



RESEARCH ARTICLE

The importance of climate-smart agriculture for small millets through legume intercropping

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Abstract

Millets are widely recognised for their resilience to high temperatures, drought and poor soil fertility, making them key components of climate-resilient agriculture. Small millets, in particular, can withstand prolonged dry spells and are predominantly cultivated under rainfed conditions. Intercropping millets with pulse crops is considered advantageous as it promotes efficient utilisation of available resources, improves soil fertility and enhances fertiliser use efficiency. Millet-pulse systems offer complementary benefits, where millets require fewer external inputs while legumes enrich the soil through biological nitrogen (N) fixation. Small millets require minimal irrigation and generally complete their life cycle within 105–120 days. Compared with many oilseeds and pulse crops, they are more efficient in nutrient uptake from the soil. In this context, the present study was undertaken to assess the production performance and energy dynamics of small millets when intercropped with legumes. Field experiments were conducted during the rabi seasons of 2021–22 and 2022–23 at the Agricultural College and Research Institute, Vazhavachanur. Finger millet was intercropped in combination with black gram (*Vigna mungo* L. Hepper) and red gram (*Cajanus cajan* L. Millsp.) under irrigated conditions using different row ratios across 7 treatments, each replicated three times. The results revealed that the finger millet-black gram intercropping system in a 4 : 1 row ratio performed significantly better throughout the crop growth period. This treatment recorded higher total dry matter production and demonstrated higher canopy efficiency, crop growth rate and more effective utilisation of solar radiation during the growing season. In addition, it resulted in a higher grain yield (3055 kg ha⁻¹) and greater economic returns compared with other treatments. In contrast, red gram-based intercropping systems showed comparatively lower performance due to greater competition for resources. The study concludes that finger millet + black gram intercropping in a 4 : 1 row ratio is an effective system for improving productivity and profitability under irrigated conditions. Furthermore, millet-legume intercropping systems may contribute to sustainable agriculture and improve the livelihoods of small and marginal farmers.

Keywords: black gram; crop growth rate; finger millet; intercropping ratio; specific leaf weight; yield

Introduction

Food-grain production must increase in proportion to population growth in developing countries such as India. Given the constraints on cultivable land, it is essential to improve productivity per unit area and time through efficient utilisation of existing resources (1, 2). *Eleusine coracana* (L.) Gaertn. (finger millet), commonly known as ragi in Tamil Nadu, is an important millet crop widely cultivated across diverse agroclimatic regions of India for both grain and fodder purposes. It is a short-duration crop, completing its life cycle within 100–120 days, requires minimal inputs and shows considerable tolerance to pests and diseases. Its resilience and adaptability make it particularly suitable for dryland farming.

Finger millet is nutritionally rich, containing approximately 65–75 % carbohydrates, 8 % protein, 15–20 % dietary fibre and 2.5–3.5 % minerals. It serves as a crucial food source for economically weaker and food-insecure populations. Intercropping

has been widely recognised as an efficient strategy to enhance productivity per unit area and time when compared with monocropping systems (3, 4). The major objectives of intercropping include maintaining ecological stability, improving resource use efficiency, increasing both yield and quality and minimising yield losses caused by weeds, pests and diseases.

Intercropping of small millets with legumes is an effective agronomic practice that improves soil fertility and overall soil quality. This system enhances soil organic matter (SOM), improves moisture retention, facilitates better aeration and increases soil enzyme activity (5–7). It also promotes better nutrient availability to plants while reducing nutrient depletion by covering exposed soil between crop rows and improving soil physical and chemical characteristics. As reported previously, organic matter plays a significant role in soil aggregation and stability, thereby preventing soil degradation (8). Furthermore, the complementary rooting patterns of monocots and dicots enhance efficient resource

utilisation. Studies have indicated that small millet-legume intercropping systems produce higher aboveground biomass compared with monoculture systems (9). Grain legumes, owing to their deep root systems, play a significant role in crop diversification and intensification and they also contribute to improved soil health through biological nitrogen (N) fixation (10).

The principle of intercropping involves cultivating two or more crops simultaneously so that the expectation that the component crops utilise environmental resources more efficiently than a single crop. Differences in plant characteristics and resource use patterns allow them to complement each other, resulting in higher overall productivity (11). Based on this concept, an experiment was designed under irrigated conditions to evaluate finger millet intercropped with legume crops such as black gram and red gram (*Vigna mungo* L. Hepper and *Cajanus cajan* L. Millsp. respectively). The study aimed to standardise suitable intercropping ratios and assess the performance of finger millet-black gram and finger millet-red gram intercropping systems by evaluating physiological growth parameters and intercropping efficiency indices, including land equivalent ratio (LER), aggressivity index (AI) and relative crowding coefficient (RCC).

Materials and Methods

Field experiments were carried out at the Agricultural College and Research Institute, Vazhavachanur, Tiruvannamalai, Tamil Nadu (12° 01'N, 79°08'E; altitude 185 m above mean sea level) during the rabi seasons of 2021–22 and 2022–23 under irrigated conditions. The experimental site has a semi-arid climate with an average annual rainfall of 920 mm. The soil was red loam in texture with a pH of 7.2, organic carbon of 0.48 %, available N of 180 kg ha⁻¹, available phosphorus (P) of 22 kg ha⁻¹ and available potassium (K) of 210 kg ha⁻¹. A recommended dose of fertiliser (40 : 20 : 20 kg N : P₂O₅ : K₂O ha⁻¹) was applied uniformly across all treatments. Irrigation was provided at critical crop growth stages (crown root initiation, active tillering, panicle initiation, flowering and grain filling) at 7–10-day intervals. The spacing adopted was 30 × 10 cm for finger millet and 30 × 20 cm for legume rows. Standard agronomic practices including two manual weedings (at 20 and 40 days after sowing (DAS)), recommended plant protection measures and uniform crop management were followed across all treatments. The objective of the experiment was to evaluate the effects of intercropping finger millet with black gram (*V. mungo*) and red gram (*C. cajan*). The experiment consisted of 7 treatments arranged in a randomized block design with 3 replications. Data were subjected to analysis of variance (ANOVA) using SPSS v26.0 (IBM Corp., USA). Homogeneity of variances was verified using Levene's test and data were log-transformed where necessary to meet normality assumptions (Shapiro–Wilk test, $p > 0.05$). Treatment means were compared using the critical difference (CD) test at a 5 % level of significance ($p \leq 0.05$). The treatments evaluated were:

- T1 – Sole finger millet (row planting)
- T2 – Finger millet + black gram (3 : 1 ratio)
- T3 – Finger millet + black gram (3 : 2 ratio)
- T4 – Finger millet + black gram (4 : 1 ratio)
- T5 – Finger millet + black gram (4 : 2 ratio)
- T6 – Finger millet + red gram (6 : 1 ratio)

T7 – Finger millet + red gram (8 : 1 ratio)

Physiological observations such as leaf area (LA), leaf area index (LAI), specific leaf weight, total dry matter production, chlorophyll content, soluble protein content, nitrate reductase activity and indole acetic acid (IAA) oxidase activity were recorded at three specific crop growth stages namely active tillering (30 DAS), panicle initiation (60 DAS) and harvest (90–105 DAS). At each stage, five representative plants per plot were sampled.

Leaf area (LA)

Leaf area for the whole sampling unit was measured by using leaf area meter (Li-Cor Model 3100) and expressed as square centimetre per plant (cm² plant⁻¹).

Leaf area index (LAI)

The LAI was calculated by employing the following formula (12):

$$\text{LAI} = \frac{\text{Leaf area per plant (cm}^2\text{)}}{\text{Ground area occupied per plant (cm}^2\text{)}}$$

Specific leaf weight (SLW)

Specific leaf weight (SLW) was calculated by using the formula (13) and expressed in milligram per square centimetre (mg cm²).

$$\text{SLW} = \frac{\text{Leaf dry weight per plant (mg)}}{\text{Leaf area per plant (cm}^2\text{)}}$$

Total dry matter production (TDMP)

Plant samples were first shade dried and then oven dried at 70 °C for 24 hr. The dry weight of whole plant including the seeds was taken and expressed in gram per plant (g plant⁻¹).

Chlorophyll content

Contents of fractions of 'a', 'b' and total chlorophyll were estimated in a fully expanded young leaf at the specified time intervals and expressed in milligram per gram (mg g⁻¹) fresh weight (14).

$$\text{Chlorophyll 'a'} = \frac{(12.7 \times \text{OD at 663}) - (2.69 \times \text{OD at 645})}{W} \times V$$

$$\text{Chlorophyll 'b'} = \frac{(22.9 \times \text{OD at 645}) - (4.68 \times \text{OD at 663})}{W} \times V$$

$$\text{Total chlorophyll} = \text{Chl 'a'} + \text{Chl 'b'}$$

Where, OD = optical density

W = fresh weight of the plant tissue sample

V = final volume of the extraction solvent

Amount of chlorophyll present in leaves was also non-destructively measured using SPAD-502 Chlorophyll meter (Minolta Co., Japan) (15).

Soluble protein content

Soluble protein content of the leaf sample is a measure of indirect assessment of the photosynthetic efficiency of crop plants. The

content of soluble protein was estimated from the leaf samples following the standard method and expressed as milligram per gram (mg g^{-1}) fresh weight (16).

Nitrate reductase activity (NRase)

Nitrate reductase activity in the leaves was determined by adopting the standard method (17) and the enzyme activity was expressed as (micrograms of nitrogen dioxide per gram per hour ($\mu\text{g of NO}_2 \text{ g}^{-1} \text{ hr}^{-1}$)).

Indole acetic acid (IAA) oxidase activity

The IAA oxidase activity of the leaf sample was estimated by the standard method (18) and the enzyme activity was expressed as microgram (μg) of unoxidised auxin per gram per hour.

Results and Discussion

Cultivating more than one crop simultaneously can improve several yield-contributing traits by stabilising genetic potential and optimising environmental resource utilisation. Intercropping finger millet with black gram and red gram is relatively uncommon, although combining cereals with legumes is a widely adopted practice known to enhance productivity (19–21). In the present study, both sole finger millet and finger millet intercropped with black gram recorded higher grain yield and grain weight compared with other intercropping treatments. Leguminous crops contribute to improved soil fertility by enriching N content through biological N fixation (22–25).

Although extensive research has been conducted on small millet-legume intercropping systems, there is still a need for detailed studies focusing on physiological traits such as growth analysis, photosynthetic efficiency, leaf area, crop growth rate, leaf size and leaf weight. Understanding these aspects can help enhance crop productivity and profitability even under limited water availability by improving physiological and biochemical processes. In this study, significant differences among treatments were observed for growth parameters including LA, LAI, specific leaf weight and crop growth rate, along with chlorophyll content (Table 1).

Among the treatments, finger millet intercropped with black gram in a 4 : 1 ratio (T4) exhibited the highest LA (688.2), which was significantly superior to the 4 : 2 ratio. Similarly, the same treatment recorded the highest LAI (2.116) and specific leaf weight (12.44), outperforming all other treatments. In contrast, intercropping finger millet with red gram at 6 : 1 and 8 : 1 ratio resulted in reduced LA, specific leaf weight and crop growth rate. This reduction may be attributed to lower dry matter accumulation

in red gram-based systems, ultimately leading to yield decline.

The inclusion of legumes in intercropping systems supports associated crops by supplying a portion of biologically fixed N (26). Chlorophyll content was found to be significantly higher in treatment T4 (3.14), followed by T2 (3 : 1 ratio) at the maturity stage. The higher chlorophyll content in these treatments may be due to better solar radiation interception, indicating enhanced photosynthetic efficiency. Intercropping black gram with finger millet significantly improved leaf area, specific leaf weight and chlorophyll content. The highest values for leaf area (646.48), crop growth rate (1.378) and chlorophyll content (3.674) were recorded in T4, whereas the lowest values were observed in T7 (380.79, 0.872 and 2.109 respectively).

Black gram, being a short-duration and low-stature legume, contributes to soil N enrichment through biological N fixation through effective nodulation, thereby enhancing growth attributes and dry matter production. Similar findings were reported in maize-cowpea intercropping systems, where N, P and K levels were increased compared with sole cropping (27). Efficient land utilisation under intercropping systems has also been highlighted as a key factor for increased productivity (28). Lower chlorophyll content observed in treatments T3 and T5 may be due to increased competition for space and nutrients between finger millet and black gram. These results are in agreement with earlier findings (29).

Ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco), the key enzyme responsible for CO_2 fixation in higher plants, constitutes nearly 40 % of soluble protein (30). An increase in soluble protein content indicates improved photosynthetic efficiency, making Rubisco activity a reliable indicator of carbon fixation efficiency. In this study, soluble protein content was highest during the flowering and pod-filling stages (Fig. 1).

Indole acetic acid (IAA) oxidase is another important enzyme regulating plant growth and development. Since IAA plays a crucial role in cell elongation and growth regulation, its activity reflects overall plant growth dynamics. Growth rate variations influenced by spacing and radiation interception in intercropping systems are associated with IAA synthesis and activity. Typically, IAA levels are lower before flowering (31). This study examined the spatial distribution of IAA oxidase activity in finger millet, showing enhanced enzyme activity under the 4 : 1 finger millet-black gram intercropping system compared with other treatments (Fig. 2).

Nitrate reductase (NRase), a key enzyme involved in the reduction of nitrate to nitrite, is a substrate-inducible enzyme.

Table 1. Evaluation of intercropping on leaf area ($\text{cm}^2 \text{ plant}^{-1}$), leaf area index, specific leaf weight (g cm^{-2}), crop growth rate ($\text{g m}^2 \text{ day}^{-1}$) and total chlorophyll content (mg/g) of finger millet and intercrop components

Treatments	Leaf area ($\text{cm}^2 \text{ plant}^{-1}$)		Leaf area index		Specific leaf weight (g cm^{-2})		Crop growth rate ($\text{g m}^2 \text{ day}^{-1}$)		Total chlorophyll content (mg/g)	
	Ragi	Intercrop	Ragi	Intercrop	Ragi	Intercrop	Ragi	Intercrop	Ragi	Intercrop
T ₁ – Sole finger millet in row planting	435.73	-	1.915	-	9.08	-	1.192	-	2.240	-
T ₂ – Finger millet with black gram 3 : 1 ratio	496.86	674.2	2.195	2.182	10.5	10.58	1.252	1.62	2.731	3.05
T ₃ – Finger millet with black gram 3 : 2 ratio	444.99	635.4	1.970	1.842	10.1	7.92	1.227	1.44	2.914	2.87
T ₄ – Finger millet with black gram 4 : 1 ratio	646.68	688.2	2.830	2.216	10.9	12.44	1.378	1.86	3.674	3.12
T ₅ – Finger millet with black gram 4 : 2 ratio	535.44	628.6	2.380	0.118	9.40	10.21	1.176	1.48	3.560	2.98
T ₆ – Finger millet with red gram 6 : 1 ratio	440.31	368.6	1.995	0.104	7.49	7.76	1.014	1.06	2.862	2.46
T ₇ – Finger millet with red gram 8 : 1 ratio	380.79	264.2	1.725	0.114	6.77	5.06	0.872	0.98	2.109	1.98
SEm	4.56	48.52	0.05	0.24	0.31	0.36	0.04	0.05	0.53	0.06
CD ($p = 0.05$)	14.04	149.49	0.15	0.75	1.12	1.10	0.13	0.17	1.68	1.18

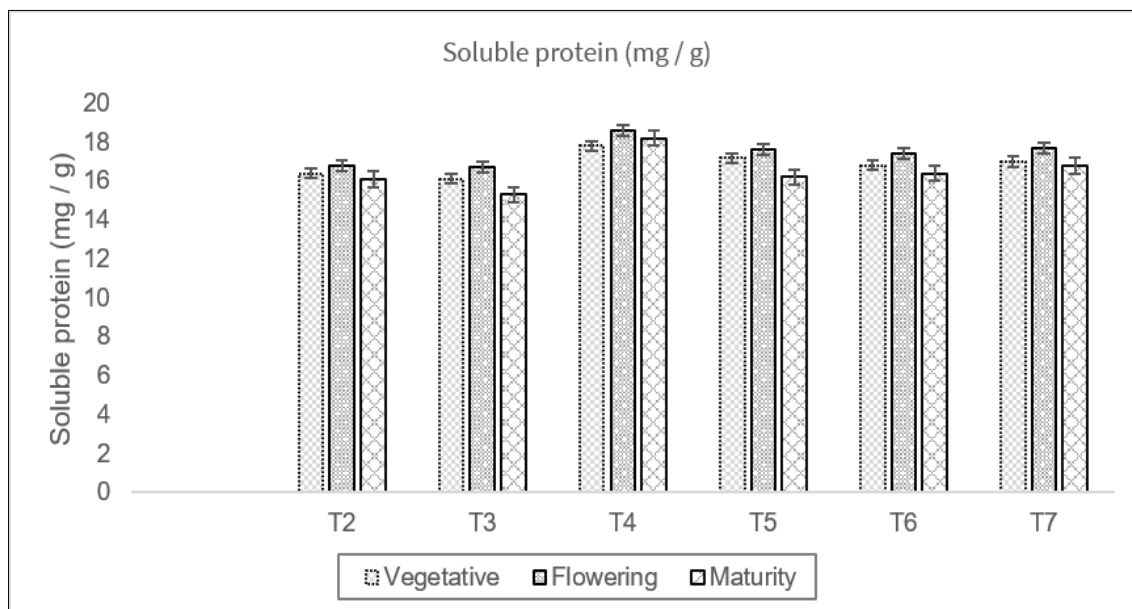


Fig. 1. Intercropping effects on soluble protein content (mg g^{-1}) in black gram and red gram.

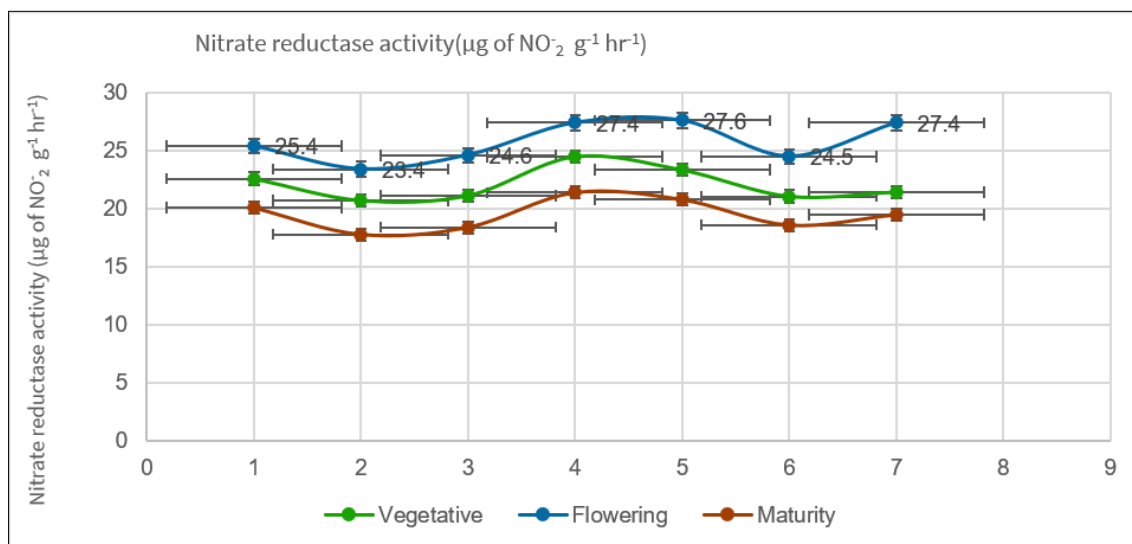


Fig. 2. Intercropping effect on nitrate reductase activity ($\text{mg of NO}_2 \text{ g}^{-1} \text{ hr}^{-1}$) in black gram and red gram.

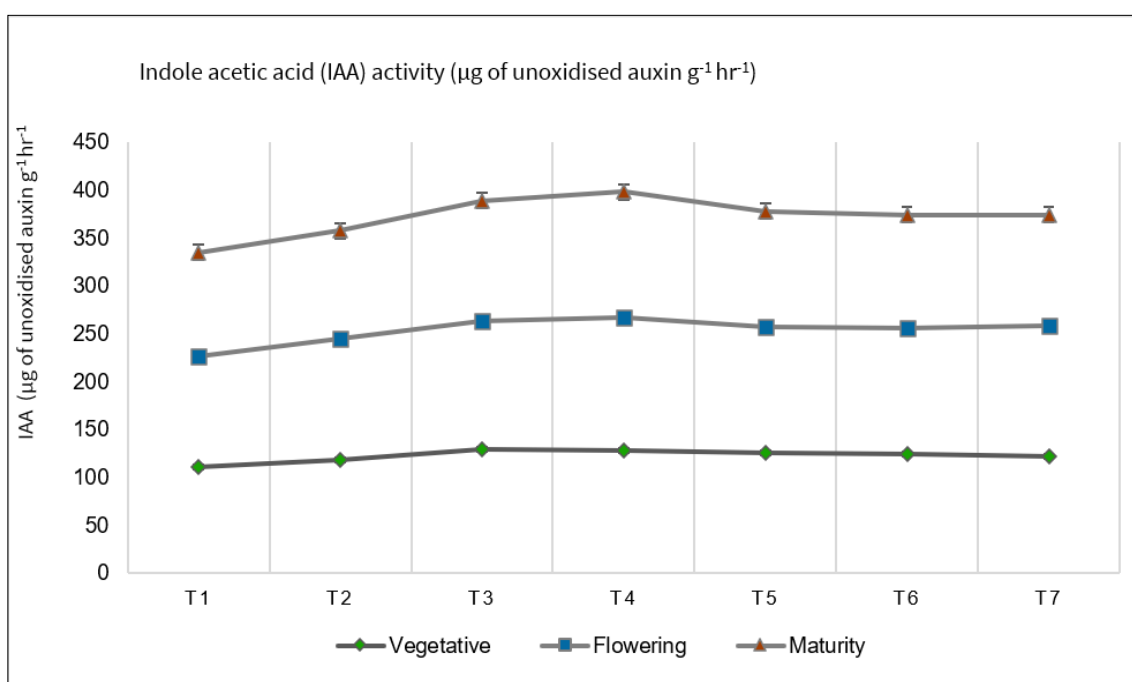


Fig. 3. Intercropping effect on indole acetic acid (IAA) oxidase activity ($\text{mg of unoxidised auxin g}^{-1} \text{ hr}^{-1}$) in black gram and red gram.

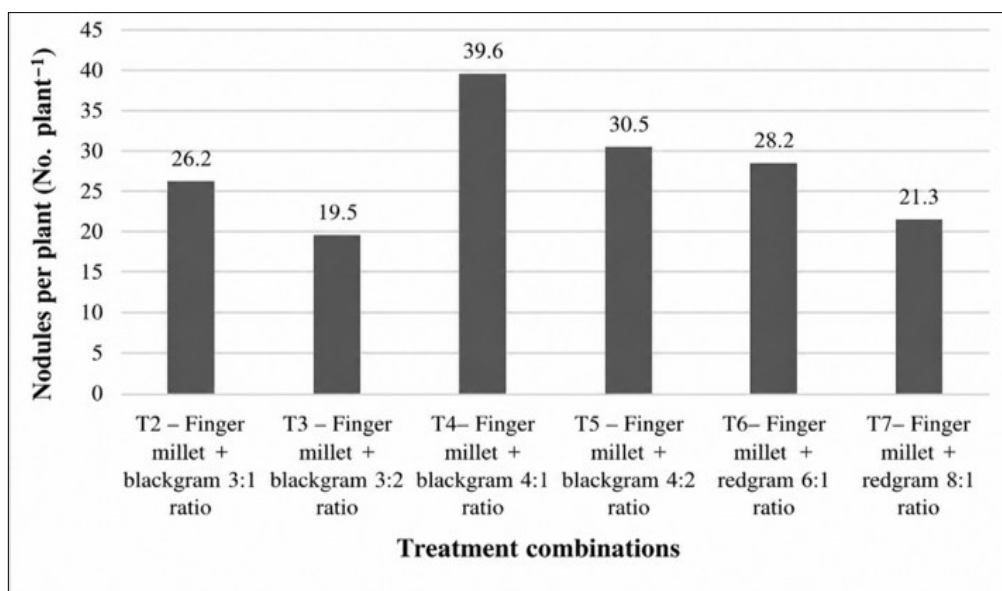


Fig. 4. Intercropping effects on nodule production black gram and red gram.

Previous studies reported that NRase activity increases during early leaf expansion stages and declines later (32). In intercropping systems, competition for resources such as light, nutrients, water and space can induce stress, which in turn influences NRase activity within plants (Fig. 3).

Overall, growing multiple crops together improves yield-related factors by enhancing resource utilisation and stabilising environmental conditions. In this study, finger millet grown either as a sole crop or intercropped with black gram produced higher yields compared with other systems (Fig. 4). Legumes improved soil fertility through N addition, thereby supporting better crop growth. Significant variations were recorded among treatments for growth parameters and chlorophyll content. The 4:1 finger millet-black gram system consistently showed superior performance with the highest LA (688.2), LAI (2.116) and specific leaf weight (12.44). In contrast, red gram-based intercropping systems (6:1 and 8:1) showed reduced performance due to increased competition (33).

Higher chlorophyll content in the 4:1 and 3:1 finger millet-black gram systems can be mechanistically explained by the complementary canopy architecture of the two species: the low-stature black gram canopy allows greater penetration of photosynthetically active radiation (PAR) to the lower finger millet leaves, sustaining chlorophyll synthesis and delaying senescence

(34). Moreover, biological N fixation by black gram nodules augments soil mineral N availability, which directly stimulates chlorophyll biosynthesis via the glutamate synthase pathway, thereby increasing LAI and specific leaf weight. Enhanced N availability from the legume component also contributed to increased biomass production (Table 2), as N is the primary determinant of Rubisco content and hence photosynthetic capacity. The highest dry matter production (25.3 g plant⁻¹) and grain yield (3055 kg ha⁻¹ in black gram intercrop; 75 % higher than the best red gram treatment at 1746 kg ha⁻¹) were recorded in the finger millet + black gram (4:1) treatment (35). In contrast, red gram's taller canopy architecture and longer crop duration (58–63 days to flowering vs. 30–32 days for black gram) intensified inter-specific competition for light, water and nutrients, suppressing finger millet growth and reducing grain yield in T6 and T7 treatments.

Conclusion

The findings of the study demonstrate that intercropping finger millet with legumes significantly affects crop growth, physiological characteristics and overall productivity. Among the various treatments evaluated, the finger millet-black gram system in a 4:1 row ratio exhibited superior performance. This combination enhanced canopy development, increased crop growth rate, improved chlorophyll content and promoted greater dry matter

Table 2. Evaluation of intercropping on total dry matter accumulation (g plant⁻¹), days to flowering, number of clusters per plant, Number of fingers/pods per plant and grain yield (kg/ha)

Treatments	TDMA (g plant ⁻¹)		Days to flowering		Finger length (cm)	No: of clusters per plant	Pods per plant	Grain yield (kg/ha)	
	Ragi	Intercrop	Ragi	Intercrop				Ragi	Intercrop
T ₁ - Sole finger millet in row planting	20.3	19.13	71	-	5.0	5.13	5.2	1843	2486
T ₂ - Finger millet with black gram 3:1 ratio	23.2	26.05	65	30	4.7	6.37	5.9	1998	2583
T ₃ - Finger millet with black gram 3:2 ratio	21.6	24.52	64	32	4.6	5.67	4.1	1720	2864
T ₄ - Finger millet with black gram 4:1 ratio	25.3	28.31	68	30	5.1	6.80	7.1	2054	3055
T ₅ - Finger millet with black gram 4:2 ratio	23.0	21.51	68	32	4.8	6.20	6.3	1865	2758
T ₆ - Finger millet with red gram 6:1 ratio	20.6	21.14	62	58	3.2	11.14	5.4	1265	1746
T ₇ - Finger millet with red gram 8:1 ratio	19.6	19.50	60	63	3.5	7.20	4.6	1077	1477
SEm	0.65	0.91	0.33	0.69	0.05	0.56	0.25	75.6	37.47
CD (p = 0.05)	1.99	2.81	1.03	2.12	0.14	1.72	0.77	232.9	115.42

accumulation, ultimately leading to higher grain yield. Therefore, the finger millet-black gram intercropping system can be effectively recommended for enhancing productivity and profitability under irrigated conditions. Furthermore, similar intercropping approaches involving millets and legumes can be adopted to promote sustainable agriculture and enhance farmers' income. Future research should focus on validating these intercropping systems under rainfed and water-limited conditions, evaluating their performance across diverse agro-climatic zones and assessing long-term soil health impacts. Additionally, studies on economic feasibility and adoption potential among small and marginal farmers are strongly recommended.

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Authors' contributions

AK contributed to the conceptualisation, methodology and preparation of the original draft. SB was responsible for data curation, formal analysis and manuscript revision. GS contributed to data visualisation. BR contributed to software-based data analysis, manuscript alignment and reference checking. BM contributed to the investigation, resource provision and validation. NKS, AKS and SK provided supervision, formal review and overall project coordination. All authors reviewed and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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