*, 2020). Raised bed sowing method

saves irrigational water (Mahmood, 2014), helps to prevent root suffocation and diseases (Hashimi *et al.*, 2021) associated with waterlogged conditions (Du *et al.*, 2022).
Besides sowing methods, plant population or planting space is also an important consideration in forage production. Fuksa *et al.* (2023) found narrow row spacing and more dense planting supporting the maize growth and weight accumulation at early stages, but the effects were non-significant at later stages. Improved airflow and reduced humidity in wider spaced plants can reduce the incidence and severity of diseases, such as fungal infections, and minimize pest pressure. Wider planting space can result in greater weed competition initially, as there is more open soil between plants where weeds can establish and these weeds can be controlled through increasing competition (Kaur *et al.*, 2018).

Research gap and objectives

Increasing livestock population demands more quality forage and yield to fulfill the feeding requirements. Mombasa grass is a promising perennial forage famous in grassland of many countries but has not been evaluated as a sole crop in croplands under different sowing methods and management practices. Therefore, current research was conducted with the hypothesis that changing sowing methods and plant spacings will affect the production and quality of mombasa grass. The objective of the study was to assess the performance of mombasa grass in croplands under different agronomic practices for small landholders.

Materials and methods

Experimental details

Experiment was conducted under RCBD split plot arrangement to examine the effect of different sowing methods and plant spacing on agronomic and forage quality traits of Mombasa grass at Student Research Area, Department of Agronomy, University of Agriculture Faisalabad, (UAF; 31° 26′ 2.18″ N, 73° 3′ 53.6″ E). Treatments used were sowing methods (S_1= Ridge sowing, S_2= Bed sowing, S_3= Flat sowing) and plant spacing (P_1= 30 cm, P_2= 60 cm, P_3= 90 cm). All the treatments were replicated three times within a plot size of 5 m × 5 m and the data was recorded from 1 m^2 sampling area of each plot. Randomization of plots was done within blocks by following random assignment. During the experiment, temperature ranged from 40-45 °C while relative humidity ranged from 20-25 %.

Field preparation and crop sowing

A nursey was established to initiate the trial with ploughing a 5 m × 2 m soil area near the field in natural conditions. Soil was well pulverized with spade and shovel to make the seed bed fine and smooth, seed were broadcasted and covered with a thin soil layer to avoid direct exposure. A light irrigation with reduced pressure was applied to make the soil wet and it was repeated for the next 7-8 days (when needed) to keep the soil surface moist. The nursery was ready to transplant after 30 days of sowing (DAS), which was manually uprooted and transferred to the field prepared using cultivator and rotavator. Beds and ridges were made in the field as per layout and the nursery was transplanted according to treatment plan. Crop was heavily irrigated to make sure the contact of plant roots and soil.

Soil analysis

Prior to transplanting nursery into field, the soil was analyzed by collecting random samples from a depth of 15-20 cm. The physical properties of soil were determined by a method given

by Bouyoucos (1962), whereas as the chemical properties of soil were analyzed using proven methods such as electrical conductivity (Corwin and Lesch, 2005), soil nitrogen (Bremner, 1960), organic matter (Harris, 1995), extractable potassium (Soltanpour and Schwab, 1977) and soil phosphorus (Olsen and Sommers, 1983). Data from the soil analysis is given in Table 1. All soil chemical analyses were conducted prior to fertilizer application to characterize the initial fertility status of the experimental site.

Table 1. Soil physicochemical analysis

Component	Unit	Value
Sand	%	44
Silt	%	38
Clay	%	13
pH		7.8
EC	dSm^{-1}	1.69
Organic matter	%	0.72
Nitrogen	ppm	209
Phosphorus	ppm	4.34
Potassium	ppm	220

Crop harvesting and data collection

Crop was harvested 60 days after transplantation (DAT) manually, tillers per plant were counted, electronic weighing balance was used for fresh and dry weights. Five plants from each plot were harvested individually and placed in a round nylon garden net with a mesh size of approximately 1–2 cm. The net was adjusted according to plant height so that the entire plant could be enclosed. The packed plants were kept under shade at room temperature for three days and were turned regularly each morning to maintain proper air circulation and facilitate uniform drying. After excess moisture had been removed, the plants were taken out of the nets, chopped into smaller pieces, and dried in an oven at 60 °C for 48 hours. Once a constant weight was achieved, the samples were ground using a laboratory grinder to pass through a 1–2 mm sieve. Plant height was measured using a measuring tape, stem diameter was measured using a digital vernier caliper and number of leaves per plant were counted manually. Forage quality parameters were analyzed using AgriNIR system, including crude protein (Simoni *et al.*, 2021), acid detergent fiber (ADF) (Arzani *et al.*, 2015), neutral detergent fiber (Cochran *et al.*, 1986, Raffrenato *et al.*, 2018) and total ash content (Pérez-Marín *et al.*, 2004).

Statistical analysis

Data collected were statistically analyzed using analysis of variance (ANOVA) approach and to compare the treatment means, LSD test at 5 % probability was used (Steel *et al.*, 1997) using Statistix (v8.1). Data was arranged in Microsoft Excel (365) and the figures were produced using Origin Lab (v 2024).

Results

Agronomic parameters

Data for agronomic parameters is given in Table 2 and Table 3. Plant height was significantly influenced by the combined effect of both sowing methods and plant spacing when S1P1 produced the tallest plants (194 cm), whereas the shortest plants (164 cm) were observed with treatment S2P2. Number of tillers per plant was also influenced by both the factors with treatment S1P3 producing the highest (36) and S3P1 producing the lowest (12.9) tillers per plant. Number of leaves per plant followed the tillers and were maximum (144) from treatment S1P3 and the minimum (51.6) from treatment S3P1. Fresh and dry weight per plant (480 g and 131 g) were also maximum with treatment S1P3 and the minimum (290 g, and 86.1 g) from treatment S2P1. However, the highest fresh forage yield (43.2 t ha^{-1}) was observed with treatment S1P1 whereas lowest fresh forage yield (21.1 t ha^{-1}) was from treatment S3P3. Maximum dry matter yield (12.85 t ha^{-1}) was noted with treatment S1P1 whereas the minimum dry matter yield (4.13 t ha^{-1}) was observed on S3P3. The highest dry matter percentage (28.66 %) was noted on ridges and lowest (20.86 %) was observed on flat sowing.

Table 2. Data for different agronomic parameters of mombasa grass influenced by varying sowing methods and plant spacing

Factor	Treatment	Observations						
		Plant height (cm)	Tillers $plant^{-1}$	Fresh weight $plant^{-1}$	Dry weight $plant^{-1}$	Fresh forage yield (t ha^{-1})	Dry matter yield (t ha^{-1})	Dry matter percentage (%)
Sowing methods (S)	S_1=Ridge sowing	186 A	28.7A	410 A	117 A	32.9 A	9.51 A	28.6 A
	S_2=Bed sowing	182 A	21.6 B	390 B	93.6 B	31.4 B	7.66 B	24.1 B
	S_3=Flat sowing	173 B	17.8 C	378 C	78.2 C	30.4 C	6.43 C	20.8 C
	LSD value (S)	7.17	2.18	10.81	16.02	0.30	0.39	1.39
Plant spacing (P)	P_1=30 cm	187 A	16.4 B	290 C	74.8 B	41.7 A	10.77 A	25.7 A
	P_2=60 cm	178 B	25.1 A	432.3 B	106 A	31.1 B	7.68 B	24.5 B
	P_3=90 cm	177 B	26.5 A	456.7 A	107 A	21.9 C	5.15 C	23.3 C
	LSD value (P)	3.16	3.58	20.97	3.29	10.20	1.24	0.81

Table 3. Data for different agronomic parameters of mombasa grass influenced by interaction of varying sowing methods and plant spacing

		Plant height (cm)	Tillers plant^{-1}	Fresh weight plant^{-1}	Dry weight plant^{-1}	Fresh forage yield (t ha^{-1})	Dry matter yield (t ha^{-1})	Dry matter percentage (%)
Interaction (S×P)	$S_1×P_1$	194 a	18.21 bc	300 f	89.2 c	43.2 a	12.85 a	29.74
	$S_2×P_1$	184 a-c	18.25 bc	290 g	73.0 d	41.7 b	10.51 b	25.18
	$S_3×P_1$	183.3 a-d	12.92 c	280 h	62.1 d	40.3 c	8.94 c	22.17
	$S_1×P_2$	187 ab	32 a	452 a	130 a	32.5 d	9.38 c	28.84
	$S_2×P_2$	164 e	23.1 b	430 d	103 b	30.9 e	7.46 d	24.09
	$S_3×P_2$	184 a-d	20.32 bc	415 e	86.3 c	29.8 f	6.22 e	20.81
	$S_1×P_3$	179 cd	36 a	480 a	131 a	23.0 g	6.30 e	27.38
	$S_2×P_3$	172 d	23.39 b	450 b	104 b	21.6 h	5.01 f	23.20
	$S_3×P_3$	180 b-d	20.15 bc	440c	86.1 c	21.1 h	4.13 g	19.58
	LSD value (S×P)	7.63	7.71	6.40	10.95	0.66	0.75	---
Values sharing same letter are statistically similar at 5 % probability of LSD test								

Quality parameters

Table 4 and Table 5 contain data for quality parameters in mombasa grass. Highest crude protein contents (19.0 %) were recorded from S1P3 while the lowest (13.4 %) from S3P3. Treatment S2P2 yielded the highest ash content value (27.93 %) among the treatment means, while treatment S3P3 produced the lowest ash content value (14.03 %). Maximum neutral detergent fiber contents (67 %) were observed with the treatment S3P1 whereas minimum (54 %) were from S1P3. The higher value of acid detergent fiber ADF (43.8 %) was recorded on Flat sowing method whereas the lower value of ADF (36.22 %) was observed on Ridge sowing method. The maximum value of ADF (43.33 %) was noted on 30 cm plant spacing whereas the minimum value of ADF (38.30 %) was observed on 90 cm plant spacing that are statistically at par with 60 cm plant spacing. The highest amount of crude fiber (33.33 %) was found at a plant spacing of 30 cm while the lowest amount (29.34 %) was found at a plant spacing of 90 cm that are statistically at par with 60 cm plant spacing. The maximum crude fiber was observed at closer spacing and decreased by increasing plant spacing.

Table 4. Data for different quality parameters of mombasa grass influenced by varying sowing methods and plant spacing

Factor	Treatment	Observations				
		Crude protein (%)	Total ash (%)	Neutral detergent fiber (%)	Acid detergent fiber (%)	Crude fiber (%)
Sowing methods (S)	S_1=Ridge sowing	16.6 A	25.40 A	56.2 B	36.2 B	26.2 B
	S_2=Bed sowing	14.9 AB	23.38 B	61.6 A	41.3 AB	31.7 A
	S_3=Flat sowing	13.6 B	20.70 C	64.1 A	43.8 A	34.52 A
	LSD value (S)	2.15	1.29	5.18	5.18	4.91
Plant spacing (P)	P_1=30 cm	14.4 B	21.30 B	63.3 A	43.3 A	33.3 A
	P_2=60 cm	14.8 B	26.91 A	59.7 B	39.7 B	29.7 B
	P_3=90 cm	16.02 A	21.27 B	58.9 B	38.3 B	29.3 B
	LSD value (P)	1.11	1.30	2.69	2.69	2.68

Table 5. Data for different quality parameters of mombasa grass influenced by interaction of varying sowing methods and plant spacing

		Crude protein (%)	Total ash (%)	Neutral detergent fiber (%)	Acid detergent fiber (%)	Crude fiber (%)
Interaction (S×P)	$S_1×P_1$	14.7 b	23.9 b	59 a-c	39	29
	$S_2×P_1$	14.9 b	16.3 c	64 ab	44	34
	$S_3×P_1$	13.6 b	23.6 b	67 a	47	37
	$S_1×P_2$	16.3 b	26.5 b	55.6 bc	35.6	25
	$S_2×P_2$	14.8 b	29.7 a	60.1 a-c	40.1	30.1
	$S_3×P_2$	13.4 b	24.4 b	63.5 ab	43.5	33.5
	$S_1×P_3$	19.0 a	25.7 bc	54 c	34	24
	$S_2×P_3$	15.1 b	24.0 b	60.6 a-c	39.7	31
	$S_3×P_3$	13.9 b	14.0 c	62.0 a-c	41.1	33
	LSD value (S×P)	3.84	3.18	9.27	---	---
Values sharing same letter are statistically similar at 5 % probability of LSD test						

Correlation and principal component analysis (PCA)

Correlation analysis revealed strong positive associations among plant height (PH), forage fresh yield (FFY), crude protein (CP), crude fiber (CF), total ash (TA), and dry matter percentage (DMP) (Figure 1), indicating that vigorous plant growth was generally accompanied by greater biomass accumulation and improved nutrient concentration. In contrast, fiber fractions, particularly ADF, showed negative relationships with dry matter yield (DMY) and DMP,

suggesting that increased fiber accumulation may reduce forage quality and digestibility. Crude protein and total ash were positively associated with growth-related traits but negatively related to fiber components, reflecting the common trade-off between nutritive value and structural carbohydrate accumulation in forage crops. These relationships indicate that management practices promoting vegetative growth can simultaneously enhance forage yield and nutritional quality while limiting excessive fiber deposition.

Principal component analysis (PCA) explained 76.5 % of the total variation, with PC1 and PC2 accounting for 44.6 % and 31.9 %, respectively (Figure 2). The PCA biplot clearly separated sowing methods and plant spacings according to their associations with yield and quality attributes. Ridge sowing (S_1), particularly when combined with the closer spacing of 30 cm (P_1), was closely associated with plant height, fresh forage yield, dry matter yield, and dry matter percentage, indicating its superiority for biomass production. In contrast, wider plant spacing showed closer associations with crude protein and reduced fiber fractions, indicating improved forage quality. The separation of treatments along the principal components demonstrates that sowing configuration and plant spacing influence resource utilization and canopy development, resulting in a trade-off between forage productivity and nutritive value. Because PCA was performed using the main effects of sowing method and plant spacing, it represents overall patterns among traits and treatments rather than specific interaction effects.

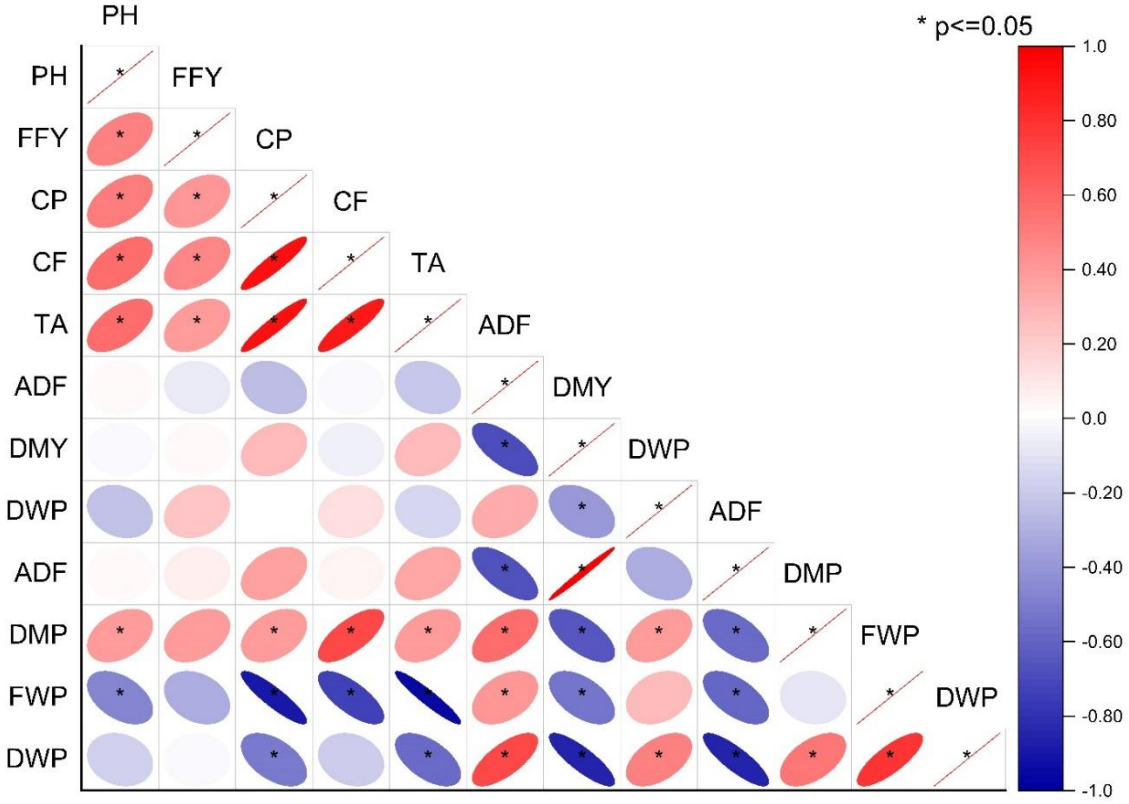


Figure 1. Correlation matrix among agronomic and quality traits of mombasa grass in response to different sowing methods and plant spacings. Red color indicates positive while blue color indicates negative correlations, with color intensity showing the strength of correlation. Ellipses reflect the strength and direction of relationships with narrow and tilted ellipses means strong correlation

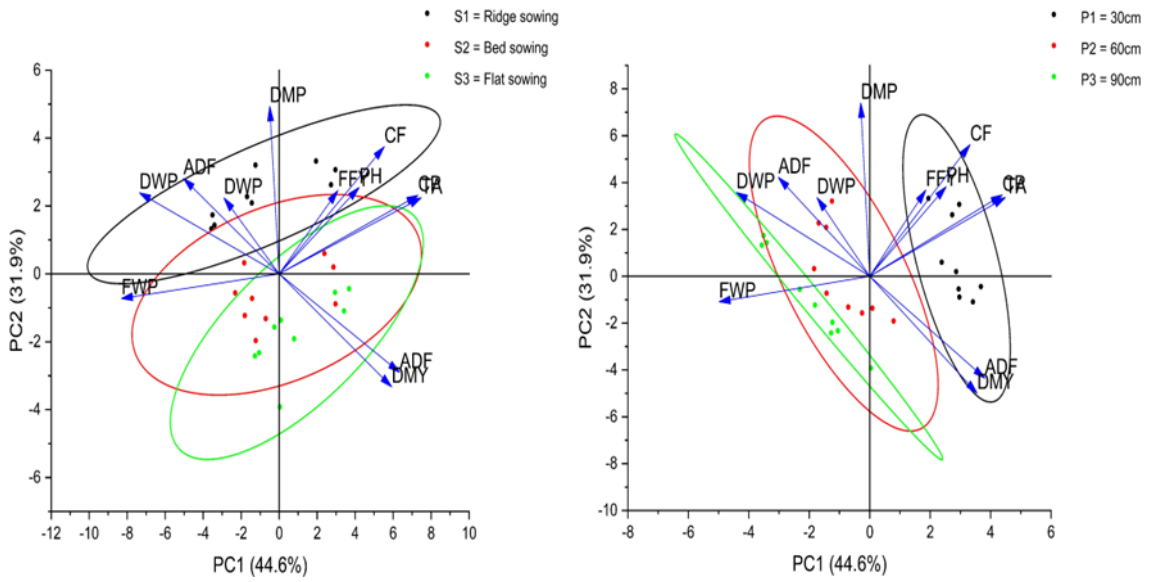


Figure 2. Principal component analysis showing the grouping of traits in response to different sowing methods and plant spacing. Dot colors represent different treatments, while each dot is a subunit. Blue lines are vectors showing the strength and direction of each variable

Discussion

Application of agronomic principles is essential for achieving higher forage productivity and maintaining forage quality under tropical production systems. Among these principles, sowing method and plant spacing play critical roles in regulating plant establishment, canopy architecture, tillering behavior, nutrient uptake, and biomass accumulation (Saleem *et al.*, 2026). Ridge sowing has been reported as an effective cultivation method for minimizing wilting, lodging, and disease incidence while improving crop growth and stand persistence (Zeb and Jan, 2021). The loose and well-aerated soil conditions created under ridge and bed planting systems may have enhanced root proliferation, microbial activity, nutrient cycling, and organic matter decomposition, ultimately improving soil productivity and plant performance (Hashimi *et al.*, 2021). In tropical forage grasses such as Bajra Napier hybrid grass and guinea grass (*Megathyrsus maximus*), proper soil aeration and root-zone development are particularly important because these grasses require rapid tiller recruitment and efficient nutrient acquisition to sustain high forage production. Moreover, raised planting systems improve drainage and air exchange around the root zone, thereby reducing the risk of root and leaf rot diseases and enhancing overall plant vigor.

The present study demonstrated that sowing methods significantly influenced plant height, number of leaves, tiller production, and forage yield. Ridge and Bed sowing methods generally improved growth and yield attributes compared with Flat sowing one. These responses were likely associated with improved soil physical conditions under ridges, including lower soil compaction, better aeration, enhanced water infiltration, and more efficient nutrient uptake. Because information on the response of guinea grass to different sowing methods is limited, the observed improvements are best explained by general plant physiological responses to favorable root-zone conditions. Improved soil aeration and water movement likely enhanced root growth and nutrient acquisition, resulting in greater tiller production, canopy development,

and biomass accumulation. Such conditions favor root elongation and root biomass development, which ultimately enhance tiller initiation and canopy expansion. Similar findings have been reported by Ibrahim *et al.* (2019) who observed greater tiller production under ridge sowing because the ridge surface facilitated better root penetration and improved utilization of water and nutrients. Likewise, Bakht *et al.* (2011) and Memon *et al.* (2007) reported that ridge sowing improved plant height, biological yield, root growth, leaf area, and dry matter accumulation because of efficient water use and improved root-zone aeration. Planting spacing influences the level of competition among individual plants for essential resources (Hortal *et al.*, 2017). In *Megathyrsus maximus* (≡*Panicum maximum*), wider spacing enhanced light interception and reduced interplant competition, thereby creating more favorable growing conditions (Vendramini and Moriel, 2020). The greater forage productivity observed under ridge sowing may therefore be attributed to improved assimilate production and partitioning resulting from enhanced photosynthetic activity and canopy development. Similar observations were also reported by Gondal *et al.* (2020), who noted that ridge sowing enhanced fresh forage yield through better nutrient accessibility, extensive root development, and favorable moisture conditions that promoted higher photosynthetic efficiency.

Plant spacing also markedly affected growth, forage yield, and quality characteristics of the crop. Narrow spacing resulted in taller plants, whereas wider spacing reduced plant height. This response can be explained by inter-plant competition for light under dense plant populations. The observed response is consistent with fundamental canopy competition theory, whereby plants growing under high density allocate more resources to vertical growth in order to maximize light interception. In contrast, reduced competition at wider spacing allows greater allocation of assimilates to tiller development, leaf expansion, and root growth. Under narrow spacing, plants experience shading pressure from neighboring plants, which stimulates stem elongation and vertical growth as a competitive strategy to intercept more solar radiation. Ganvit *et al.* (2019) similarly reported greater plant height under closer spacing because of increased competition for light and growing space. In contrast, wider spacing reduced canopy competition and allowed plants to allocate more assimilates toward lateral growth, root development, and tiller production rather than stem elongation. As a result, wider spacing promoted greater fresh weight per plant, increased tiller number, and improved root growth due to greater availability of light, nutrients, moisture, and physical space for individual plant development (Ullah *et al.*, 2013). Similar results were reported by Velayudham *et al.* (2011), who observed maximum tiller production and greater fresh and dry matter yield under wider spacing in Bajra Napier hybrid grass because of reduced intra-specific competition and improved individual plant growth.

The present results suggest that forage productivity is determined not only by the performance of individual plants but also by stand density. Although wider spacing improved growth on an individual plant basis, narrow spacing may still contribute to higher forage yield per unit area because of increased plant population density. This indicates the existence of a density compensation mechanism in forage grasses, where reductions in individual plant biomass under closer spacing are partially compensated by a greater number of plants per unit area. Such responses are common in tropical forage grasses where canopy structure and tillering dynamics strongly regulate forage accumulation and light interception efficiency. Optimal plant spacing therefore represents a balance between maximizing individual plant growth and maximizing total stand productivity. Consequently, management decisions should consider both plant-level growth and population-level productivity when optimizing forage production systems.

The present findings further indicated that dry matter accumulation was influenced by both sowing method and plant spacing. Ridge sowing produced the highest dry matter percentage, likely because improved moisture availability, nutrient uptake, and root activity enhanced

photosynthetic assimilation and biomass accumulation. Furthermore, narrow spacing increased dry matter percentage, probably because intense competition for light stimulated stem elongation and accumulation of structural carbohydrates in plant tissues. This increase may reflect greater accumulation of structural biomass under competitive growing conditions. As plants compete for light, stem elongation and cell wall development are often enhanced, leading to increased dry matter concentration. Similarly, Saleem *et al.* (2026) reported higher dry matter production in mombasa grass under narrow spacing due to greater inter-plant competition and enhanced vertical growth responses.

Forage quality parameters, particularly crude protein and crude fiber contents, were also significantly influenced by sowing methods and plant spacing. The higher crude protein content observed under ridge sowing may be associated with improved nutrient availability, enhanced nitrogen uptake, and better root development under favorable soil conditions. Improved moisture retention and nutrient cycling under ridge planting likely supported greater nitrogen assimilation and leaf development, which contributed to increased crude protein concentration. The greater crude protein concentration under ridge sowing suggests that improved root activity and nutrient acquisition supported more efficient nitrogen assimilation (Saleem *et al.*, 2026). Enhanced leaf development under favorable growing conditions may have further contributed to the increase in protein concentration.

Crude fiber content increased under closer spacing, likely because higher plant density intensified competition for light and other growth resources, stimulating stem elongation and structural tissue development. The increase in fiber concentration likely reflects a shift toward structural growth under competitive conditions. Greater stem elongation and support tissue formation generally increase the proportion of structural carbohydrates, which can improve stand persistence but may reduce forage digestibility and nutritive value. This increase in structural components consequently raises crude fiber concentration and may reduce forage digestibility. Similar findings were reported by Sultan *et al.* (2019), who observed greater crude fiber content under dense plant populations because of increased structural carbohydrate deposition associated with shading stress and stem development. These findings indicate that canopy structure and plant density not only regulate forage yield but also substantially influence forage nutritive value in tropical forage grasses.

Conclusion

The results demonstrated that ridge sowing combined with 30 cm plant spacing (S_1P_1) produced the highest fresh forage yield (43.2 t ha^{-1}), dry matter yield (12.85 t ha^{-1}), and dry matter percentage (29.74 %). In contrast, ridge sowing with 90 cm spacing (S_1P_3) resulted in superior individual plant growth and forage quality, producing the highest crude protein content (19.0 %) and the lowest fiber fractions. These findings indicate a trade-off between forage yield and nutritive value, where narrower spacing favors biomass production while wider spacing improves forage quality. Therefore, ridge sowing with 30 cm spacing is recommended when maximizing forage yield is the primary objective, whereas 60 cm spacing may provide a practical compromise between productivity and forage quality for livestock feeding. Since this study was conducted during the establishment phase of Mombasa grass and evaluated only a single harvest under Faisalabad conditions, the findings should be considered preliminary recommendations. Further multi-harvest and multi-location studies are required to validate the long-term effects of sowing methods and plant spacing on forage productivity and quality. Given the limited research available on Mombasa grass in Pakistan, the present study provides

baseline information for the development of improved production practices for this emerging forage crop.

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Data availability statement
Data can be provided only on the request of journal, if required.

Author contribution
AI: research idea, guidelines, reviewed the written manuscript. **SA**: conducted the research trial, collected the data, wrote the draft. **MAS**: analyzed the data, created visual diagrams and reviewed the main article. **SN, MA**, **MMA**: helped in trial initiation, and data collection, whereas **MAE**: helped in materials arrangement and other needful activities.

Competing Interest declaration
There was no conflict of interest among the listed authors in any case.

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