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ASSESSING MULTIPLE CEREAL-LEGUME INTERCROPS FOR SUSTAINABLE FODDER PRODUCTION AND QUALITY UNDER SEMI-ARID ENVIRONMENT

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Abstract
Sustainable forage production is essential for combating climate change, and agronomic practices like sorghum-legume intercropping can provide quality livestock feed in changing climates. This practice can boost yields, improve resource efficiency, and enhance system resilience. A study was conducted to assess different sorghum-legume intercrops for sustainable silage production in semi-arid environments. The experiment used a randomized complete block design (RCBD) with the following treatments: T1 = sole sorghum, T2 = sorghum + cluster bean, T3 = sorghum + cowpea, T4 = sorghum + black-eyed pea, T5 = sole cluster bean, T6 = sole cowpea, and T7 = sole black-eyed pea, with three replications and net plot size of 6 m × 2.4 m. Parameters such as plant population, plant height, number of leaves, fresh forage yield, dry forage yield, and silage quality were recorded. The highest leaf area index (5.93) was found in sole sorghum, while the highest plant population (97.22 plants/m²) and number of leaves (12.50) were observed in sorghum + black-eyed pea. Sorghum + black-eyed pea (T4) also showed the highest plant height (255.42 cm), green forage yield (91.67 tons/ha), and crude protein (9.84%) 60 days after sowing. The sorghum + cluster bean system (T2) had the highest dry forage yield (17.13 tons/ha) and crude protein content (11.48%). The highest neutral detergent fiber (58.50%) was recorded in sorghum + black-eyed pea. The study concludes that sorghum-black-eyed pea and sorghum-cluster bean intercrops are ideal for maximizing silage production and improving forage quality, respectively.

1. INTRODUCTION

In Pakistan, the agricultural sector plays a pivotal role, contributing significantly to the nation's economy. The livestock subsector is vital, generating 62.68% of agricultural value addition and 14.36% of the country's GDP in FY2022 (GOP, 2022). However, the sector faces significant challenges, primarily due to the limited availability of high-quality forage for livestock, which directly affects productivity. As the population grows and urbanization increases, the demand for dairy products also escalates, further exacerbating the need for sustainable feed sources (GOP, 2022).

The semi-arid and arid regions of Pakistan, where agriculture heavily depends on livestock, face hardships in fodder production. The area dedicated to forage crops is shrinking, and the availability of green fodder is inadequate, often reducing by 75% during feed crises (Bashir et al., 2001). The scarcity of quality forage is a primary constraint in improving livestock productivity, prompting the need for innovative solutions to ensure a steady and nutritious supply of feed (Ullah et al., 2010). Consequently, intercropping systems, such as sorghum-legume combinations, are being explored as viable options to enhance forage production in these regions.

Sorghum (Sorghum bicolor), a drought-tolerant, high-biomass forage crop, is well-suited for Pakistan's semi-arid climate. It requires significantly less water than other forage crops like maize and is known for its ability to thrive in adverse environmental conditions, making it an ideal candidate for regions facing water scarcity ((Chadalavada et al., 2021; Sarwar et al., 2002). Sorghum's high forage yield and nutritional value have been well-documented, with studies indicating that it can provide excellent feed for dairy livestock, especially when grown in intercropping systems with legumes (Iqbal et al., 2015).

Legumes such as cluster beans (*Cyamopsis tetragonoloba*) and cowpea (Vigna unguiculata) are rich in protein and can complement the nutritional profile of sorghum, thus improving the overall quality of the mixed forage (Hussain & Mahajan, 2025; Iqbal et al., 2018). By combining cereals like sorghum with legumes, intercropping not only boosts yield but also enhances soil fertility, promotes resource efficiency, and reduces the risk of crop failure (Lithourgidis et al., 2007). Furthermore, legumes fix nitrogen in the soil, which can benefit the subsequent crops and enhance system sustainability, making intercropping an attractive strategy for resource-limited environments.

The practice of intercropping is particularly beneficial in enhancing the quality of fodder, a vital feed resource in the lean season. Fodder preservation ensures a consistent supply of fedd, even during periods of low green fodder availability (Kaiser et al., 2004). When properly managed, intercropping systems that include legumes can significantly improve the protein content and overall nutritional value of fodder, thus supporting better animal health and productivity (Iqbal et al., 2018). As climate change and water scarcity continue to threaten traditional forage production, the integration of sorghum with legumes presents a promising solution for sustainable livestock farming in Pakistan's challenging agro-ecosystems.

Materials and methods

Experimental setup

The experiment was conducted in a semi-arid region of Pakistan, characterized by limited rainfall and high temperatures, under conditions that are typical for regions facing challenges in forage production. The study utilized a Randomized Complete Block Design (RCBD) with seven treatment combinations and three replications. The treatments were as follows:

- T_1: Sole Sorghum (Sorghum bicolor)
- T_2: Sorghum + Cluster Bean (*Cyamopsis tetragonoloba*)
- T_3: Sorghum + Cowpea (*Vigna unguiculata*)
- T_4: Sorghum + Black-eyed Pea (*Vigna sinensis*)
- T_5: Sole Cluster Bean
- T_6: Sole Cowpea
- T_7: Sole Black-eyed Pea

Each treatment was assigned to experimental plots of 6 m × 2.4 m, with each treatment replicated three times to ensure statistical validity.

Crop husbandry and experimental management

The experimental plots were systematically arranged with sorghum as the main crop intercropped with legumes. Seedbed preparation was conducted using tractor machinery to achieve optimal soil conditions, with sowing operations completed during the last week of April 2022. The planting utilized recommended seed rates of 80 kg/hectare for sorghum, 45-50 kg/hectare for cluster bean, and 30 kg/hectare for both cowpea and black-eyed pea, employing line sowing with drill method on flat seedbeds. Crop management followed standardized agricultural practices including application of recommended fertilizer rates at sowing, scheduled irrigation regimes, and insecticide applications to prevent crop injury. Harvesting was conducted manually at 60 days after sowing, followed by chopping and silage preparation in boxes for subsequent analysis.

Site and climatic conditions

The experiment was conducted at a research station located in the semi-arid region of Pakistan, where the environmental conditions typify the challenges of forage production in areas with limited water availability. The region experiences a hot, dry climate with temperatures frequently exceeding 40°C during the growing season, and irregular rainfall, making water management crucial. The experiment aimed to assess forage systems capable of withstanding such conditions, with a focus on drought-tolerant crops like sorghum.

Table1: Soil attributes of experimental site

Parameters	Depths		Status
	0-15 (cm)	15-30 (cm)	
pH	7.9	8	Alkaline
EC (dSm^{-1})	1.09	1.1	Saline
Saturation (%)	36	34	
P_2O_5 (ppm)	22.9	17.5	High
K_2O	186	174	Medium
Organic Matter	1.75	1.61	Medium
Sand (%)	20	19	
Silt (%)	17	16	
Clay (%)	63	65	

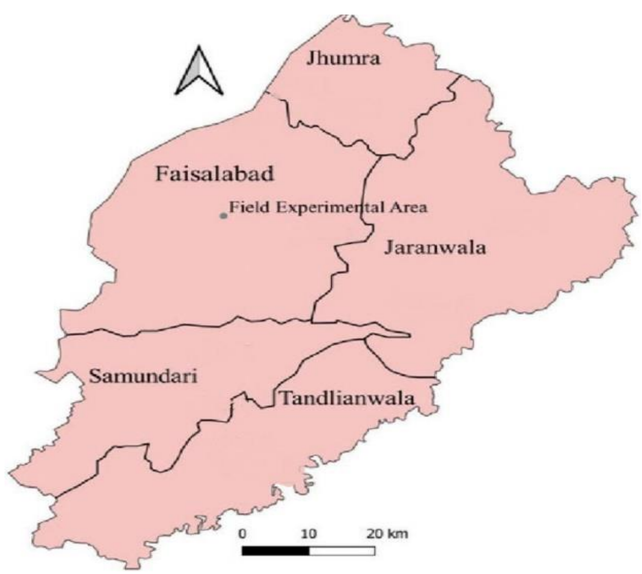

Figure 1: Study area

Destructive sampling started after 30 days of sowing. Each Parameter

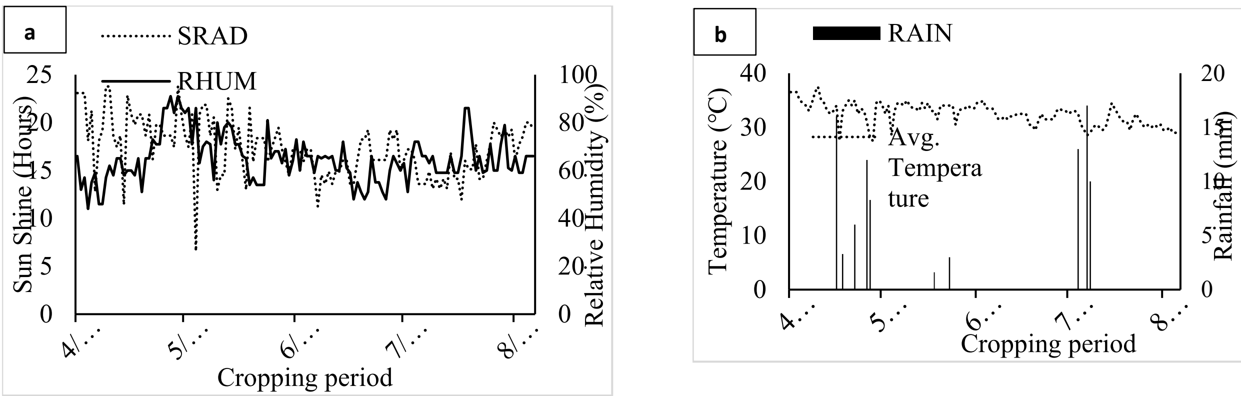

Figure 2: (a) Status of sunshine hours and relative humidity, (b)rainfall and temperature in cropping season

plot was sampled and harvested from a 1 ft^2 area at ground level with 15 days interval. The fresh weight of harvested samples was recorded. Each sample had a sub-sample taken from it, with all its components (leaf and stem) being segregated. The weight of the components was recorded while they were fresh, and then they were oven-dried and weighed separately. The leaf area of 5g leaves subsamples were quantified by using graph method.

Leaf Area Index (LAI)
The ratio of overall leaf area to overall land area is said to be leaf area index. A sub-sample of 5g leaves were utilized to calculate the leaf area using graph method.

$$LAI = \frac{Leaf\ area}{Land\ area} \qquad \text{Eq.1}$$

Crop Growth Rate (CGR) (g m^{-2} d^{-1})
Crop growth rate was calculated according to Hunt's method calculation (1978).

$$CGR = \frac{W_2 - W_1}{t_2 - t_1} \qquad \text{Eq.2}$$

The total dry weights i.e. W_1 and W_2 were collected at time t_1 and t_2.
Leaf Area Duration (LAD) (days)
Leaf area's duration was calculated using Hunt's method. (1978).

$$LAD = \frac{LAI_1 - LAI_2}{2} \times t_2 - t_1 \qquad \text{Eq.3}$$

The leaf area duration at time t_1 and t_2 are LAI_1 and LAI_2.

Net Assimilation Rate (NAR) (g m^{-2} d^{-1})
Using Hunt's formula, the average net assimilation rate (NAR) was measured (1978).

$$NAR = \frac{TDM}{LAD} \qquad \text{Eq.4}$$

Agronomic parameters

A series of agronomic and quality parameters were measured to assess the performance of the various intercropping systems:

1. Fresh forage yield (ton/ha): At harvest, the total fresh weight of forage was measured and converted to tons per hectare.
2. Dry forage yield (ton/ha): A representative sample of the fresh forage was collected, dried in an oven at 65°C for 72 hours, and the dry matter content was used to calculate the dry forage yield.
3.

Proximate composition

Samples were analyzed using the methods of the Association of Official Analytical Chemists (AOAC, 2006).

Protein determination %: A one-gram aliquot of finely ground forage sample was digested in a 500 mL Kjeldahl flask with a 5-gram catalyst mixture (K_2SO_4: $CuSO_4$: $FeSO_4$ in an 85:10:5 ratio) and 30 mL of concentrated sulfuric acid. The flask was heated in a digestion chamber until the contents achieved a clear, colorless state, indicating complete mineralization. The digested material was then quantitatively transferred to a 250 mL volumetric flask and diluted to the mark with distilled water. A 10 mL aliquot of this solution was subjected to micro-Kjeldahl distillation following the addition of 10 mL of 40% sodium hydroxide. The nitrogen, liberated as ammonia, was distilled and quantitatively trapped in a receiving solution of 4% boric acid containing methyl red indicator. Upon reaching the distinctive golden-yellow endpoint, the receiving beaker was removed. The absorbed ammonia was then titrated against a standardized 0.1 N sulfuric acid solution until a persistent pink color marked the final endpoint. The nitrogen percentage was subsequently calculated using the established formula.

$$\text{Nitrogen (\%)} = \frac{0.1\ ml\ N\ H_2SO_4 \times 0.0014 \times 250}{Wt.of\ sample \times volume\ of\ diluted\ sample}$$

Eq.5

The following formula was used to find out CP.

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

Eq.6

*(6.25 is a formula factor)

Ether-extractable fat was determined via Soxhlet extraction: A two-gram aliquot of an oven-dried sample was loaded into an extraction thimble and sealed with cotton. The thimble was placed into the central chamber of the Soxhlet apparatus, which consists of a condenser, an extraction chamber, and a boiling flask. Approximately 250 mL of diethyl ether was added to the flask, and the condenser related to a continuous water coolant supply. The apparatus was placed on a hot plate to ensure gentle, indirect heating. The ether was heated to its boiling point (40-60°C), vaporized, and traveled upward into the condenser, where it liquefied. The condensed solvent dripped onto the sample in the thimble, progressively dissolving the fat. Once the solvent level in the chamber surpassed the siphon arm's height, the fat-laden ether siphoned back into the boiling flask. This cyclic extraction process was repeated continuously for 6 to 8 hours to ensure exhaustive lipid recovery. Following extraction, the flask was carefully detached. The ether-fat mixture was then transferred to a pre-weighed petri dish and placed in an oven at 70°C to evaporate the solvent. The mass of the residual fat was determined gravimetrically.

$W_3 = W_1 - W_2$ = weight of pure fat

Where W_1 = weight of the empty petri dish,

W_2 = weight of beaker – fat from 2.0 g sample of dried plant material fat percentage was calculated as follows.

$$\text{EEF (\%)} = \frac{W3}{Sample\ wt.} \times 100$$

Eq.7

OR

$$\text{EE (\%)} = \frac{Wt.\ of\ residue}{Wt.\ of\ sample} \times 100$$

Eq.8

Crude fiber%: Crude fiber content was quantified gravimetrically. A two-gram aliquot of the oven-dried sample was first defatted using a Soxhlet apparatus. The resulting fat-free residue was subsequently digested with 200 mL of 1.25% sulfuric acid solution, maintained at boiling temperature for 30 minutes. The digested mixture was filtered through a thick-lined cloth, and the residue was thoroughly washed with distilled water.

This residue was then subjected to a second digestion using 200 mL of 1.25% sodium hydroxide solution, also under reflux for 30 minutes. Following alkali digestion, the mixture was again filtered and washed exhaustively with distilled water. The insoluble residue was transferred to a pre-weighed porcelain crucible and dried in a forced-air oven at 105°C until a constant weight was achieved, recorded as the dry weight. The crucible was then placed in a muffle furnace and ignited at 600°C until inorganic, grey-white ash was obtained. The weight of this residual ash was recorded. The crude fiber percentage was calculated from the loss in mass upon ignition.

$$CF\ (\%) = \frac{Wt.\ of\ dreied\ residues - wt.\ of\ ash}{Wt.\ of\ sample} \times 100 \quad \text{Eq.9}$$

*Determination of total ash (%)***:** For determining ash 5-gram oven dried sample was placed in a clean, previously weighted, China dish (W_1). The sample was placed in a muffle furnace at dull red heat (500-800°C) until white or gray ash was obtained. After that, residues were cooled in a desiccator and the weight (W_2) recorded and then percentage was recorded as below:

$$Ash\ (\%) = \frac{Wt.of\ Ash}{Wt.of\ sample} \times 100 \quad \text{Eq.10}$$

Determination of neutral detergent fiber (NDF)%: (NDF) quantifies the insoluble fractions of forage, primarily comprising cellulose, hemicellulose, and lignin. This analytical method selectively removes non-structural cellular components, including soluble proteins, sugars, lipids, and pectin, using a neutral detergent solution. It is important to note that certain constituents, such as silica and some tannins, are also solubilized and are therefore not part of the NDF value.

The NDF solution was prepared by dissolving the following reagents in distilled water to a final volume of 1 liter:

- Sodium Lauryl Sulfate: 30 g
- Disodium EDTA Dihydrate: 18.60 g
- Sodium Tetraborate Decahydrate: 6.80 g
- 2-Ethoxyethanol: 10 mL
- Disodium Hydrogen Phosphate: 4.56 g

The pH of the solution was subsequently adjusted to 6.95 ± 0.05 using 0.1 N NaOH or H_2SO_4. A one-gram sample was weighed into a conical flask, and 100 mL of the NDF reagent was added. The flask was fitted with an air condenser and heated at reflux for 60 minutes. After the digestion period, the flask was cooled to ambient temperature, and the condenser was removed. The contents were filtered under vacuum through a pre-weighed ceramic crucible. The residual fiber was washed thoroughly with hot distilled water (4-5 times) to remove all soluble matter, followed by two washes with acetone to dehydrate the residue. The crucible containing the residue was transferred to a hot-air oven and dried at 105°C for 24 hours. Upon completion of drying, the crucible was placed in a desiccator to cool to room temperature and then weighed to determine the constant dry weight of the NDF residue.

Neutral detergent fiber was calculated according to:

$$NDF\ (\%) = \frac{Wt.\ of\ crucible + Dried\ NDF\ residues - Wt.\ of\ crucible}{Wt.\ of\ sample} \times 100 \quad \text{Eq.11}$$

Determination of acid detergent fiber (ADF)%: The acid detergent reagent was prepared by dissolving 20 g of cetyltrimethylammonium bromide (CTAB) in a 1 N sulfuric acid solution, brought to a final volume of 1 liter. The residue obtained from the (NDF) determination was quantitatively transferred to a 500 mL conical flask. One hundred milliliters of the Acid Detergent solution was added to the flask. The apparatus was assembled with an air condenser, and the mixture was heated under reflux for 60 minutes. Following digestion, the flask was cooled, and the contents were filtered under vacuum through a pre-weighed ceramic crucible. The residual fiber was washed thoroughly with hot distilled water (4-5 times) to remove acid residues, followed by two successive washes with acetone to dehydrate the material. The crucible and its contents were placed in a hot-air oven and dried at 105°C for 24 hours until a constant mass was achieved. The crucible was subsequently transferred to a desiccator, allowed to cool to ambient temperature, and weighed to record the mass of the dried residue. The acid detergent fiber content was calculated gravimetrically according to the official method of AOAC (2006).

$$ADF\ (\%) = \frac{Wt.of\ ash\ with\ crucible\ after\ treatment - Wt.of\ crucible}{Wt.of\ sample} \times 100 \quad \text{Eq.12}$$

Statistical analysis

The obtained data were analyzed statistically using Fisher's analysis of variance and treatment means were compared by using Tukey's HSD at a 5% significance level by using Statistix 8.1 (Analytical Software, USA; Steel *et al.*, 1997).

Results and discussion

Growth parameter analysis of sorghum-legume intercropping systems

The investigation of growth parameters revealed significant variations across different sorghum-legume intercropping systems, with Leaf Area Index (LAI) demonstrating distinct patterns among treatments. Sole sorghum (T1) recorded the highest LAI value of 5.93, closely followed by sorghum intercropped with black-eyed pea (T4) at 5.73, while sorghum-cowpea intercrop (T3) showed the lowest sorghum LAI at 5.53. In the legume components, sole black-eyed pea (T7) achieved the maximum LAI of 2.11, statistically comparable to black-eyed pea intercropped with sorghum (T4) at 2.07. Conversely, cluster bean systems, both as sole crop (T5) and intercropped with sorghum (T2), yielded the lowest legume LAI of 0.26. These LAI patterns align with Akhtar et al. (2013), who documented superior leaf area development in monoculture sorghum systems, attributing this advantage to reduced competition for growth resources and more efficient utilization of light, water, and nutrients.

Further analysis of growth dynamics revealed that Leaf Area Duration (LAD) followed similar trends, with sole sorghum (T1) demonstrating the highest LAD at 124.27 days, closely followed by sorghum with black-eyed pea (T4) at 118.85 days. The compatibility between sorghum and black-eyed pea appeared to facilitate enhanced resource use efficiency, resulting in prolonged photosynthetic activity. Crop Growth Rate (CGR) assessments showed that sorghum intercropped with cluster bean (T2) achieved the highest growth rate at 105.00 g m^{-2} d^{-1}, surpassing even sole sorghum (T1) at 95.50 g m^{-2} d^{-1}. This accelerated growth in sorghum-cluster bean systems can be attributed to enhanced nitrogen fixation and efficient resource complementarity, as supported by Langat et al. (2006). Net Assimilation Rate (NAR) evaluations revealed that sole sorghum (T1) maintained the highest rate at 20.82 g m^{-2} d^{-1}, with sorghum-cluster bean (T2) following closely at 20.04 g m^{-2} d^{-1}. The consistent performance of sorghum-black-eyed pea systems in LAI and LAD, coupled with the superior CGR in sorghum-cluster bean arrangements, highlights the potential for strategic intercropping combinations to optimize different aspects of growth performance in forage production systems.

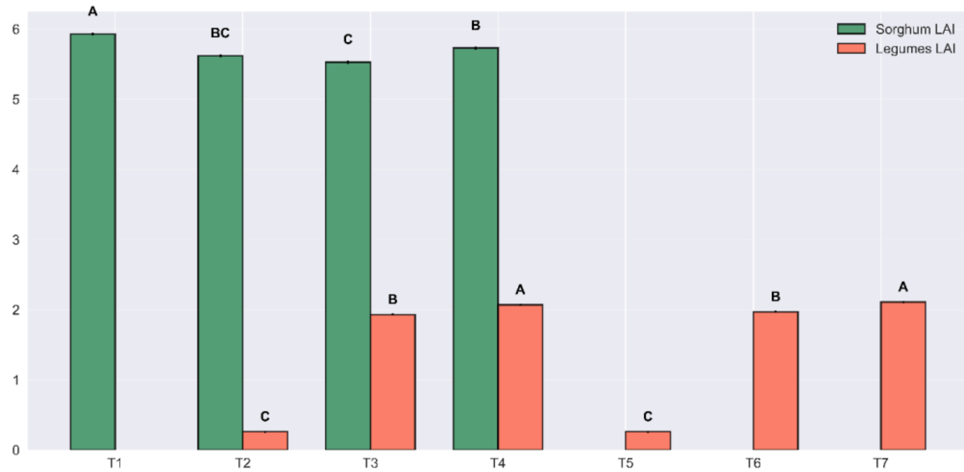

Figure 3: Leaf Area Index (LAI) of sorghum and legume components under different treatments

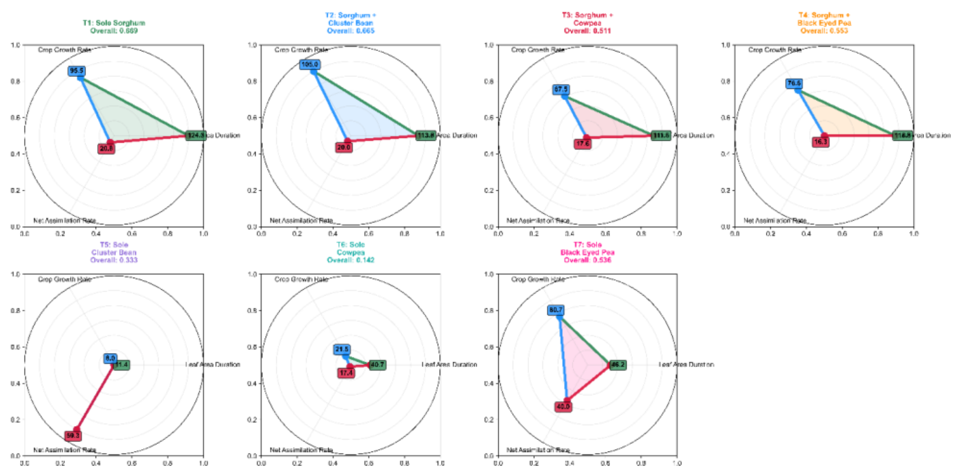

Figure 4: Growth attributes of sorghum–legume cropping treatments

Yield performance of sorghum-legume intercropping systems

The evaluation of fresh forage yield demonstrated significant variations among different sorghum-legume intercropping systems, with sorghum intercropped with black-eyed pea (T4) achieving the highest yield of 91.67 t ha^{-1}, closely followed by sorghum with cluster bean (T2) at 80.00 t ha^{-1}. In contrast, sole cowpea (T6) produced the lowest fresh forage yield at 11.66 t ha^{-1}. The superior performance of sorghum-black-eyed pea systems can be attributed to enhanced agronomic characteristics including increased plant population at harvest, greater plant height, and improved leaf development. The reduced yield in sorghum-cowpea combinations potentially resulted from inadequate nodule formation for effective biological nitrogen fixation, creating competitive interactions that limited sorghum productivity. These findings align with Carruthers et al. (2000), who emphasized the positive correlation between increased plant density and mixed crop yield enhancement in intercropping systems.

Dry forage yield assessment revealed similar patterns, with sorghum-cluster bean intercrops (T2) producing the highest dry matter yield of 17.13 t ha^{-1}, followed by sorghum-black-eyed pea systems (T4) at 16.66 t ha^{-1}. Sole cowpea (T6) again recorded the lowest yield at 1.84 t ha^{-1}. The elevated dry matter production in sorghum-cluster bean intercropping suggests efficient resource utilization and potentially improved nutrient availability from the legume component. These results corroborate Kumar et al. (2005), who documented that while individual component yields in intercropping systems might be lower than sole crops, the combined dry matter yield in sorghum-legume systems often exceeds that of monoculture sorghum. The consistent superiority of sorghum-black-eyed pea and sorghum-cluster bean systems across both fresh and dry yield parameters highlights their potential for optimizing forage production through complementary resource use and reduced interspecific competition.

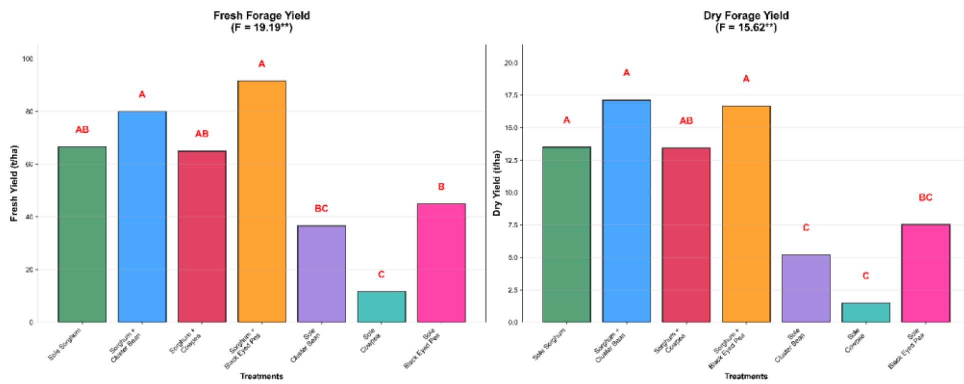

Figure 5: Effect of sorghum–legume cropping systems on fresh and dry forage yield (t/ha).

Nutritional quality of sorghum-legume intercropping systems

The evaluation of crude protein content across different sorghum-legume intercropping systems revealed substantial variations, with sole cowpea (T6) demonstrating the highest crude protein content at 16.40%, closely followed by sole black-eyed pea (T7) at 14.22%. Among the intercropping systems, sorghum with cluster bean (T2) showed the most favorable protein content at 11.48%, while sorghum with cowpea (T3) recorded the lowest at 8.20%. These findings align with Marer et al. (2007), who documented that intercropping sorghum with legumes significantly enhances crude protein content in silage due to improved nitrogen availability from biological nitrogen fixation. Sanchez et al. (2010) further corroborated these results, emphasizing cowpea's superior performance in protein enhancement among legume intercrops.

Crude fiber analysis indicated that sorghum intercropped with black-eyed pea (T4) yielded the highest fiber content at 38.00%, followed by sorghum with cowpea (T3) at 37.00%. The lowest fiber content was observed in sole cowpea (T6) at 17.50%. The increased nitrogen content from legume intercrops contributed to reduced crude fiber levels in mixed forages, as noted by Pal and Sheshu (2001), who found that sorghum-legume intercropping effectively decreases fiber content while enhancing overall forage quality. This reduction in fiber content is particularly beneficial for improving digestibility and animal performance. The assessment of crude fat content demonstrated that sorghum with black-eyed pea (T4) achieved the highest value at 4.16%, with sorghum and cluster bean (T2) following at 3.50%. Sole cowpea (T6) recorded the lowest fat content at 2.16%. These results support the findings of Rashid and Himayatullah (2003), who reported that intercropping sorghum with legumes significantly improves ether extractable fat percentage, with sorghum-black-eyed pea combinations showing particularly enhanced fat content. This enhancement in fat content provides essential energy reserves for livestock production.

Crude ash content, indicating mineral richness, was highest in sole cowpea (T6) at 27.25%, followed by sole black-eyed pea (T7) at 16.00%. Among intercropping systems, sorghum with cluster bean (T2) showed the best performance at

10.50%. The diverse mineral composition in intercropped silage provides essential nutrients supporting various metabolic processes in animals, addressing potential mineral deficiencies that could lead to health issues in livestock.

Neutral Detergent Fiber (NDF) analysis revealed that sorghum with black-eyed pea (T4) had the highest content at 58.50%, while sole cluster bean (T5) recorded the lowest at 39.00%. These findings are consistent with Amole et al. (2013), who observed elevated NDF levels in intercropped silage systems. The variation in NDF content across treatments reflects differences in feed type and harvest timing, as noted by Aderinola et al. (2014), with higher fiber content potentially affecting digestibility and forage quality. Acid Detergent Fiber (ADF) evaluation showed that sorghum with cluster bean (T2) had the highest content at 23.00%, while several treatments including sole cluster bean (T5), sole cowpea (T6), and sole black-eyed pea (T7) recorded the lowest at 9.50%. Jahanzad et al. (2016) observed that increasing legume proportions in mixtures generally reduces ADF and NDF contents, supporting the current findings where legume-dominant systems showed lower fiber content. The fiber characteristics observed align with Oflaz (2019) for cluster bean silages and demonstrate the complex interactions between sorghum and legume components in determining final forage quality parameters.

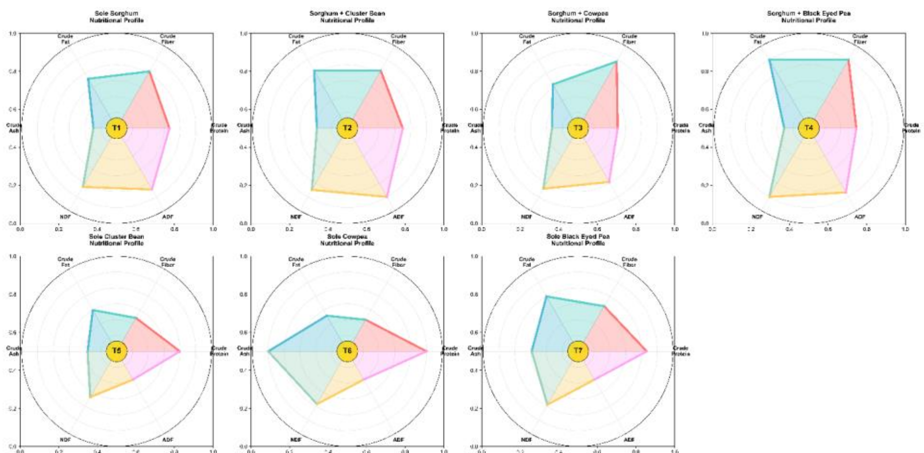

Figure 6: Nutritional profile of sorghum–legume cropping treatments

Hierarchical cluster analysis (HCA) and Principal component analysis (PCA)

The hierarchical cluster analysis (HCA) presented in Figure 5 shows the grouping of sorghum–legume cropping treatments based on their growth, yield, and nutritional characteristics using Euclidean distance. The dendrogram clearly separates the treatments into two major clusters. The first cluster consists of T1 (Sole Sorghum), T2 (Sorghum + Cluster Bean), T3 (Sorghum + Cowpea), and T4 (Sorghum + Black Eyed Pea), which are closely related and represent high-yielding and better-performing treatments. The second cluster includes T5 (Sole Cluster Bean), T6 (Sole Cowpea), and T7 (Sole Black-Eyed Pea), which show relatively lower yield and distinct growth or nutritional attributes. The greater Euclidean distance between the two clusters indicates a strong differentiation between sole legume systems and sorghum-based intercropping systems, emphasizing that the inclusion of sorghum in mixtures significantly influences overall performance.

The principal component analysis (PCA) biplot shown in Figure 6 explains 88% of the total variability among treatments, with the first principal component (PC1) accounting for 75.0% and the second principal component (PC2) explaining 13.0%. PC1 is mainly associated with yield and growth traits such as fresh yield, dry yield, crop growth rate, leaf area duration, ADF, NDF, crude fiber, and crude fat, while PC2 represents nutritional components including crude protein, crude ash, and net assimilation rate. Treatments T1, T2, T3, and T4 cluster on the right side of the biplot, indicating high yield and superior growth performance, whereas T5, T6, and T7 are positioned on the left, corresponding to higher crude protein and ash contents but lower yield. The vector orientation reveals strong positive correlations among yield-related parameters, while crude protein and ash show negative correlations with yield traits. Overall, the PCA highlights that the Sorghum + Black Eyed Pea (T4) and Sorghum + Cluster Bean (T2) combinations exhibited the most balanced performance in terms of yield, growth, and nutritional quality.

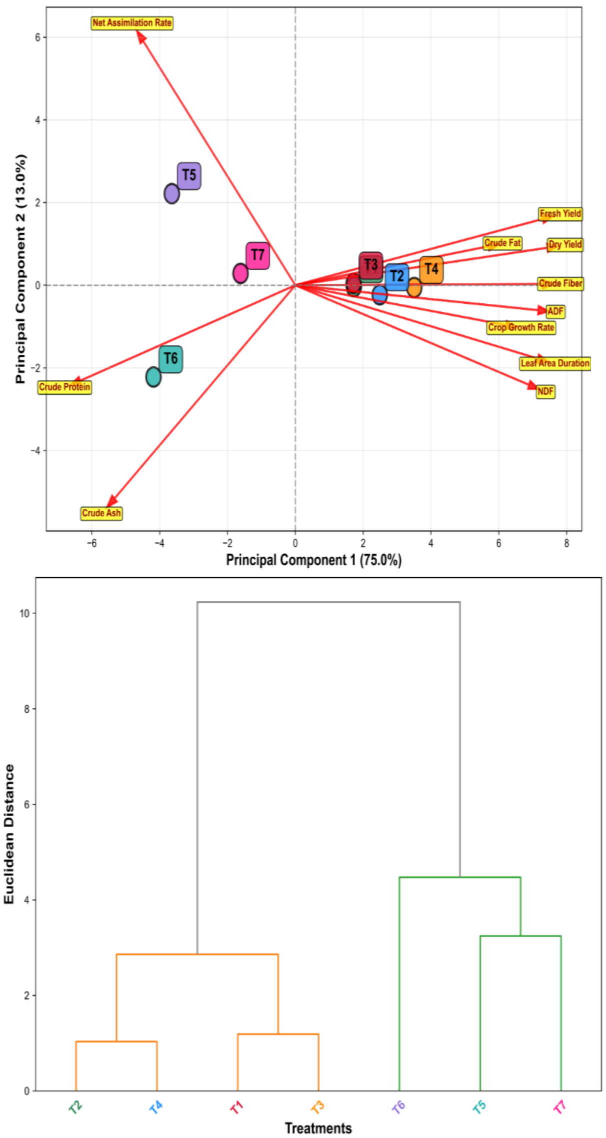

Figure 7: Multivariate analysis of sorghum–legume cropping treatments using Hierarchical Clustering and Principal Component Analysis (PCA)

Conclusion

This study highlights the potential of sorghum–legume intercropping systems for enhancing forage yield and nutritional quality in semi-arid environments. Sorghum + Black-eyed Pea (T4) and Sorghum + Cluster Bean (T2) performed the best, offering high green and dry forage yields,

improved protein content, and superior growth attributes. Intercropping significantly improved resource-use efficiency, with legumes contributing to better nitrogen availability. The multivariate analyses confirmed that sorghum-based mixtures were superior in yield and nutritional value compared to sole crops. These findings suggest that sorghum–legume intercropping is a viable, sustainable approach to boost forage production and livestock feed quality, supporting resilient farming systems in water-scarce regions.

Author contributions

All authors have contributed to various aspects of the study, including conceptualization, writing, editing, and revisions.

Conflict of interest disclosure

The authors declare that they are entirely free from any financial or ties that may have influenced the results presented in this work.

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