



RESEARCH ARTICLE

Nitrogen-driven improvement of biomass yield and forage quality in sustainable year-round fodder systems

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Received: 04 November 2025; Accepted: 05 December 2025; Available online: Version 1.0: 07 January 2026

Cite this article: Dileep KC, Yogananda SB, Denesh GR, Suma R, Chandrakala H, Girish KS. Nitrogen-driven improvement of biomass yield and forage quality in sustainable year-round fodder systems. *Plant Science Today*. 2026;13(sp1):01–11. <https://doi.org/10.14719/pst.12587>

Abstract

A consistent supply of nutritious fodder is vital for sustaining livestock productivity and reducing dependence on external feed resources. To bridge the fodder deficit, year-round sustainable fodder production systems with efficient nitrogen management are essential for enhancing biomass yield and forage quality. To address this need, the field experiment was conducted during the *rabi* (October-February), summer (March-May) and *kharif* (June-October) season of 2023-24 and 2024-25 at the ZARS, V. C. Farm, Mandya, Karnataka. The primary objective of this research was to identify the most productive cereal-legume cropping system with optimizing nitrogen levels, that enhances quantity and quality of biomass production while reducing the gap between the supply and demand of quality fodder throughout the year. Among cropping systems evaluated, Fodder Oats + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1) - Fodder Maize + Cowpea (3:1) recorded significantly higher green forage yield (977 q ha⁻¹ year⁻¹), dry matter yield (204 q ha⁻¹ year⁻¹), crude protein yield (28.23 q ha⁻¹ year⁻¹), total carbohydrate yield (150.6 q ha⁻¹ year⁻¹), land equivalent ratio (1.34) and economic profitability (B:C ratio 2.81). Likewise, application of 125 % Recommended Dose of Nitrogen (RDN) significantly increased green forage yield (998 q ha⁻¹ year⁻¹), dry matter yield (214 q ha⁻¹ year⁻¹), crude protein content (14.13 %) and profitability (B:C ratio 2.86). Hence, adopting a diverse fodder cropping system integrated with intercrop cowpea in cereal fodder crops and applying 125 % RDN ensures sustainable year-round fodder production with enhanced yield, nutritive quality and profitability, offering viable strategy for livestock-intensive farming.

Keywords: cropping system; fodder; nitrogen levels; quality; yield

Introduction

Livestock farming is an indispensable pillar of global agriculture, playing a crucial role in rural economies, food security and sustainable farming systems (1). In India, livestock sector is deeply interwoven with crop production, forming a mutually beneficial relationship that enhances farm productivity, soil fertility and resource efficiency (2). Economically, the livestock sector contributes approximately 4.1 % to India's Gross Domestic Product (GDP) and accounts for nearly 25 % of the agricultural GDP, making a vital component of national development (3). The 20th Livestock Census (2019) reports that India has a vast and diverse livestock population, comprising 302.79 million bovines (cattle and buffaloes), 148.88 million goats and 74.26 million sheep (4). However, the expansion of livestock farming has outpaced the availability of quality fodder, creating a substantial feed deficit. Estimates from the National Institute of Animal Nutrition and Physiology (NIANP) highlight a 35 % shortfall in green fodder, 11 % in dry fodder and 44 % in concentrate feed (5). These severe fodder deficit in India poses a major challenge to livestock productivity, farm profitability and rural livelihoods. This scarcity, particularly acute during lean seasons, negatively impacts milk yield, meat production and reproductive efficiency while forcing

farmers to rely on costly commercial feed supplements. With the expanding livestock population and increasing demand for high-quality fodder, it is imperative to develop scientific and sustainable strategies to ensure continuous fodder availability (6).

Feeding dairy animals solely with green forages is considerably more economical compared to concentrate feeding. In milk production, nearly two-thirds of the total cost is attributed to feed when both concentrates and green fodders are provided in a mixed ration. However, if milk yield relies mainly on concentrate-based diets, the feeding cost may rise to about 80 % of the production expenditure, whereas forage-based rations account for only around 40 %. Therefore, supplying adequate quantities of green fodder in place of expensive concentrates can substantially lower the cost of milk production. Moreover, forages serve as a valuable source of nutrients, containing 8-10 % protein in cereals and 18-22 % in legumes, along with essential minerals such as calcium and phosphorus, vitamins like β -carotene, carbohydrates and micronutrients. Their *in-vitro* dry matter digestibility (IVDMD) typically ranges from 55 to 75 % (7).

Cereal-legume intercropping systems involving annual fodder crops, including high-yielding varieties and hybrids, offer an effective

strategy to meet the increasing demand for quality forage. These systems support sustainable intensification by improving fodder productivity while maintaining continuous soil cover, which contributes to weed suppression, reduced pest and disease incidence, lower soil erosion and enhanced nitrogen availability through biological nitrogen fixation (8, 9). Improved dry matter productivity has been reported under sorghum-lima bean intercropping (10, 11), while pearl millet intercropped with cluster bean has shown higher forage yield with better nutritive value (12). The superiority of cereal-legume combinations in enhancing forage yield and quality is well documented (8, 13-15). Globally, cereal-legume-based forage systems contribute to environmental sustainability by reducing dependence on synthetic fertilizers, increasing soil carbon storage, decreasing runoff losses, improving drought resilience and enhancing profitability for livestock farmers (8-10, 13). Although more common in low-input farming regions, interest in such systems has increased in high-input production zones due to growing emphasis on conservation agriculture and feed security.

Nitrogen management plays a decisive role in enhancing crop productivity within fodder cropping systems. Optimized nitrogen application improves chlorophyll content, photosynthetic efficiency, leaf area development and tillering, resulting in greater biomass accumulation and green forage yield in cereals (16-18). In legumes, adequate nitrogen supports efficient nodulation and biological nitrogen fixation, contributing to higher crude protein content and improved forage nutritive quality (16, 19, 20). Studies have reported substantial increases in dry matter yield, crude protein yield, total carbohydrates and overall forage productivity with increasing nitrogen levels up to optimal thresholds (17, 20, 21). Integration of cereal-legume intercropping with appropriate nitrogen management is therefore critical for maximizing year-round fodder production, forage quality and economic returns.

Despite the proven advantages of cereal-legume intercropping, limited research exists on forage quality and overall fodder productivity under year-round cropping sequences involving annual fodder crops and their seasonal rotations. Therefore, this study was undertaken to identify the most efficient cereal-legume fodder system, combined with improved nitrogen levels, capable of maximizing biomass yield and nutritive quality throughout the year, thereby reducing the gap between the supply and demand of quality livestock feed.

Materials and Methods

Experimental site description: Weather and soil

Field experiment was carried out during *rabi*, summer and *kharif* seasons of 2023-24 and 2024-25 at the Zonal Agricultural Research Station (ZARS), Vishweshwaraiah Canal (VC) Farm, Mandya. It is situated in southern dry zone (ACZ-VI) of Karnataka between 12° 45' and 13° 57' North latitude and 76° 45' and 78° 24' East longitude at an altitude of 695 m above mean sea level. The year-round cropping period extended from November to August in both experimental years. During 2023-24, peak rainfall occurred in May with 230.2 mm, while in 2024-25, the highest rainfall of 156 mm was also recorded in May. To mitigate moisture stress during the dry months, life saving irrigation was applied at 15 day intervals using water classified under irrigability class II. The maximum and minimum temperatures during 2023-24 were recorded in April (37.5 °C) and January (18.0 °C), respectively. In 2024-25, the highest temperature of 35.8 °C was

observed in March, while the lowest temperature of 16.2 °C occurred in January. Relative humidity ranged from a maximum of 88 % in July to a minimum of 55 % in April during 2023-24, whereas in 2024-25, it varied between 84 % in June and 54 % in August. (Fig. 1a, b).

The experimental site is characterized by red, lateritic soils, derived from granite-gneiss under sub-tropical semi-arid climate. According to the USDA soil classification system, the soils are categorized as fine, kaolinitic, isohyperthermic typic Kandiuastalf. The soil of experimental site was neutral in reaction (7.24) with moderate electrical conductivity of 0.36 dS m⁻¹, medium in organic carbon content (0.58 %), medium in available N and K₂O (296.52 and 180.40 kg ha⁻¹), high in available P₂O₅ (50.64 kg ha⁻¹).

Experimental details

A split-plot design was selected in this experiment because it was more practical and efficient for evaluating the combined effects of fodder cropping systems and nitrogen levels across multiple seasons. The cropping systems (main-plot factor) involved large-scale field operations such as intercropping arrangements and crop rotation sequences, which required more space and were difficult to randomize and manage at smaller plot sizes. In contrast, nitrogen levels (subplot factor) were easier to apply uniformly in smaller units within the main plots. Therefore, the split-plot approach facilitated better resource utilization, operational convenience and realistic field management while enabling the evaluation of treatment interactions between cropping systems and nitrogen levels. The experiment consists of eighteen treatments combination (six main plots x 3 sub plots) which were replicated thrice. Complete treatment details were given in Table 1.

The investigation comprised of six crops: Oats (Variety Kent), Maize (African tall), Sorghum (Variety CNFS-1), Bajra (Variety BAIF bajra-1), Cowpea (Variety MFC-09-1), Field bean (Variety 1373 line). Seeds of main and intercrops were line-sown at the recommended row proportions as per the treatments, maintaining a spacing of 30 cm x 10 cm. Intercrops were sown as a replacement series between the rows of maincrop in 3:1 proportion. The recommended fertilizer for the fodder crops in this study as follows: fodder oats (100 kg N ha⁻¹, 60 kg P ha⁻¹ and 40 kg K ha⁻¹), fodder maize (150 kg N ha⁻¹, 75 kg P ha⁻¹ and 75 kg K ha⁻¹), fodder sorghum (90 kg N ha⁻¹, 50 kg P ha⁻¹ and 40 kg K ha⁻¹), fodder bajra (100 kg N ha⁻¹, 60 kg P ha⁻¹ and 40 kg K ha⁻¹), fodder cowpea (25 kg N ha⁻¹, 50 kg P ha⁻¹ and 25 kg K ha⁻¹) and fodder field bean (25 kg N ha⁻¹, 50 kg P ha⁻¹ and 25 kg K ha⁻¹). Chemical fertilizers (P and K) were applied in the furrows and thoroughly mixed with the soil at the time of sowing as per the package of practices except for nitrogen, which was applied according to the treatment specifications. For all crops, 50 % of the recommended nitrogen (N) was applied as a basal dose at the time of sowing and remaining 50 % was top-dressed 30 days after sowing. The full recommended doses of phosphorus (P) and potassium (K) were applied at the time of sowing.

Biomass measurement

The crops were harvested as per the predetermined schedule based on their respective growth stages. Seasonal maize and sorghum were harvested at the milking and full flowering stages, while pearl millet, oats, field bean and cowpea were harvested at 50 % flowering. From each experimental plot, crops within the net plot area were harvested separately and their weights were recorded using a spring balance. The recorded weights were converted to a hectare basis and expressed as green fodder yield (GFY) in quintals per hectare.

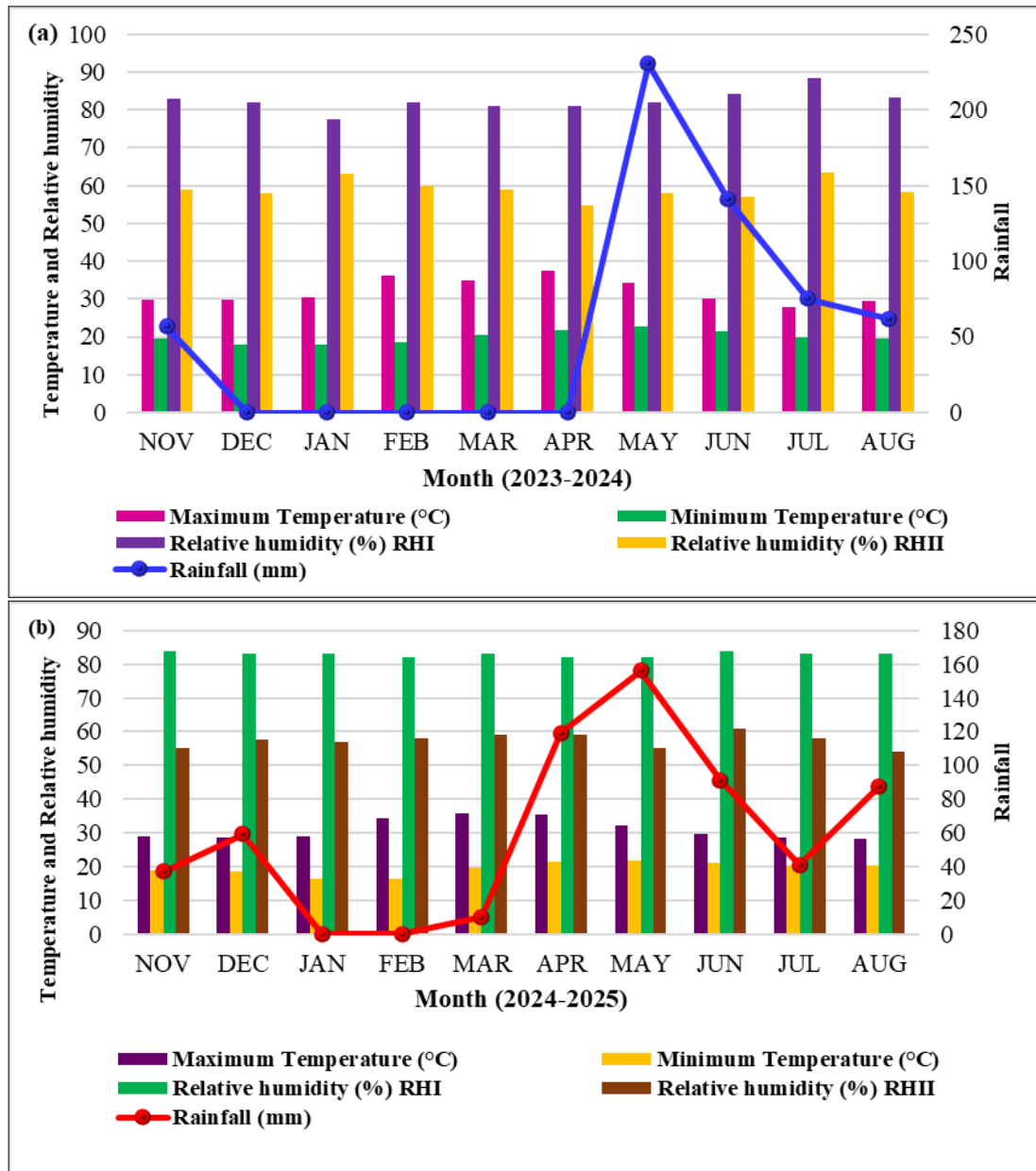


Fig. 1. Weather parameters including minimum and maximum temperatures, relative humidity (RHI and RHII) and monthly rainfall recorded during the two experimental years-2023-24 (a) and 2024-25 (b) at the research site, Zonal Agricultural Research Station, Mandya, Karnataka, India.

Table 1. Details of experimental treatments

Sl. No	Abbreviation	Treatments
Main plot (Cropping system)		
1.	C ₁	Fodder Oats + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1) - Fodder Maize + Cowpea (3:1)
2.	C ₂	Fodder Oats + Cowpea (3:1) - Fodder Bajra + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1)
3.	C ₃	Fodder Oats + Cowpea (3:1) - Fodder Maize + Cowpea (3:1) - Fodder Bajra + Cowpea (3:1)
4.	C ₄	Fodder Oats + Field bean (3:1) - Fodder Sorghum + Field bean (3:1) - Fodder Maize + Field bean (3:1)
5.	C ₅	Fodder Oats + Field bean (3:1) - Fodder Bajra + Field bean (3:1) - Fodder Sorghum + Field bean (3:1)
6.	C ₆	Fodder Oats + Field bean (3:1) - Fodder Maize + Field bean (3:1) - Fodder Bajra + Field bean (3:1)
Sub plot (Nitrogen levels)		
7.	N ₁	75 % Recommended Dose of Nitrogen
8.	N ₂	100 % Recommended Dose of Nitrogen
9.	N ₃	125 % Recommended Dose of Nitrogen

To determine dry matter (DM) content, a known quantity of representative fresh samples from each plot was initially shade-dried for a few days, followed by oven drying at $70 \pm 5^\circ\text{C}$ for 48 hr to ensure complete moisture removal. The dry weight was recorded and the dry matter yield (DMY) was computed by multiplying the DM content (%) with the corresponding GFY.

$$\text{DM (\%)} = \frac{\text{Dry weight of sample}}{\text{Fresh weight of sample}} \times 100$$

$$\text{DMY (q/ha)} =$$

$$\frac{\text{Dry matter (\%)} \times \text{Green forage yield (g/ha)}}{100}$$

100

Quality analysis

Plant samples from each treatment were collected at harvest, oven dried, powdered and used for the analysis of quality parameters. In the intercropping systems, the plant samples from the main and intercrops were mixed as per the adopted row proportion and further used for the analysis. The dried samples were ground in Willey mill using a 2 mm sieve for estimation of quality parameters. The quality parameters were estimated according to the standard procedure recommended by previous researchers (22) and their respective yields were calculated by multiplying with the dry matter yield of the crops. All the forage quality parameters are reported on a dry matter (DM) basis.

Crude Protein (%) = Nitrogen (%) x 6.25

Ether extractable fat (%) =

$$\frac{\text{Weight of ether extract}}{\text{Weight of the dried plant sample taken}} \times 100$$

CHO (%) = 100 - (CP (%) + Crude fat (%) + CF (%) + Ash (%) + moisture (%))

Land equivalent ratio and land use efficiency

Land equivalent ratio and land use efficiency were calculated for each cropping system to assess the productivity and efficiency. Sole crops grown separately in same experimental field to work out land equivalent ratio.

$$LER_{ab} = \frac{Y_{ab}}{Y_{aa}} + \frac{Y_{ba}}{Y_{bb}}$$

Where,

Y_{aa} = sole crop yield of species 'a', Y_{ab} = intercrop yield of species 'a' in combination with species 'b'

Y_{bb} = sole crop yield of species 'b', Y_{ba} = intercrop yield of species 'b' in combination with species 'a'

$$LUE = \frac{\sum_{i=1}^n D_i}{365} \times 100$$

Where, $i = 0, 1, 2, \dots, n$; n = total number of crops; and D_i = number of days occupied by i^{th} crop.

Statistical analysis

The experimental data on various parameters were analysed statistically using the analysis of variance (ANOVA) technique as described by Gomez and Gomez (23). To compare the treatment means, the least significant difference (LSD) test was employed at the 5 % level of significance ($p < 0.05$). Whenever significant differences were observed, the critical difference (CD) at the 5 % probability level was computed to determine the variation between treatment means. Initially, the data from both years of the study were analyzed separately and since the results exhibited a similar trend across years, the findings have been interpreted based on the pooled mean of the two years data.

Results

Green fodder and dry matter yield

A significant variation in green forage yield and dry matter yield was observed in cropping systems and nitrogen levels on pooled basis which are presented in Table 2. Among the cropping systems, Fodder Oats + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1) - Fodder Maize + Cowpea (3:1) recorded higher green forage yield (977 q ha⁻¹ year⁻¹) and dry matter yield (204 q ha⁻¹ year⁻¹), which was significantly on par with fodder cropping system, Fodder Oats + Field bean (3:1) - Fodder Sorghum + Field bean (3:1) - Fodder Maize + Field bean (3:1) (962 and 201 q ha⁻¹ year⁻¹). Among nitrogen levels, higher green forage yield (998 q ha⁻¹ year⁻¹) and dry matter yield (214 q ha⁻¹ year⁻¹) was obtained with the application of 125 % RDN, which were significantly superior over 100 % RDN (947 and 198 q ha⁻¹ year⁻¹) and 75 % RDN (875 and 176 q ha⁻¹ year⁻¹).

Table 2. Green forage yield, dry matter yield and dry matter concentration as influenced by different cropping system and nitrogen levels

Treatments	Green forage yield (q ha ⁻¹ year ⁻¹)	Dry matter yield (q ha ⁻¹ year ⁻¹)	Dry matter (%)
Main plot (Cropping systems)			
C ₁	977	204	20.87
C ₂	914	193	21.02
C ₃	949	195	20.54
C ₄	962	201	20.82
C ₅	906	190	20.90
C ₆	932	191	20.46
S.Em. ±	7.7	1.14	0.09
CD (p=0.05)	24.2	3.60	0.30
Sub plot (Nitrogen levels)			
N ₁	875	176	20.02
N ₂	947	198	20.86
N ₃	998	214	21.41
S.Em. ±	8.5	2.74	0.17
CD (p=0.05)	24.8	7.99	0.49
Interaction (CxN)			
S.Em. ±	20.8	6.70	0.41
CD (p=0.05)	NS	NS	NS

Main plot treatment

- C₁: Fodder Oats + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1) - Fodder Maize + Cowpea (3:1)
 C₂: Fodder Oats + Cowpea (3:1) - Fodder Bajra + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1)
 C₃: Fodder Oats + Cowpea (3:1) - Fodder Maize + Cowpea (3:1) - Fodder Bajra + Cowpea (3:1)
 C₄: Fodder Oats + Field bean (3:1) - Fodder Sorghum + Field bean (3:1) - Fodder Maize + Field bean (3:1)
 C₅: Fodder Oats + Field bean (3:1) - Fodder Bajra + Field bean (3:1) - Fodder Sorghum + Field bean (3:1)
 C₆: Fodder Oats + Field bean (3:1) - Fodder Maize + Field bean (3:1) - Fodder Bajra + Field bean (3:1)

Sub plot treatment

- N₁: 75 % RDN
 N₂: 100 % RDN
 N₃: 125 % RDN

Quality attributes

The quality composition of biomass was significantly influenced by different cropping systems and nitrogen levels (Table 3 and Fig. 2). Among the fodder cropping systems, crude protein (CP) content varied significantly, ranging from 13.04 % in C₅ system to 13.83 % in C₃ fodder system, with the latter recording the higher CP (13.83 %) concentration in Fodder Oats + Cowpea (3:1) - Fodder Maize + Cowpea (3:1) - Fodder Bajra + Cowpea (3:1) cropping system. The systems C₁ (13.72 %) and C₆ (13.45 %) also maintained comparably on par with fodder cropping system C₃. Ash content followed a similar trend, being higher in C₁ (9.59 %) and lower in C₅ (9.15 %) system. Fat content showed minor variations across fodder

cropping systems (2.59 to 2.74 %), with the maximum fat content (2.74 %) in Fodder Oats + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1) - Fodder Maize + Cowpea (3:1) system. Fiber content ranged between 27.99 % (C₃) to 28.86 % (C₄), in which cropping system C₄ recorded the higher fibre content (28.86 %), while the lower value (27.99 %) was noted in C₃ system. Compared with C₃, fibre content increased by 3.1 % in C₄, 3.0 % in C₅, 2.5 % in C₁ and 2.1 % in C₂ fodder systems, indicating only marginal differences among the cropping systems. Non-fiber carbohydrates (NF-CHO) were higher in C₄ (33.37 %), closely followed by C₅ (33.18 %), while total carbohydrates (T-CHO) ranged from 73.93 % (C₃) to 75.15 % (C₅).

Table 3. Quality content of crude protein (CP), total digestible crude protein (TDCP), ash, fat, fibre, non-fiber carbohydrates (NF-CHO) and total carbohydrates (T-CHO) in the biomass as affected by varying cropping systems and nitrogen levels

Treatments	CP (%)	Ash (%)	Fat (%)	Fibre (%)	NF-CHO (%)	T-CHO (%)
Main plot (Cropping systems)						
C ₁	13.72	9.59	2.74	28.68	32.98	73.94
C ₂	13.32	9.22	2.72	28.59	32.98	74.73
C ₃	13.83	9.57	2.66	27.99	32.28	73.93
C ₄	13.36	9.51	2.66	28.86	33.37	74.46
C ₅	13.04	9.15	2.67	28.84	33.18	75.15
C ₆	13.45	9.51	2.59	28.20	32.63	74.45
S.Em. ±	0.08	0.04	0.01	0.11	0.24	0.14
CD (p=0.05)	0.27	0.14	0.04	0.35	0.70	0.44
Sub plot (Nitrogen levels)						
N ₁	12.65	9.08	2.48	30.22	31.44	75.79
N ₂	13.64	9.52	2.73	28.33	31.58	74.11
N ₃	14.07	9.67	2.82	27.03	32.15	73.43
S.Em. ±	0.17	0.07	0.02	0.19	0.57	0.26
CD (p=0.05)	0.51	0.20	0.06	0.54	NS	0.75
Interaction (CxN)						
S.Em. ±	0.43	0.17	0.05	0.46	1.39	0.63
CD (p=0.05)	NS	NS	NS	NS	NS	NS
Main plot treatment			Sub plot treatment			
C ₁ : Fodder Oats + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1) - Fodder Maize + Cowpea (3:1)			N ₁ : 75 % RDN			
C ₂ : Fodder Oats + Cowpea (3:1) - Fodder Bajra + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1)			N ₂ : 100 % RDN			
C ₃ : Fodder Oats + Cowpea (3:1) - Fodder Maize + Cowpea (3:1) - Fodder Bajra + Cowpea (3:1)			N ₃ : 125 % RDN			
C ₄ : Fodder Oats + Field bean (3:1) - Fodder Sorghum + Field bean (3:1) - Fodder Maize + Field bean (3:1)						
C ₅ : Fodder Oats + Field bean (3:1) - Fodder Bajra + Field bean (3:1) - Fodder Sorghum + Field bean (3:1)						
C ₆ : Fodder Oats + Field bean (3:1) - Fodder Maize + Field bean (3:1) - Fodder Bajra + Field bean (3:1)						

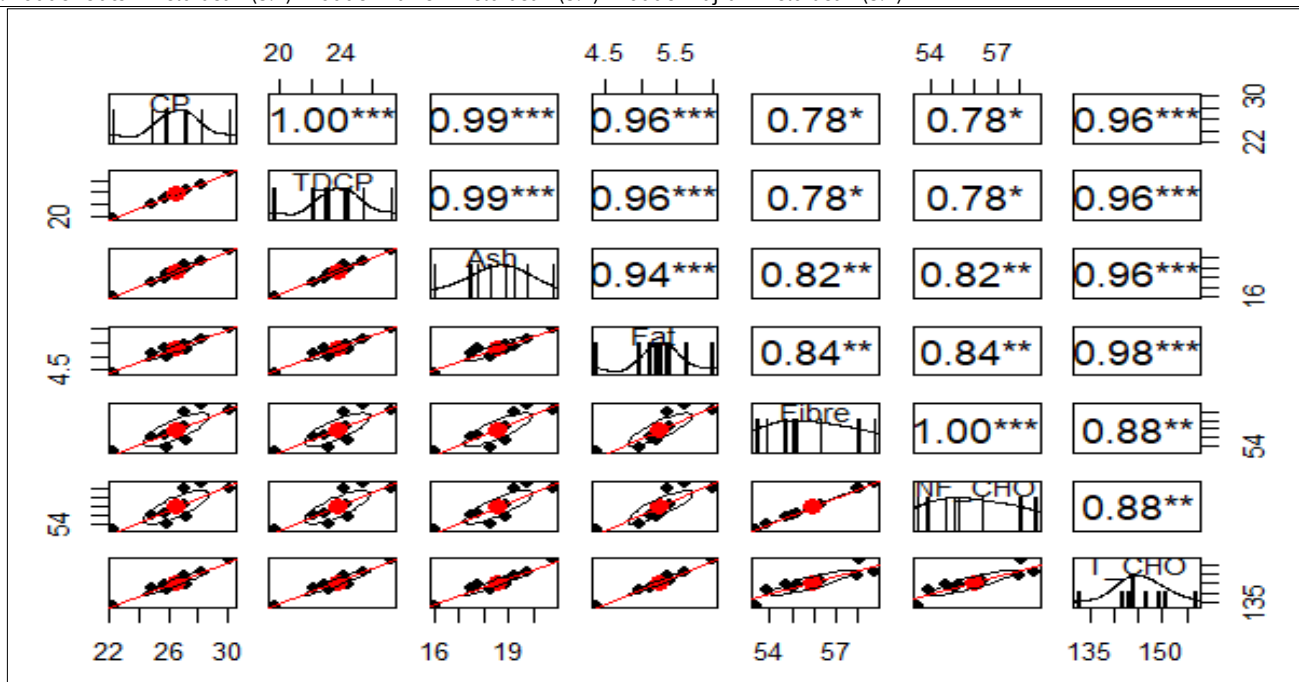


Fig. 2. Correlation matrix depicting the relationships among fodder quality parameters under different cropping systems and nitrogen levels. Parameters include nitrogen (N), crude protein (CP), ash, fat, non-fiber carbohydrates (NF-CHO) and total carbohydrates (T-CHO). Asterisks indicate significance levels: *, ** and ***, corresponding to $p < 0.05$, 0.01 and 0.001 , respectively.

Nitrogen application levels exerted a pronounced influence on the quality parameters (Table 3). The higher CP (14.07 %) and fat (2.82 %) contents were obtained with N₃ (125 % RDN), which were significantly superior to N₂ (13.64 %) and N₁ (12.65 %). Conversely, fibre content declined with increasing nitrogen level, from 30.22 % (N₁) to 27.03 % (N₃), suggesting enhanced forage quality under higher nitrogen supply. Ash content increased marginally with nitrogen rate, whereas NF-CHO content remained statistically non-significant in all seasons. Total carbohydrate (T-CHO) content showed a decreasing trend with higher nitrogen levels, being higher under 75 % RDN (75.79 %) and lower under 125 % RDN (73.43 %).

Yields of quality attributes

Nitrogen and protein composition are widely recognized as reliable measures of forage quality, as they directly reflect the nutritional value of fodder for livestock (Table 4). Cropping system in sequence of oats in *rabi*, sorghum in summer and maize in *kharif* grown with intercrop cowpea in 3:1 proportion recorded higher crude protein yield (28.23 q ha⁻¹), ash yield (19.73 q ha⁻¹), ether extractable fat yield (5.63 q ha⁻¹), crude fibre yield (58.73 q ha⁻¹), Non-fibre carbohydrate yield (57.24 q ha⁻¹) and total carbohydrate yield (150.6 q ha⁻¹) which despite in Table 4. The enhancement in quality with higher nitrogen levels clearly indicates the positive response of crops to nitrogen application. The statistical analysis confirmed that application of 125 % RDN recorded higher crude protein yield (30.17 q ha⁻¹), ash yield (20.75 q ha⁻¹), ether extractable fat yield (6.02 q ha⁻¹), crude fibre yield (58.07 q ha⁻¹), non-fibre carbohydrate yield (70.19 q ha⁻¹) and total carbohydrate yield (156.9 q ha⁻¹).

System productivity, stability and efficiency

Green fodder productivity (GFP) and dry matter productivity (DMP) were significantly influenced by the cropping systems and nitrogen levels, whereas their interaction (C × N) was non-significant (Fig. 3). Among the cropping systems, GFP ranged from 427 to 460 kg ha⁻¹

day⁻¹, while DMP varied from 90 to 96 kg ha⁻¹ day⁻¹. The higher GFP and DMP were recorded in the Fodder Oats + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1) - Fodder Maize + Cowpea (3:1) system (460 and 96 kg ha⁻¹ day⁻¹, respectively), which was statistically on par to Fodder Oats + Field bean (3:1) - Fodder Sorghum + Field bean (3:1) - Fodder Maize + Field bean (3:1) cropping system (453 and 95 kg ha⁻¹ day⁻¹). The lower productivity was observed in Fodder Oats + Field bean (3:1) - Fodder Bajra + Field bean (3:1) - Fodder Sorghum + Field bean (3:1) (427 and 90 kg ha⁻¹ day⁻¹), indicating a comparatively lower biomass accumulation in this cropping system. Nitrogen application significantly enhanced both GFP and DMP. With application different levels of nitrogen higher productivity were obtained with 125 % RDN (470 and 101 kg ha⁻¹ day⁻¹), which was significantly superior over 100 % RDN (446 and 93 kg ha⁻¹ day⁻¹) and 75 % RDN (412 and 83 kg ha⁻¹ day⁻¹). The increase in productivity with higher nitrogen levels may be attributed to improved vegetative growth, leaf area expansion and photosynthetic efficiency.

The Land Equivalent Ratio (LER), Competition Ratio (CR) and Land Use Efficiency (LUF) exhibited noticeable variation among different cropping systems (Table 5). The LER values ranged from 1.30 to 1.34, indicating a yield advantage of intercropping systems over sole cropping. The higher LER (1.34) was observed in Fodder Oats + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1) - Fodder Maize + Cowpea (3:1) cropping system, followed closely by C₃ (1.33) and C₄ (1.32) cropping system, suggesting more efficient utilization of land resources in these systems. All LER values being greater than unity revealed a biological and yield advantage of intercropping over monocropping. Land Use Efficiency (LUF) followed a similar trend to LER, ranging from 57.0 % to 58.9 % among different cropping systems. The higher LUF (58.9 %) was recorded in C₁ and C₄ intercropping system, indicating better temporal utilization of land resources, while the lower value (57.0 %) was associated with C₂ and C₅ systems.

Table 4. Quality yield of crude protein (CP), total digestible crude protein (TDCP), ash, fat, fibre, non-fiber carbohydrates (NF-CHO) and total carbohydrates (T-CHO) in the biomass as affected by varying cropping systems and nitrogen levels

Treatments	CP (q ha ⁻¹ year ⁻¹)	TDCP (q ha ⁻¹ year ⁻¹)	Ash (q ha ⁻¹ year ⁻¹)	Fat (q ha ⁻¹ year ⁻¹)	Fibre yield (q ha ⁻¹ year ⁻¹)	NF-CHO (q ha ⁻¹ year ⁻¹)	T-CHO (q ha ⁻¹ year ⁻¹)
Main plot (Cropping systems)							
C ₁	28.23	25.38	19.73	5.63	58.73	58.73	150.6
C ₂	25.75	22.97	17.80	5.29	55.25	55.25	143.9
C ₃	27.26	24.43	18.87	5.23	54.70	54.70	143.9
C ₄	27.02	24.20	19.21	5.37	57.99	57.99	149.0
C ₅	24.90	22.14	17.46	5.12	55.08	55.08	142.8
C ₆	25.91	23.12	18.31	4.97	53.87	53.87	141.7
S.Em. ±	0.32	0.32	0.18	0.10	0.52	0.52	0.7
CD (p=0.05)	0.99	0.97	0.58	0.28	1.63	1.63	2.1
Sub plot (Nitrogen levels)							
N ₁	22.29	19.61	16.05	4.37	53.42	53.42	132.8
N ₂	27.08	24.25	18.89	5.41	56.32	56.32	146.3
N ₃	30.17	27.26	20.75	6.02	58.07	58.07	156.9
S.Em. ±	0.68	0.66	0.38	0.11	1.13	1.13	1.6
CD (p=0.05)	1.98	1.92	1.12	0.31	3.31	3.31	4.8
Interaction (CxN)							
S.Em. ±	1.66	1.61	0.94	0.26	2.77	2.77	4.0
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS

Main plot treatment

C₁: Fodder Oats + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1) - Fodder Maize + Cowpea (3:1)
 C₂: Fodder Oats + Cowpea (3:1) - Fodder Bajra + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1)
 C₃: Fodder Oats + Cowpea (3:1) - Fodder Maize + Cowpea (3:1) - Fodder Bajra + Cowpea (3:1)
 C₄: Fodder Oats + Field bean (3:1) - Fodder Sorghum + Field bean (3:1) - Fodder Maize + Field bean (3:1)
 C₅: Fodder Oats + Field bean (3:1) - Fodder Bajra + Field bean (3:1) - Fodder Sorghum + Field bean (3:1)
 C₆: Fodder Oats + Field bean (3:1) - Fodder Maize + Field bean (3:1) - Fodder Bajra + Field bean (3:1)

Sub plot treatment

N₁: 75 % RDN
 N₂: 100 % RDN
 N₃: 125 % RDN

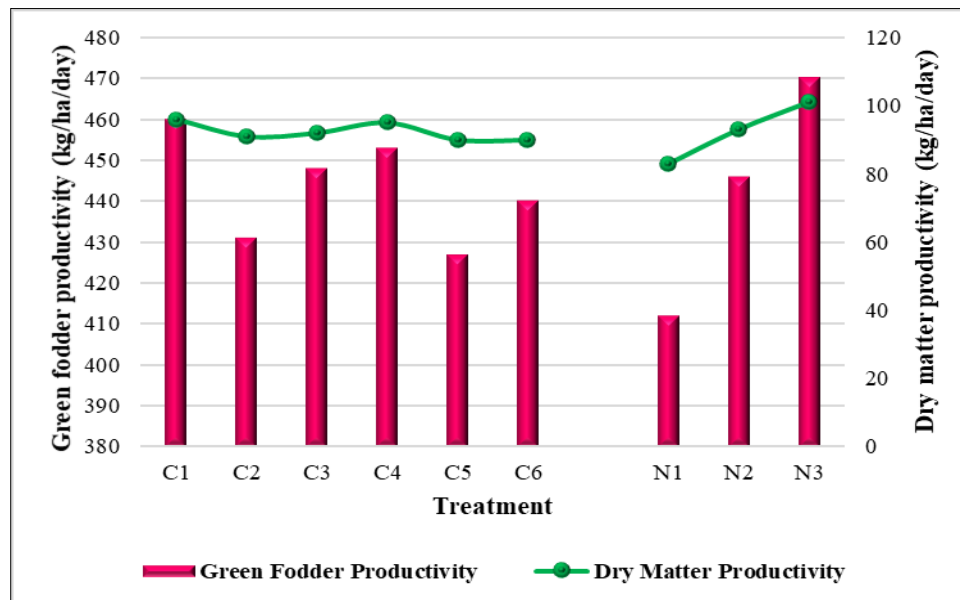


Fig. 3. Productivity of different cropping systems influenced by nitrogen levels.

Table 5. Land equivalent ratio, land use efficiency and competition ratio of different cropping systems

Treatments	LER	Competition ratio		LUF
		Main crops (CR _a)	Inter crops (CR _b)	
Main plot (Cropping systems)				
C ₁	1.34	0.78	1.29	58.9
C ₂	1.31	0.77	1.30	57.0
C ₃	1.33	0.77	1.30	58.4
C ₄	1.32	0.78	1.29	58.9
C ₅	1.30	0.76	1.31	57.0
C ₆	1.31	0.79	1.28	58.4

Main plot treatment

C₁: Fodder Oats + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1) - Fodder Maize + Cowpea (3:1)
 C₂: Fodder Oats + Cowpea (3:1) - Fodder Bajra + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1)
 C₃: Fodder Oats + Cowpea (3:1) - Fodder Maize + Cowpea (3:1) - Fodder Bajra + Cowpea (3:1)
 C₄: Fodder Oats + Field bean (3:1) - Fodder Sorghum + Field bean (3:1) - Fodder Maize + Field bean (3:1)
 C₅: Fodder Oats + Field bean (3:1) - Fodder Bajra + Field bean (3:1) - Fodder Sorghum + Field bean (3:1)
 C₆: Fodder Oats + Field bean (3:1) - Fodder Maize + Field bean (3:1) - Fodder Bajra + Field bean (3:1)

The competition ratio (CR) is an important index that quantifies the degree of competition between component crops in an intercropping system. In the present study, CR values showed clear variation among the different cropping systems, reflecting differential competitiveness between main and intercrops (Table 5). The CR of main crops (CR_a) ranged from 0.76 to 0.79, whereas for intercrops (CR_b), the values varied between 1.28 and 1.31 across the treatments. A competition ratio value greater than unity for intercrops indicated their superior competitive ability in utilizing growth resources such as light, nutrients and moisture compared to the main crops. Conversely, CR values less than one (CR < 1) for main crops suggested that, they were less competitive under intercropping conditions. Among the various treatments, cropping system C₆ recorded the higher CR for the main crop (0.79), indicating slightly better competitiveness compared to other systems, while system C₅ (0.76) exhibited the lower CR, implying relatively weaker competition from the main component. Similarly, the intercrop CR was higher in fodder system C₅ (1.31), followed by C₂ (1.30) and C₃ (1.30), indicating a stronger dominance of intercrops in these combinations. The lower CR for intercrops (1.28) was observed in fodder system C₆, where the competition between the component crops appeared more balanced.

Economics

The economic analysis of different year-round cereal-legume fodder cropping systems and nitrogen levels revealed distinct variations in profitability (Table 6). Among the cropping systems, sequence of Fodder Oats + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1) - Fodder Maize + Cowpea (3:1) grown from *rabi* to *kharif* season recorded the higher gross returns (Rs. 303553 ha⁻¹) and net returns (Rs. 196731 ha⁻¹), resulting in a benefit-cost (B:C) ratio of 2.81. This was followed by C₃ (Rs. 299082 ha⁻¹ gross and Rs. 192705 ha⁻¹ net returns) and C₄ (Rs. 298616 ha⁻¹ gross and Rs. 191247 ha⁻¹ net returns) system, both of which performed comparably. The lowest gross (Rs. 259955 ha⁻¹) and net returns (Rs. 159404 ha⁻¹) were recorded in C₅, with the lower B:C ratio (2.59), indicating its relatively lower economic efficiency.

Nitrogen application also had a pronounced effect on the economic parameters. Increasing nitrogen levels from 75 % to 125 % of the recommended dose significantly enhanced profitability. The maximum gross returns (Rs. 303731 ha⁻¹) and net returns (Rs. 198233 ha⁻¹) were obtained with 125 % RDN, accompanied by a superior B:C ratio of 2.86. This was followed by 100 % RDN, which achieved gross and net returns of Rs. 288308 ha⁻¹ and Rs. 183668 ha⁻¹, respectively, with a B:C ratio of 2.74. The lowest values were associated with 75 % RDN, which yielded gross and net returns of Rs. 266332 ha⁻¹ and Rs. 162447 ha⁻¹, respectively, with a B:C ratio of 2.54.

Table 6. Economics of different cropping systems influenced by nitrogen levels

Treatments	Gross returns (Rs. ha ⁻¹)	Net returns (Rs. ha ⁻¹)	B:C ratio
Main plot (Cropping systems)			
C ₁	303553	196731	2.81
C ₂	262042	162078	2.62
C ₃	299082	192705	2.79
C ₄	298616	191247	2.75
C ₅	259955	159404	2.59
C ₆	293493	186529	2.72
Sub plot (Nitrogen levels)			
N ₁	266332	162447	2.54
N ₂	288308	183668	2.74
N ₃	303731	198233	2.86
Main plot treatment		Sub plot treatment	
C ₁ : Fodder Oats + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1) - Fodder Maize + Cowpea (3:1)		N ₁ : 75 % RDN	
C ₂ : Fodder Oats + Cowpea (3:1) - Fodder Bajra + Cowpea (3:1) - Fodder Sorghum + Cowpea (3:1)		N ₂ : 100 % RDN	
C ₃ : Fodder Oats + Cowpea (3:1) - Fodder Maize + Cowpea (3:1) - Fodder Bajra + Cowpea (3:1)		N ₃ : 125 % RDN	
C ₄ : Fodder Oats + Field bean (3:1) - Fodder Sorghum + Field bean (3:1) - Fodder Maize + Field bean (3:1)			
C ₅ : Fodder Oats + Field bean (3:1) - Fodder Bajra + Field bean (3:1) - Fodder Sorghum + Field bean (3:1)			
C ₆ : Fodder Oats + Field bean (3:1) - Fodder Maize + Field bean (3:1) - Fodder Bajra + Field bean (3:1)			

Discussion

Impact of seasonal weather conditions on year-round forage production

Seasonal weather conditions during 2023-24 and 2024-25 significantly influenced forage crop growth and productivity. The uneven rainfall pattern with dry months from November to March and peak showers in May created variable moisture regimes. Moisture stress during early crop stages was minimized through life saving irrigation, while May rainfall promoted vigorous vegetative growth before the *kharif* season. High summer temperatures (up to 37.5 °C) accelerated growth in warm-season cereals but occasionally reduced succulence and forage quality. Cooler temperatures in January favoured legumes by enhancing nodulation and nitrogen fixation. Relative humidity also played a key role, higher humidity during June-July supported lush biomass and improved nutritive value, whereas low humidity in April-August increased evaporative demand and reduced leafiness. Overall, the interaction of rainfall, temperature and humidity shaped biomass yield and quality across seasons, helping identify resilient cereal-legume forage systems suitable for year-round production.

Biomass yield (Green forage and dry matter yield)

The superior productivity of cereal-legume system can be attributed to several physiological, ecological and agronomic interactions. Firstly, the sequential inclusion of high-yielding cereal fodders (oats, sorghum and maize) with a short-duration legume (cowpea) ensures efficient utilization of growth periods across all seasons, thereby maintaining continuous biomass production (24, 25). Oats and sorghum perform optimally during the *rabi* and summer seasons respectively, while maize provides high *kharif* productivity, allowing the system to exploit year-round resource availability such as solar radiation, temperature and moisture (24). Secondly, biological nitrogen fixation by cowpea plays a crucial role in improving soil fertility and enhancing the growth of subsequent cereal components (26). Legume intercropping enriches soil nitrogen through rhizobial activity and residue incorporation, which contributes to better nutrient uptake and photosynthetic activity in companion cereals (27, 28). Thirdly, the cereal-legume complementarity in canopy architecture and rooting depth improves resource use efficiency. Cereals with their erect and deep-rooted systems, exploit nutrients and moisture from deeper soil

layers, while legumes utilize nutrients from the upper profile (25). This vertical stratification of root systems minimizes competition and maximizes total system productivity (29).

The yield enhancement in higher nitrogen supply can be attributed to improved chlorophyll synthesis, enhanced photosynthetic efficiency and greater assimilate translocation to vegetative organs, resulting in vigorous tillering, leaf expansion and biomass accumulation (30, 31). Adequate nitrogen availability also increased dry matter concentration (21.41 %) by promoting structural carbohydrate formation and delayed senescence, thereby sustaining photosynthetic activity over a longer duration. Similar positive responses to nitrogen fertilization in forage-based systems have been reported in previous studies (32), observed that nitrogen enhances canopy development, nutrient uptake and resource use efficiency in cereal-legume fodder systems. Conversely, reduced nitrogen (N₁) limited vegetative growth and chlorophyll content, leading to lower biomass accumulation, a finding consistent with earlier reports (33). Overall, the results reaffirm that improved nitrogen nutrition (125 % RDN) is essential for maximizing forage yield, maintaining nutrient balance and sustaining high productivity in intensive cereal-legume fodder cropping systems (34).

Quality attributes and its yields

The improvement in protein concentration and digestibility in this fodder system may be attributed to enhanced biological nitrogen fixation and complementary resource utilization between cereals and legumes, which together improve nitrogen assimilation efficiency and carbon-nitrogen balance within the crop canopy (35, 36). The presence of cowpea in rotation and intercropping sequences contributes residual nitrogen through root nodulation and litter return, enriching soil fertility and stimulating protein synthesis in the succeeding cereal fodders (37). Furthermore, the differential canopy architecture and rooting depth between cereals and legumes facilitate efficient light interception, nutrient absorption and photosynthate partitioning, leading to higher crude protein and lower structural carbohydrate accumulation (38).

Nitrogen fertilization exerted a decisive role in determining the biochemical composition of the forage. The 125 % RDN treatment (N₃) achieved maximum crude protein (14.07 %) and fat (2.82 %) content with minimum fibre levels (27.03 %), indicating improved nutrient density and digestibility (20, 39, 40). These

responses stem from greater chlorophyll biosynthesis, enhanced photosynthetic activity and efficient translocation of assimilates toward protein formation under increased nitrogen supply (20). Conversely, limited nitrogen availability (N_1) restricted amino acid and protein synthesis while accelerating lignin and cellulose deposition, thereby increasing fibre and total carbohydrate contents (6). The observed trends emphasize that balanced nitrogen nutrition and inclusion of nitrogen-fixing legumes in sequential cereal systems -such as in C_1 and C_3 optimize nitrogen use efficiency, improve crude protein content and sustain high-quality forage production across all seasons (41, 42).

Land use efficiency and system productivity in different cropping systems

Efficiency indices further demonstrated ecological and agronomic superiority of cereal-legume systems. Cropping system C_1 recorded the higher land equivalent ratio (1.34) and land use efficiency (58.9 %), indicating a clear advantage of intercropping and sequential diversification over monocropping (43). LER values greater than one signify better utilization of land and temporal resources, arising from complementary interactions between the component crops in intercropping (38). Balanced competition ratios between cereals (0.78) and legumes (1.29) revealed a positive association, where legumes improved the nitrogen status of the system without suppressing cereal growth. Similar synergistic effects of legume inclusion in cereal systems have been reported by previous researchers (43-45), who observed enhanced productivity through canopy complementarity and synchronized nutrient uptake.

Productivity indices in cropping system reflecting efficient conversion of radiation and nutrients into biomass (Fig. 2). Nitrogen fertilization reinforced these trends, adequate nitrogen enhances photosynthetic efficiency, leaf area development and biomass partitioning, resulting in superior daily productivity (46). Reduced productivity under N_1 indicates the sensitivity of fodder systems to nitrogen limitation and the importance of balanced nutrient management for maintaining system sustainability (32).

Economics

Economic analysis revealed substantial differences among the cereal-legume fodder systems and nitrogen management levels. The economic superiority of these systems can be attributed to their sustained biomass production, enhanced forage quality and efficient nutrient cycling through legume integration, which reduced fertilizer dependency and improved nitrogen availability (24, 35). Inclusion of cowpea not only improved soil nitrogen status through symbiotic fixation but also contributed to higher crude protein and digestibility, increasing the market value of the fodder (38). Moreover, diversified cereal-legume sequences like C_1 ensured year-round productivity and risk mitigation against seasonal variability, aligning with the findings of previous studies (46), it emphasized the economic resilience of legume-based systems.

Nitrogen application further enhanced profitability, with 125 % RDN (N_3) producing the highest gross returns, net returns and benefit-cost ratio. The economic gains under optimal nitrogen nutrition stem from improved photosynthetic efficiency, nutrient uptake and forage yield, which together enhance overall resource use efficiency (32). Conversely, nitrogen deficiency restricted biomass accumulation and reduced returns due to limited chlorophyll formation and impaired on biomass production (33). These results are consistent with findings from integrated nutrient

management studies that report higher profitability and sustainability under adequate nitrogen regimes in cereal-legume systems (47). Overall, the combination of efficient cropping design (C_1) and balanced nitrogen management (N_3) maximized economic efficiency, demonstrating a viable strategy for enhancing profitability and sustainability in year-round fodder production systems (42, 46).

Sustainable strategies to promote fodder production in India and around the world

The findings of this study have broad applicability beyond the dry zones of Karnataka, extending to other regions of India and similar agro-climatic areas globally where fodder scarcity is a major constraint. In most semi-arid and dryland ecosystems, the expansion of land area for fodder cultivation is limited due to competing land-use priorities and environmental concerns. Consequently, future gains in forage availability must be achieved through enhanced productivity per unit area and time, facilitated by the adoption of improved and sustainable fodder production systems. The present research demonstrates that, year-round fodder production, integrating annual cereal-legume systems, offers a promising strategy to maximize resource use efficiency and system productivity. The identified crops and genotypes exhibit wide adaptability and can be effectively incorporated into diverse farming systems, including food-forage-based rotations, orchard intercropping, agroforestry and silvi-pastoral systems. Short-duration fodder crops also provide opportunities for inclusion in rice fallows, thereby increasing cropping intensity and optimizing land utilization. Moreover, perennial and annual fodders can be cultivated on marginal lands, field boundaries, wastelands and problematic soils, contributing to land rehabilitation and sustainable biomass generation. Although the study was conducted under the agro-ecological conditions of Karnataka, the principles and system designs identified here have relevance for regions worldwide that share similar climatic and resource limitations. The integration of cereal-legume forage systems supports both crop and livestock productivity by improving soil fertility, enhancing nutrient cycling and providing high-quality feed resources. Thus, the outcomes of this research contribute to the broader goal of sustainable intensification in mixed farming systems and can serve as a replicable model for advancing forage-based agricultural resilience in semi-arid environments. Annual forage cultivation systems in subtropical regions of UK (48), USA (49), Africa (50, 51) and other developing countries play a vital role in enhancing agroecosystem sustainability. These systems improve soil fertility, nutrient cycling and ground cover while reducing erosion and supporting long-term soil health. Integrating annual forages into crop rotations has been shown to enhance soil organic matter, water-use efficiency and feed availability (48). In African mixed farming systems, forage integration improves soil structure, minimizes erosion and increases overall productivity and resilience (50, 51).

Conclusion

The study demonstrated that cereal-legume intercropping systems, supported by efficient nitrogen management, significantly improved biomass yield, forage quality and the sustainability of year-round fodder production. The sequence of fodder oats + cowpea (3:1) - fodder sorghum + cowpea (3:1) - fodder maize + cowpea (3:1), when combined with 125 % of the recommended nitrogen dose, produced the highest green and dry fodder yields and superior

quality attributes, including higher crude protein, ash and ether extractable fat contents. The complementary interaction between cereals and legumes enhanced resource-use efficiency, particularly for nitrogen, light and moisture, leading to improved productivity and nutritive value. Legume inclusion also contributed to biological nitrogen fixation, improved soil fertility and reduced dependence more on synthetic fertilizers, ensuring greater system sustainability. Overall, integrating annual cereal-legume systems with optimized nitrogen levels proved effective for achieving both quantitative and qualitative gains in forage production while maintaining soil health and year-round fodder availability. These findings provide practical options for livestock farmers in India and regions with similar agro-climatic conditions to sustainably meet fodder demands, reduce feed costs and enhance the resilience of smallholder livestock systems. The tested crop combinations also hold potential for wider adaptation in other dryland regions, following region-specific agronomic refinement, thereby contributing to the broader goal of sustainable livestock production.

Acknowledgements

The authors are grateful to the Dr. B G Shekara and College of Agriculture, V C Farm, Mandya, UAS(B), Karnataka, India for the support and encouragement.

Authors' contributions

DKC, YSB, DGR, SR, CH and GKS contributed to the study. DKC was responsible for investigation, formal analysis and preparation of the original draft. YSB contributed to the conceptualization, methodology and supervision of the work. DGR, SR, CH and GKS were involved in visualization and in writing, reviewing and editing the manuscript. All authors have read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare no conflict of interest.

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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