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RESEARCH ARTICLE

Biometric and yield response of redgram (*Cajanus cajan* (L.)) understrip intercropping and land configurations in a rain-fed environment

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Abstract

Strip intercropping is practiced for efficient resource utilization, mechanization and increased productivity per unit area. In India, no studies have evaluated the suitability of strip intercropping system for redgram. The growth and yield performance of redgram with different component crops in strip intercropping remains unknown. To address this knowledge gap, field experimentation was conducted at Institute of Agriculture, TNAU, Kumulur during 2020-21, 2021-22 and 2022-23 using split plot design to explore the redgram-based strip intercropping system and land configurations under rain-fed condition. In this, 3 land configurations and 7 strip intercropping systems were kept as main plot and sub plot treatments with 3 reproductions. On average, strips of blackgram (S1), greengram (S2) and groundnut (S4) intercropped redgram produced higher plant height (32%), leaf area index (8.7%) and dry matter production (138%) over redgram intercropped with cotton strips (S6). Growth functions viz., relative growth rate (RGR), crop growth rate (CGR) and biomass duration (BMD) of redgram were increased in average of 94%, 67% and 42.5% respectively in treatments S1, S2 and S4 over pure redgram (S7). Grain yield of redgram was increased as on average 621 kg/ha in S1,S2 and S4 treatments over redgram yield (286 kg/ha) in S6. S6 gave higher crop equivalent yield (CEY) of 954 kg/ha and 975 kg/ha during 2020-21 and 2021-22 respectively. In 2023-24, S2 produced higher CEY of 1054 kg/ha. From AMMI, it was observed that redgram with blackgram/greengram strip intercropping under compartmental bunding was more stable than any other system.

Keywords

CEY; cropping system; land configuration; LER; redgram; strip intercropping

Introduction

Redgram is considered as one of themain grain legume crops of the regions comes under tropical and subtropical, particularly rain-fed conditions of the semi-arid tracts (1). It accounts for 1.76% and 22% of the gross cropped area (4.42 million ha) and total pulse production (4.02 million tonnes) respectively, in India and it is second most cultivated and produced crop after bengalgram with standardyield of 909 kg/ha (2). Redgram grain legume is a primary part of the Indian foods and encompassing protein, fat, carbohydrate and ash with 20-

22%, 1.2%, 65% and 3.8% respectively (3). In Tamil Nadu, redgram was cultivated in 0.056 million ha with the output of 0.048 million tonnes grain and the mean productivity of913 kg/ha during 2016 - 2017. The redgram sowing commonly done after the first receipt of southwest monsoon rainfall with less population as a border crop or component crop in-between the main crop like groundnut, cotton, etc. In addition to providing biological insurance, it ensures maximum yield advantage than sole cropping due to efficient utilization of resources (4). Even though, it has good yield potential, the production of redgram is still lacking due to the cultivation practiced under resource poor environment like rain-fed condition and semi-arid tracts, where water scarcity is frequent constrain caused by uncertainty in receipt of rainfall and its poor distribution throughout the cropping period (5). In addition to that, poor soil fertility status of the semi- arid region restricts the potential yield outcome of redgram (6).

For the first time, an attempt was made to evaluatethe possibility of increasing redgram productivity by adopting strip intercropping system with other component crops (blackgram, greengram, cowpea, groundnut, sesame and cotton) from the conventional method where redgram raised as secondary crop (7). Strip intercropping system is the type of intercropping system, where more than one crop raised in alternate strips. Each strip has been maintained with number of component crop rows and structured as wider and as longer than conventional row intercropping. This system permits easy intercultural operations without affecting component crops which essential for mechanization and it restrict the competition at border rows alone and decreasing towards inner rows (8). In addition to strip intercropping, land configuration was added as secondary factor to test the biological and economic yield of redgram-based strip intercropping system. Land configurations are essential to conserve the rainwater under rain-fed ecosystem where runoff and excess evapo-transpiration are common ways led to loss soil moisture (9).

As a consequence, the present study was conducted with following objectives: (i) to determine the most effective land configuration for maximising redgram growth and yield; (ii) to understand the growth and yield performance of redgram under strip intercropping system with different component crops and their yield advantages; (iii) and to identify superior strip intercropping system with steady yield performance across3 cropping periods with different land configurations.

Materials and Methods

The research was experimented during the kharif season of 2020-21, 2021-22 and 2022-23 at Eastern farm of Agriculture Engineering College and Research Institute, Tamil Nadu Agricultural University, Kumulur, Tamil Nadu. The purpose of this investigation was to analyse the impact of strip intercropping and land configurations on redgram growth, yield attributes, yield and cropping system indices and their stability over different cropping periods and land configurations. The experimental site's long-term average yearly rainfall (mean of 30 years) was 720.8 mm dispersed over 47 wet days. The 2 monsoon seasons, SWM and NEM, produced 26.2 and 51.6% of the rainfall respectively, with October being the wettest month (186.0 mm). The location's long-term mean maximum and lowest temperatures are 31.9°C and 21.4°C respectively.

The soil of the experimental field is clay loam with 8.3 pH, 0.38% organic matter and total N, P, K of 336 kg/ha, 17.5 kg/ha and 613 kg/ha respectively. Total rainfall received during the cropping period of 2020-21, 2021-22 and 2022-23 was 530 mm, 721 mm and750 mm respectively. The experiment was set up using a split plot statistical design with seven sub factors of S1: Redgram/Blackgram, S2: Redgram/Greengram, S3: Redgram/Cowpea, S4: Redgram/Groundnut, S5: Redgram/Sesame with 4:5 ratio; S6: Redgram/Cotton with 4:4 ratio and S7: Redgram pure crop. Three main factors of land configurations as CB: compartmental bunding, BBF: Broad Bed Furrow and R and F: Ridges and furrow, all of which were replicated 3 times. The cultivars were used Co (Rg) 7 for redgram, Co 6 for blackgram, Co8 for greengram, VBN 1 for cowpea, TMV 13 for groundnut, TMV 7 for sesame and Co 14 for cotton. For each treatment, the grass plot size of 8.6 m × 3.8 m and 7.8 m × 3.0 m net plot size were maintained. The compartmental bunding, broad bed furrows and ridges and furrows were formed manually by using spade. In broad bed furrow, width of bed, width of furrow and depth of furrows were maintained as 150 cm, 30 cm and 15 cm respectively. Redgram and cotton were sown in ridges and furrows spaced 45 cm apart, while blackgram, greengram, cowpea, groundnut, and sesame were sown in ridges and furrows spaced 30 cm apart.

The package of practices given in TNAU crop production manual (10) was adopted for all test crops. For observation, 5 redgram plants from every plot were randomly selected after crop establishment and tagged in order to record growth and yield parameters. In each plot, at flowering stage, parameters of the third leaf from the top of the tagged plants were measured. At the harvest stage of crop growth, plant height was measured from the soil surface to the terminal part of shoot. The growth and growth functions of leaf area index (11), relative growth rate (12), crop growth rate (13), biomass duration (14) was computed by using Eqn.1, Eqn. 2, Eqn. 3 and Eqn. 4 respectively, for the flowering stage of redgram. The plant samples collected at flowering and harvest stage were air dried and then baked at 65°C ± 5 °C until they attained a stable weight and total dry matter production (DMP) was expressed in kg/ha. After being harvested and having the crop threshed by beating it with wooden rods, the plants were bundled and let too dry in the sun. Seed yield per net plot was measured, cleaned and dried before being winnowed, cleaned and converted to kg/ha. To assess the yield advantages and land use advantages, Crop Equivalent Yield (CEY) (15) and Land Equivalent Ration (CEY) (16) had arrived through the Eqn. 5 and Eqn. 6 respectively.

Leaf Area Index (LAI) =

$$\frac{\text{A x No. of green leaves per plant}}{\text{Plant spacing (cm}^2\text{)}} \qquad \text{(Eqn. 1)}$$

where,

A: Leaf area of terminal leaflet

L and W: Length and Width of terminal leaflet

Relative Growth Rate (RGR) =

$$\frac{\log_e W2 - \log_e W1}{t2 - t_1} \quad g/kg/day \qquad \text{(Eqn. 2)}$$

where,

W_1: DMP in kg ha^{-1} at times t_1; W_2: DMP in kg ha^{-1} at times t_2

Crop Growth Rate (CGR) =

$$\frac{W_2 - W_1}{P(t_2 - t_1)} \quad Kg/ha/day \qquad \text{(Eqn. 3)}$$

where,

W_1: DMP in kg ha^{-1} at times t_1; W_2: DMP in kg ha^{-1} at times t_2

P: the ground area occupied by the plant in m^2.

Bio Mass Duration (BMD)=

$$\frac{(TDM_1 + TDM_2)}{2} \times (t_2 - t_1) \text{ g. day} \qquad \text{Eqn. 4}$$

where,

BMD: Biomass duration between time $_2$ and time$_1$

TDM_1: DMP in kg ha^{-1} at times t_1; TDM $_2$ - DMP in kg ha^{-1} at times t_2

$$CropEquivalentYield\ (CEY) = \sum_{i-1}^{n} (Yi \times ei) \qquad \text{(Eqn. 5)}$$

where,

Y: The economic yield I to 'n' number of crops (kg/ha)

e: The crop equivalent factor

$$LandEquivalentRatio(LER) = La + Lb = \left\{\frac{Ya}{Sa} + \frac{Yb}{Sb}\right\} \qquad \text{(Eqn. 6)}$$

where,

La: LER for main crop in the mixture; La: LER for component crop in the mixture

Ya: Main crop yields in an intercropping situation; Yb: Component crop yields in an intercropping situation

Sa: Yield of main in pure stand; Sb: Yield of component crop in pure stand.

LER values of >1, 1 and <1 is indicates yield advantage, no gain no loss and yield loss respectively.

The data were examined statistically in accordance with the guidelines (17). Critical variations were calculated at a 5% probability level and the values were included in the relevant tables and figures wherever the treatment differences were determined to be significant (F test).

To explain the interaction of the strip intercropping system with the environment and assess its stability, a stability analysis was performed. The GGE biplot and AMMI were used to show the multivariate stability analysis using R Studio, a streamlined version of R statistical software developed by the R Core Team in 2016. This package generally used to know the interaction between genotypes and environment interaction. In this study, instead of gene and environment, strip intercropping system and environment (land configurations with cropping periods) respectively substituted to understand the interaction and assess the stability. ANOVA was used to analyse the quantitative characteristics to estimate the existence variations among the strip intercropping systems, land configurations, cropping periods, strip intercropping system by land configurations, strip intercropping system by cropping periods and strip intercropping system by land configurations by cropping periods (strip intercropping system by environment) using R studio version 4.1. The environment (land layouts and cropping times) was viewed as random factors while the strip intercropping systems were treated as fixed variables. GGE biplots were implemented using the GUI package of R studio, whereas AMMI (18) was implemented using the Agricolae package. These 2 concepts were the biplot concept (19) and the GGE concept (20).

Results and Discussion

Effect of land configurations

Growth parameters, yield attributes and yield of strip intercropped redgram **:** Land configurations were significantly influenced all growth parameters (Plant height (cm), Dry Matter production (DMP) and Leaf Area Index (LAI)) and growth functions of strip intercropped redgram throughout all 3 cropping periods of the experiment. Between the various land configurations, sowing in ridges and furrow (R and F) was noted higher redgram plant height of 118.6 cm (2020-21), 144.8 cm (2021-22) and 145.5 cm (2022-23). Similarly, highest DMP of 1357, 1423 and 1440 kg/ha and LAI of 2.10, 2.34 and 2.36 were recorded in R and F during 2020-21, 2021-22 and 2022-23 respectively (Fig. 1). These results were comparable with growth parameters (plant height (cm), DMP and LAI) of redgram strip raised in compartmental bunding (CB). The average (3 years) increment was 12.75% for redgram plant height (cm), 9.16% for DMP and 12.97% for LAI in R and F sown redgram over the redgram raised in CB. Broad bed furrow (BBF) sown redgram produced shorter plants, less DMP (kg/ha) and Leaf Are Index (Fig. 1) than other land configurations (CB and R and F).

Similar to growth parameters, relative growth rate (RGR), crop growth rate (CGR) and biomass duration (BMD) were calculated from leaf production and biomass production during the peak flowering period of the redgram (60 - 90 DAS). During all the cropping periods (2020-21, 2021-22 and 2022-23), physiological growth functions *viz*., LAI, RGR, CRG and BMD were significantly different between land configurations (Fig. 1). Between the various land configurations, sowing in R and F gave higher values of RGR (0.242, 0.329 and 0.334 g/g/day), CGR (2.446, 2.441 and 2.49 g/m^2/day) and BMD (724, 717 and 729 g. day) at flowering stage of redgram during all 3 cropping periods (2020-21, 2021-22 and 2022-23) (Fig. 1). In average of 3 cropping periods, RGR,

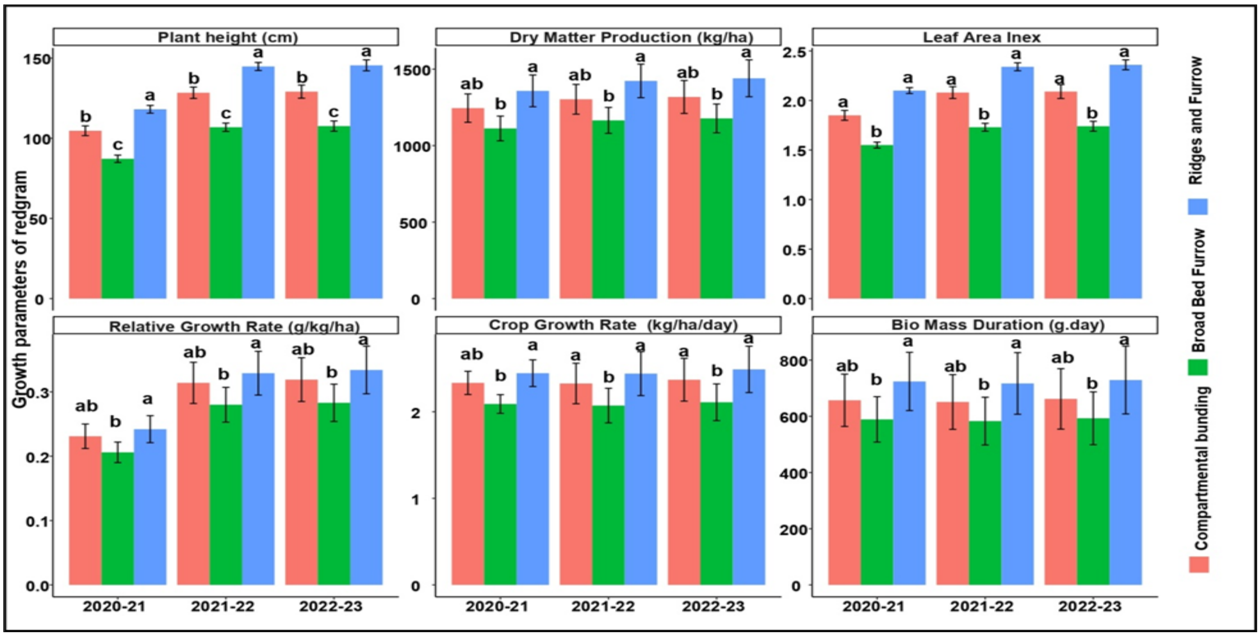

Fig. 1. Plant height (cm), dry matter production (kg/ha), leaf area index, relative growth rate (g/kg/day), crop growth rate (kg/ha/day) and biomass duration (g. day) of pigeon pea under different land configurations over 3 different growing seasons. Vertical bars denote standard errors of the average. Different letters denote significant variations (P < 0.05) between treatments.

CGR and BMD were increased 17.63%, 17.61% and 22.94% respectively in R and F sown redgram over the redgram sown in BBF.

In yield indices and yield of redgram, maximum number of pods were recorded in R and F as 94, 110 and 111 pods/plant in order to 2020-21, 2021-22 and 2022-23 cropping period. The number of pods/plant was reflected on grain yield of redgram raised in R and F land configuration. It was 541, 588 and 616 kg/ha during 2020-21, 2021-22 and 2022-23 respectively and these were on par with redgram sown in CB method (Table 1). The R and F sowing increased 13.30% in pods per plant of redgram and 22.5% in grain yield in average of 3 cropping periods of redgram strips over CB method due to increased and uniform soil moisture conservation through entire plot. The lowest pods per plant and grain yield of redgram were recorded in BBF sowing. Throughout all cropping periods, there was no discernible variation in the quantity of redgram seeds or pods across various land configurations.

All the growth parameters and physiological functions of redgram in strip intercropping were recorded in R and F land configuration was superior to other land configurations. A study (21) shows that R and F produced taller plants in pearl millet and sorghum, which was in line with the findings of this study. Increased dry matter production of cowpea, pearl millet, cotton and sunflower under R and F were reported in previous studies (21-24). The results of physiological growth functions are in line with the findings of past study (23), which reported, higher LAI of cotton planted in ridges and furrow land configuration. More leaves with more branches were the cause of this increase in LAI (25) and it was accordance to previous study results (21). The yield results are confirmed by previous investigation (26), which reported that higher yield causative characters i.e. pods per plant, number of grains per plant, weight of pods per plant and weight of grains per plant were recorded in ridges and furrow method of sowing over opening of furrows after every 2 rows and flatbed sowing in soybean. Earlier reports (27), shows that the effect of planting method on pod length, number of seed per pod and 100 seed weight were insignificant. The increased grain yield of groundnut (28), sorghum, cowpea, bengalgram and sunflower (29) in ridges and furrow were reported in earlier studies.

These growth and yield advantages of redgram strips in R and F land configuration was due to the favourable soil environment, which is necessary for optimum growth and development (21). In rain-fed farming ecosystem, soil

Table 1. Impact of strip intercropping systems and land configurations on redgram yield characteristics and yield in rain-fed ecosystems

Treatment	No of pods/plant			No. of seeds/pod			Redgram grain yield (kg/ha)		
Strip Intercropping	2020-21	2021-22	2022-23	2020-21	2021-22	2022-23	2020-21	2021-22	2022-23
S1: Redgram / Blackgram	109.4a	123a	530b	530b	530b	4.25	530b	661b	702b
S2: Redgram / Greengram	106.7a	120a	521bc	521bc	521bc	4.06	521bc	621c	696b
S3: Redgram / Cowpea	70b	84b	412d	412d	412d	4.01	412d	398d	387c
S4: Redgram / Groundnut	107.5a	118a	512c	512c	512c	4.11	512c	633c	709b
S5: Redgram / Sesame	62c	76c	370e	370e	370e	4.01	370e	336e	319d
S6: Redgram / Cotton	45d	59d	332f	332f	332f	4.03	332f	267f	258e
S7: Redgram pure crop	59c	75c	770a	770a	770a	4.03	770a	830a	853a
LSD (0.05)	6.52	7.41	17.50	17.50	17.50	2.02	17.50	18.58	19.46
Level of significance	***	***	***	***	***	NS	***	***	***
Land configuration									
CB: Compartmental bunding	83a	97a	494ab	494ab	494ab	4.08	494ab	537ab	563ab
BBF: Broad Bed Furrow	63b	74b	442b	442b	442b	4.04	442b	480b	503b
R and F: Ridges and Furrow	94a	110a	541a	541a	541a	4.10	541a	588a	616a
LSD (0.05)	11.66	13.85	56.80	56.80	56.80	0.55	56.80	58.20	59.51
ICXLC	NS	NS	NS	NS	NS	NS	NS	NS	NS

moisture plays a crucial role in determining the success and failure of cropping system. Soil moisture was favourable in R and F land configuration (21). After receipt of rainfall or post monsoon, R and F system conserves the soil moisture by alternate ridges (runoff barrier) and furrows (water storage), and it extends the water availability period (30) to crop growth and development. This augmented soil moisture accessibility in R and F enhances soil nutrient availability and uptake by crop plants (21). Apart from the moisture conservation benefits, alternate furrows can act as drainage channel to drain excess water (30). Likewise, an alternate ridge facilitates soil aeration (21) due to its elevation from the furrow surface (Fig. 2). In this way R and F provides favourable soil environment by conserving moisture, improving nutrient availability and aeration. Cumulative effect of all these reasons reflected on constant physiological functions Viz., cell division and elongation for every incremental increase in crop growth by increased photosynthesis (31). Subsequently, it increased the vertical and lateral growth of redgram plants and ensures higher dry matter accumulation (31) and higher yield attributes and yield of redgram (32). The reduced growth and yield of redgram in strip intercropping system under CB and BBF land configuration was due to the unfavourable soil environment under rain-fed condition. Excess soil moisture and uneven distribution within the plot are main problem in CB. In BBF, early soil moisture scarcity is the main constrain due to excess drainage of soil moisture and elevated planting zone.

Crop Equivalent Yield and Land Equivalent Ratio

Similar to yield attributes and yield parameters, Crop Equivalent Yield (CEY) was significantly varied over different land configurations. R and F sowing was recorded higher crop equivalent yield of redgram as 851, 946 and 985 kg/ha in order

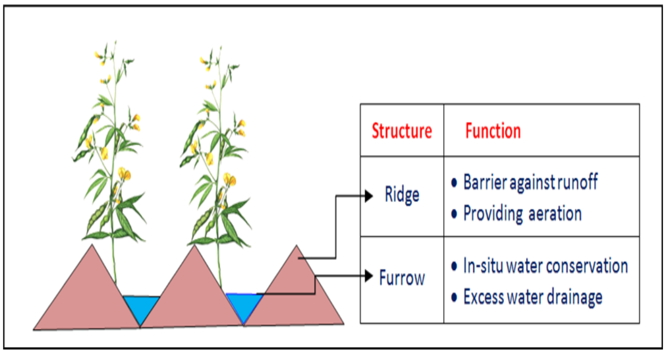

Fig. 2. Structure and function of ridges and furrow land configuration under rainfed cropping system.

to 2020-21, 2021-22 and 2022-23 cropping periods. The lower crop equivalent yield was recorded in CB method and BBF sowing method during all cropping periods (Table 2). Previous studies have documented that yield advantages of sorghum, bajra, maize (33), spinach (34) and cotton (32) based intercropping system in ridges and furrow in earlier studies. The increased CEY in R and F was due to the increased growth and yield of both main crop and component crops (Table 2). Land configurations didn't influence the land equivalent ratio (LER) of different strip intercropping systems significantly (Table 2).

Effect of strip intercropping system

Growth parameters, yield attributes and yields of redgram : Strip intercropping significantly influenced the redgram growth, growth functions and yield with various intercrops. Redgram pure crop (S7) produced the highest plant height (cm) during all the cropping periods (2020-21, 2021-22 and 2022-23) in the order of 111 cm, 135.8 cm and 139.2 cm (Fig. 3). The plant height of redgram in pure crop was nearly equal with height of redgram plants in strips intercropped with blackgram (S1), greengram (S2) and groundnut (S4) strips. In average, these treatments (S1, S2 and S4) produced redgram plants with heights of 111.4 cm, 133.8 cm and137.8 cm during 2020-21, 2021-22 and 2022-23 cropping period respectively. These were 17.95%, 11.22% and 17.30% taller than redgram plants in strips intercropped with cotton strips in order to 2020-21, 2021-22 and 2022-23 cropping periods. Similarly, redgram pure crop (S7) was produced higher dry matter production (kg/ha) during the cropping period of 2020-21, 2021-22 and 2022-23 in the order of 1830, 1983 and 2012 kg/ha in dry matter production (kg/ha). The DMP of redgram reduced under strip intercropping due to lower population than pure redgram (S7). In that, redgram produced more dry matter when interplanted with blackgram (S1), greengram (S2) and groundnut (S4) strips and there was no significant difference (P>0.05) between these treatments (S1, S2 and S3). Dry matter production of redgram strip intercropped with blackgram strip was increased by 143.70%, 127% and 151.90% higher than cotton strip intercropping (S6) system throughout all cropping periods (2020-21, 2021-22 and 2022-23) of the experiment.

Unlike plant height (cm) and DMP (kg/ha), growth functions (LAI, RGR, CGR and BMD) were recorded as lower in pure stand of redgram (S7). The increased LAI, RGR, CGR and total BMD were recorded in redgram intercropped with

Table 2. Impact of strip intercropping systems and land configurations on cropping system indices in rain-fed ecosystems

Treatment	Intercrop yield (Kg/ha)			Crop Equivalent yield (Kg/ha)			Land Equivalent Ratio		
Strip Intercropping	**2020-21**	**2021-22**	**2022-23**	**2020-21**	**2021-22**	**2022-23**	**2020-21**	**2021-22**	**2022-23**
S1: Redgram / Blackgram	285	352	360	756cd	940ab	987b	1.129a	1.340a	1.379a
S2: Redgram / Greengram	352	409	435	811b	958a	1054a	1.143a	1.291a	1.416a
S3: Redgram / Cowpea	393	459	500	628e	649d	661d	1.001b	1.024b	1.060b
S4: Redgram / Groundnut	586	659	697	745d	895b	986b	1.149a	1.307a	1.430a
S5: Redgram / Sesame	360	413	431	791bc	820c	824c	0.954bc	0.949bc	0.951c
S6: Redgram / Cotton	805	916	899	954a	975a	953b	0.909c	0.865c	0.845d
S7: Redgram pure crop	0	0	0	770bcd	830c	853c	1.000b	1.000b	1.028bc
LSD (0.05)	-	-	-	41.86	46.94	47.31	0.072	0.076	0.081
Level of significance	-	-	-	***	***	***	***	***	***
Land configuration									
CB: Compartmental bunding	520	591	489	786a	874b	911b	1.039a	1.109a	1.157a
BBF: Broad Bed Furrow	460	522	431	701b	780c	812c	1.042a	1.113a	1.160a
R and F: Ridges and Furrow	543	617	504	851a	946a	985a	1.041a	1.111a	1.158a
LSD (0.05)	-	-	-	67.42	70.41	71.71	0.144	0.148	0.15
ICXLC	-	-	-	NS	NS	NS	NS	NS	NS

blackgram (S1), greengram (S2) and groundnut (S4) at flowering stage (60-90 DAS) and these were on par with each other during all the cropping periods (Fig. 3 and 4). In average, these treatments were shown increment of 2.16%, 2.12% and 2.15% in LAI; 70%, 106% and 106% in RGR; 48%, 106% and 107% in CGR and 9%, 58% and 60% in BMD over redgram pure crop (S7) during the all 3 cropping periods (2020-21, 2021-22 and 2022-23). The results of growth parameters and growth functions were reflected on yield attributes and yield of redgram (Table 1). Among the strip intercropping systems, the higher number of pods per plant and grain yield wasobserved in redgram intercropped with blackgram (S1), greengram (S2) and groundnut (S3) and these were on par with each other through all cropping periods (Table 1). Redgram intercropped with blackgram strips yielded a greater number of pods per plant and grain yield. The number of pods/plant increased by 85.42%, 80.85% and 82.20% over redgram pure crop, while grain yield increased by 59.6%, 147% and 172% over redgram intercropped with cotton strips in 2020-21, 2021-22 and 2022-23 respectively. The increased plant height (cm) and DMP of redgram intercropped with blackgram (S1), greengram (S2) and groundnut (S4) strips are similar to the findings of earlier experiments (35). The previous experimental reports (36) strengthen the findings of this study as increased growth functions of redgram under strip intercropping system S1, S2 and S4. The yield benefits of redgram in S1, S2 and S4 are in accordance with the previous experimental results (47).

There were no appreciable differences in the plant heights (cm) of redgram pure crop and redgram interplanted with blackgram, because there was no antagonism between the 2 component crops and that it actually favoured to increase redgram plant height and DMP (37). The lower plant height of redgram was recorded with intercropping of cowpea (S3) strips, followed by sesame (S5) and cotton (S6) strips (Fig. 5) due to the taller plant height and more biomass production of cowpea, sesame and cotton (37) have reduced the growth of neighbour redgram strips (Fig. 5), where the growth pace was usually lower during early growth phase of redgram. The cowpea (S3), sesame (S5) and cotton (S6) strip intercropping scheme was associated with a decreased

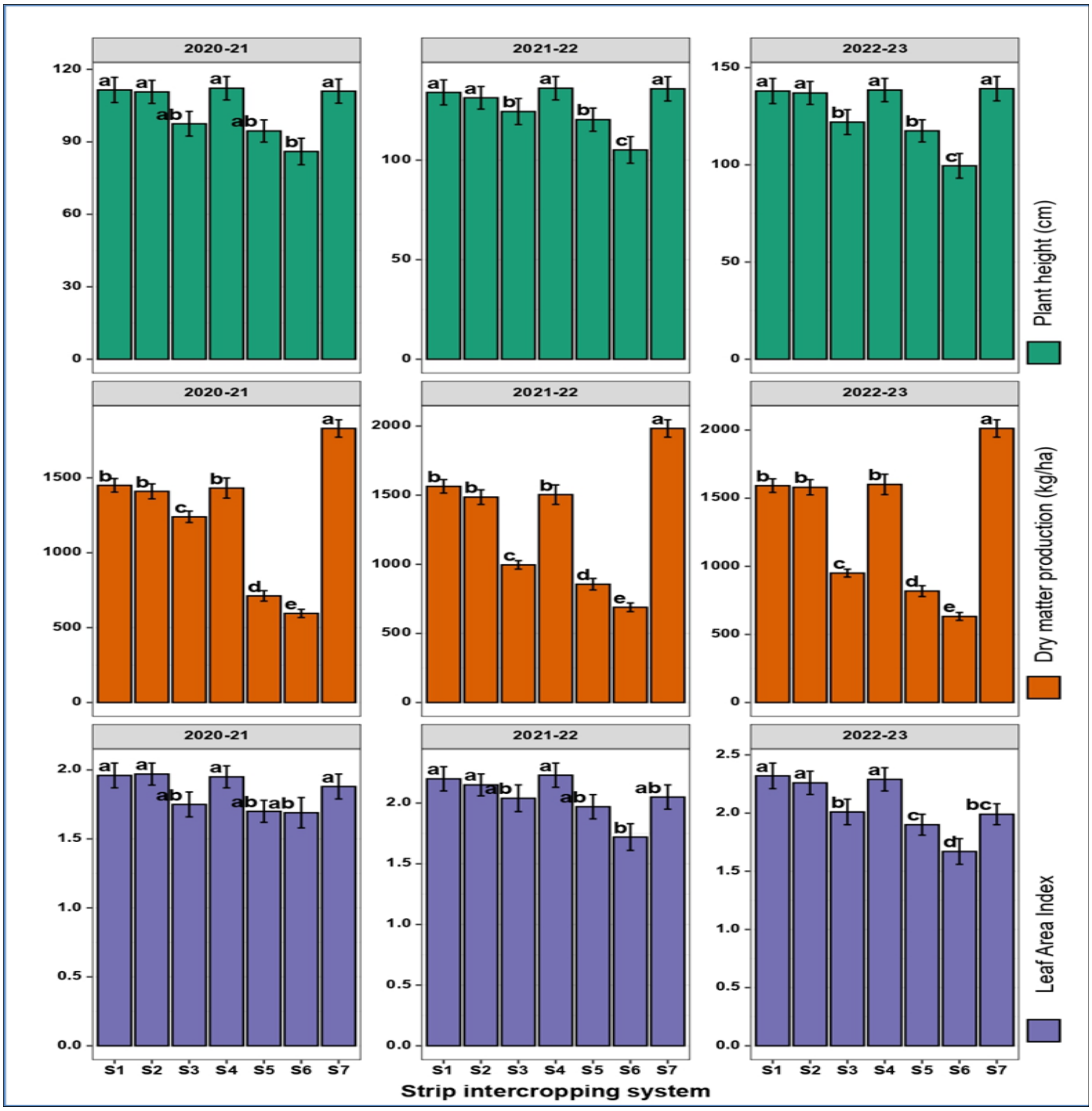

Fig. 3. Plant height (cm), dry matter production (kg/ha), leaf area index, relative growth rate (g/kg/day), crop growth rate (kg/ha/day) and biomass duration (g. day) of pigeon pea under different land configurations over 3 different growing seasons. Vertical bars denote standard errors of the average. Different letters denote significant variations (*P* <0.05) between treatments.

redgram dry matter output (Fig. 3) and these outcomes were consistent with earlier (38) findings.

In contrast to plant height and DMP, the reduced growth functions of redgram in pure stand might be the reason of intra plant competition between redgram in sole crop (S7) for light interception, nutrient and moisture uptake. In strip intercropping, short duration and shorter statured legume crops shows anidation effect with redgram by wider space availability between each 4 rows of redgram (Fig. 6), which might have resulted in increased growth of redgram in border rows by receiving more light, soil moisture and nutrients without any competition and resulted in more growth rate (39) and other growth functions. This factor facilitated to produce maximum number of leaves and leaf area index (31).

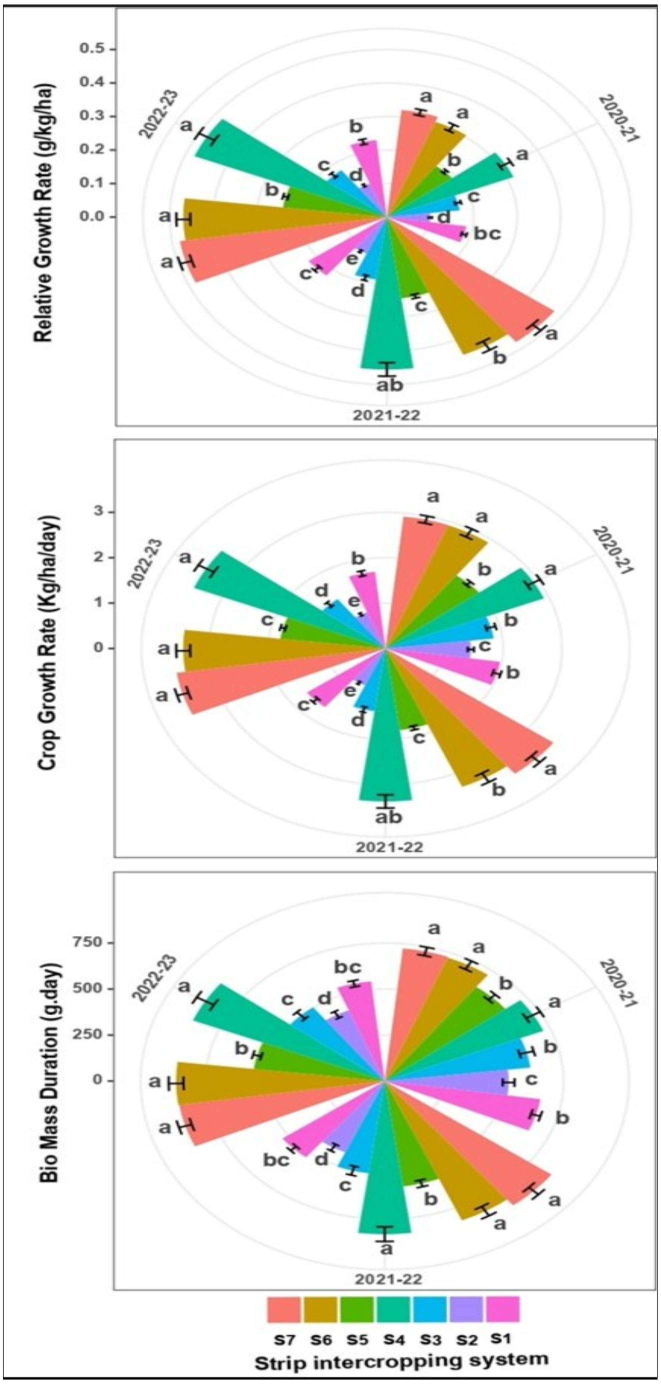

Fig. 4. Relative growth rate (g/kg/day), crop growth rate (kg/ha/day) and biomass duration (g. day) of pigeon pea under strip intercropping system. Vertical bars denote standard errors of the average. Different letters denote significant variations (P < 0.05) between treatments.

Fig. 5. Reduced growth of strip intercropped redgram with competitive intercrops (cowpea and cotton).

The zero of antagonism between the redgram and component crops (blackgram, greengram and groundnut) in strip intercropping system as well as the availability of additional area encouraged to extend more branches of redgram (Fig. 7) due to the shorter plant height, shorter growing season and early maturity of component crops. This led to the production of maximum number of branches per plant and pods per plant of redgram (Table 1). In the same way, earlier research published that, intercropping greengram with redgram had no negative effects on the grain production of redgram (40) in intercropping system. The different feeding zone (root distribution) of main crop and component crop to absorb nutrient and water might be resulted zero competition below ground surface and finally it reflected as increased yield indices and yield of redgram.

Redgram intercropped with cotton exhibited lower pod numbers and grain yield due to competition for resources, as the taller cotton plants overshadowed redgram growth (Fig. 5). It was found that, strip intercropping systems had no effect on yield attributes *viz*., pod length, number of seeds/pod and 100 seed weight of redgram.

Crop Equivalent Yield and Land Equivalent Ratio : In different strip intercropping systems, redgram and cotton (S6) strip intercropping system gave higher crop equivalent yield (CEY) during 2020-21 and 2021-22 with the increment of 23.8% (2020-21) and 17.46% (2021-22) over pure redgram yield (Table 1). During 2020-21, rainfall received only 530 mm which was insufficient to support the potential growth of both redgram and component crops. In redgram + Cotton

Fig. 6. Space available after harvest of intercropped strips (blackgram, greengram and groundnut) in between redgram strip.

Fig. 7. Well-developed branches with a greater number of pods in redgram strip intercropped with blackgram, greengram and groundnut strips.

strip intercropping, poor growth and development of both crops led to poor competition for resource and both crops were produced substantial yield than other systems. Rest of the component crops (blackgram, greengram, cowpea, groundnut and sesame) were completed their growth cycle before the receipt of entire rainfall of 530 mm (Fig. 8). In addition to that, flower shedding was observed due to rainfall during the flowering stage of intercrops, and this resulted in below average yield (Table 1). In the same condition, redgram and cotton received entire rainfall (530 mm) due their long duration nature (Fig. 8). Combined effect of these factors aided to produce maximum CEY of redgram + cotton strip intercropping system during 2020-21. The increased rainfall (721 mm) in 2021-22 reduced the CEY gap between redgram intercropped with blackgram, greengram and cotton strips. Even though cotton reduced the redgram grain yield (Table 2) by competitive effect, the CEY was increased due to the highest production of cotton and its higher cost per unit of produce. Similar findings were made by earlier investigation (41) on sandy loam soil and discovered that cotton intercropping had an impact on redgram's grain yield but boosted overall productivity in terms of redgram equivalent output.

In 2022-23, highest CEY was recorded in redgram + greengram treatment (S2), which recorded 23.56% more equivalent yield compared to redgram pure crop yield (Table 2). Next to these treatments, redgram intercropped with blackgram and groundnut was higher in CEY. Similarly, earlier findings (40) reported that, the intercropping of greengram with redgram did not affect grain yield of redgram instead produced additional grain yield of greengram. This additional grain yield of greengram along with the grain yield of redgram significantly produced higher redgram equivalent yield over sole redgram as well as sole greengram. In 2022-23, CEY was reduced in cotton intercropped treatment due to early withdraw of rainfall (Fig. 8), which reduced the cotton yield and reflected negatively on total crop equivalent yield. This was also confirmed with the findings of prior experiment (42), which observed that redgram intercropped with groundnut was higher redgram equivalent yield of 13.8 q/ha compared to sole redgram (9.4 q/ha). Similar findings were reported in redgram + soybean intercropping system (43), redgram with French bean (2932 kg/ha) and groundnut (2406 kg/ha) intercropping system (44), redgram + groundnut (45) and redgram and greengram intercropping system (46).

Among the strip intercropping systems, higher land equivalent ratio (LER) was recorded in redgram intercropped with blackgram (S1) groundnut (S4) and greengram (S2) strips and these were comparable with each other (Table 2). These treatments in average 14%, 31% and 41% greater LER than redgram pure crop during the cropping period of 2020-21, 2021-22 and 2022-23 respectively. Similar findings were reported in a previous trial (25) on redgram+ greengram intercropping (25). Another study (46) reported that redgram + greengram 1:3 row ratio followed by redgram + red kidney beans in 1:3 row ratio gave higher LER. This increase was attributed to the enhanced productivity of redgram without compromising the yield of intercrops. In contrast, the lower LER recorded in sesame and cotton intercropping was due to reduced redgram productivity under intercropping system, which might have reduced the performance of redgram by competitive effect. This was in line with the findings of prior investigation (47) which reported that, the lower LER in redgram + pearl millet intercropping due to competitive effect.

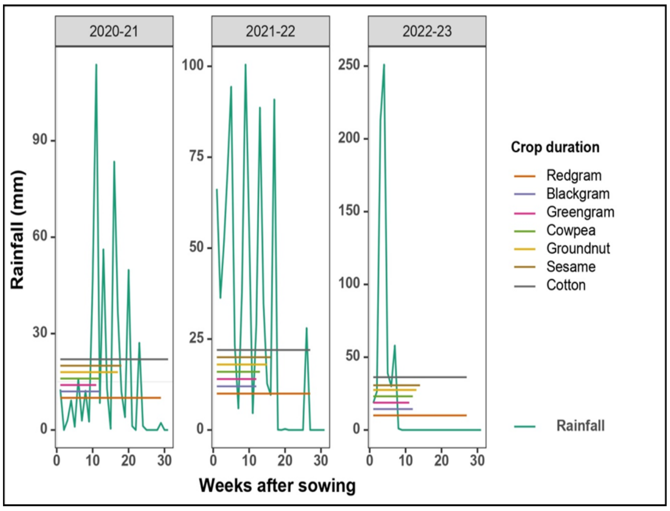

Fig. 8. Week wise rainfall distribution during the cropping period of redgram and intercrops.

Stability of strip intercropping system (SIC)

AMMI 1 analysis : In this study, Fig. 9 (A, B, C and D) showing the multiplicative interaction and additive primary effects of 7 SIC system and 9 environments for the trait dry matter production (DMP), No. of pods/plant (NP), redgram grain yield (RGY) and crop equivalent yield (CEY) respectively. For DMP (Fig. 9A) ENV5 (BBF, 2021-22), ENV4 (CB, 2021-22) and ENV 8 (BBF, 2022-23); ENV 1 (CB, 2020-21), ENV 4 (CB, 2021-22) and ENV 6 (R and F, 2021-22) for number of pods (Fig. 9B); ENV 5 (BBF, 2021-22) and ENV 4(CB, 2021-22) for redgram grain yield (Fig. 9C) and ENV 5 (BBF, 2021-22), ENV 6 (R and F, 2021-22) and ENV 4 (CB, 2021-22) for Crop Equivalent yield (Fig. 9D) had a PCA1 score or vector was closer to zero, indicating a decreased interaction impact and nearly confirming the steady function of all SIC systems in these environments. This stability of BBF and CB was due to their nature to drain the excess water and allowing water stagnation respectively during the excess rainfall (48).

In strip intercropping (SIC) perspective, For DMP, the SIC systems RG+SM and RG+CT (Fig. 9A); for number of pods per plant (NP) the SIC systems RG+CP and RG+SM (Fig. 9B); for redgram grain yield (GY) and crop equivalent yield (CEY) the SIC systems redgram pure crops (Fig. 9C) had around zero scores on the first PCA1 axis which point out that these SIC systems were less subjective by the environment for respective indices. Although agronomists often like and are drawn to SIC systems that are high-yielding and comparatively more resource-intensive, certain SIC systems (RG+SM and RG+CT) did perform below average on regular. Whereas PC1 vectors with the same sign and score but separate from zero lines of the biplot suggested that SIC systems were tailored to a specific environment, SIC systems with PC1 scores close to zero lines of the biplot suggested that SIC systems were suitable for all situations. For DMP, SIC systems RG+BG, RG+GG and RG+GN with ENV 6 (R and F, 2021-22) (Fig. 9A); for NP, pure crop with ENV 5 (BBF, 2021-22) and RG+GN with ENV 6 (R and F, 2021-22) (Fig. 9B); for grain yield (GY), SIC systems RG+GN, RG+GG and RG+BG with ENV 9 (R and F, 2022-23) and for crop equivalent yield (CEY), SIC systems RG+BG with ENV 7 (CB, 2022-23) were achieved same signs at PCA axis and it implies the positive

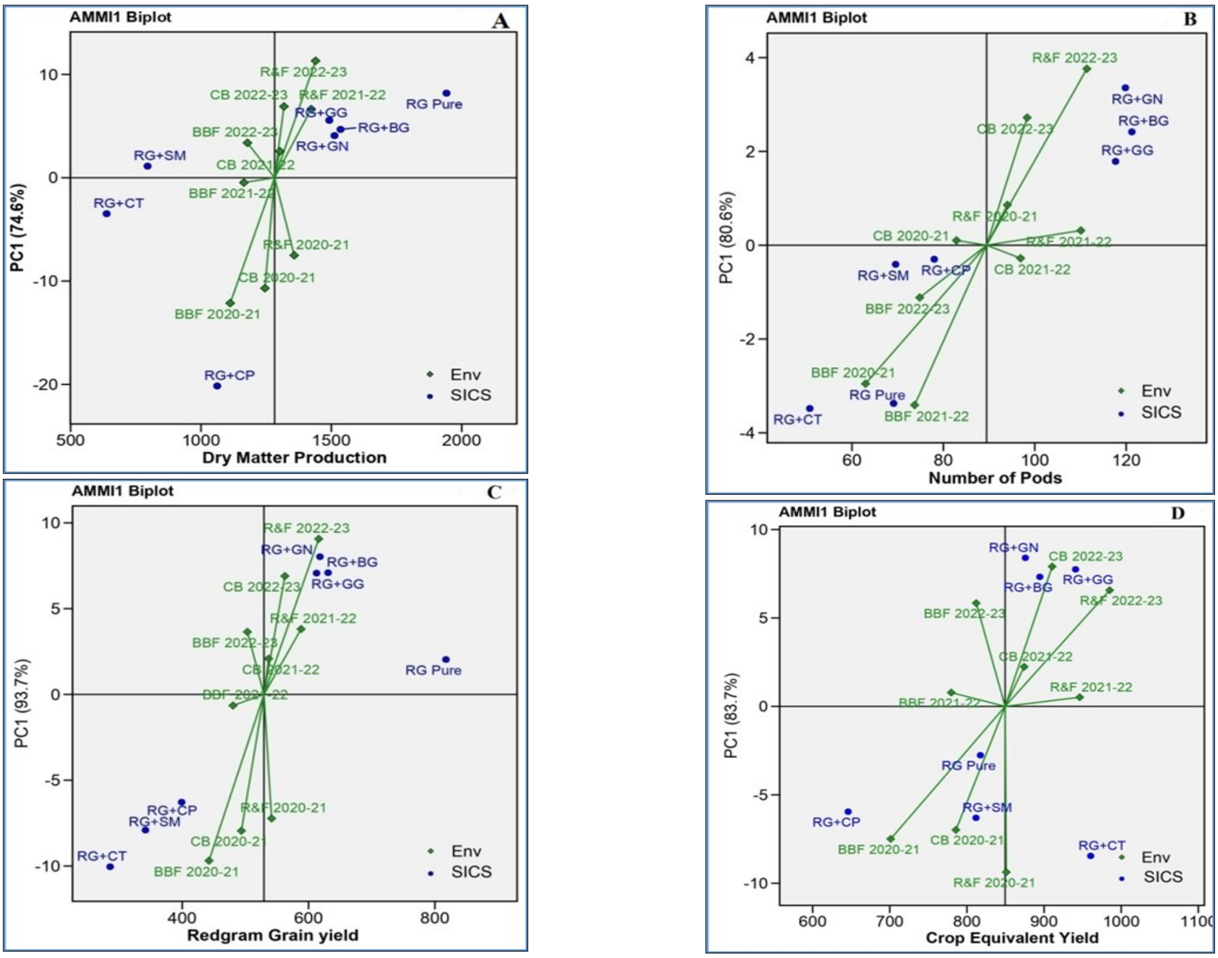

Fig. 9. The biplot 'AMMI 1' depicted the main impact and first principal component (PC1) impact of both strips intercropping system and environment under 3 land configurations and 3 cropping period for (A) dry matter production (DMP), (B) number of pods (NP), (C) redgram grain yield (GY), (D) crop equivalent yield (CEY).

interactions among these SIC systems and environments. These combinations are positively correlated and will give maximum outcome.

AMMI 2 analysis : According to AMMI 2 biplot analysis, Fig. 10 depicted the first 2 principal component interaction of the AMMI 2 biplot model. In this model, we found ENV4 (CB, 2021-22) for DMP (Fig. 10A), ENV1 (CB, 2020-21) and ENV4 (CB, 2021-22) for number of pods per plant (NP) (Fig. 10B), ENV4 (CB, 2021-22) for redgram grain yield (GY) (Fig. 10C) and ENV5 (BBF, 2021-22) and ENV1 (CB, 2020-21) for CEY (Fig. 10D) had short vector over other environments (Land configurations and cropping period). The environment indicator with a shorter vector, that is, closer to the biplot origin, is less interactive and is regarded as the ideal index for choosing a cropping system with average performance and adaptability, according to an early report (49). The stable performance of compartmental bunding was due to conversion of inter-bund area into square parcels were useful for temporary impounding of water (50). Over different strip intercropping system, RG+GN and RG+BG for DMP; RG+GG for NP; RG+GG and RG+BG for grain yield; and redgram pure crop for CEY were observed as stable. The absence of competition and complementary interaction between redgram and its component crops (blackgram, greengram and groundnut) contributed to this stability. The majority of the cropping systems for the attributes DMP, NP, GY and CEY were put together in close proximity to the biplot origin (Fig. 10). However, compared to SIC systems that are placed apart from one another, assembled or clustered SIC systems on the biplot origin demonstrate that SIC systems produce the same outcome in all contexts examined.

Conclusion

From the detailed discussion of the results obtained from this experiment, it was concluded that adapting a redgram-based strip intercropping system under a rainfed ecosystem significantly enhances productivity by 37% to 65% compared to redgram grown as a pure crop with crop insurance. In regions with a late onset of monsoon, it is advised to adopt a redgram + cotton strip intercropping system. In cases of early withdrawal of monsoon, redgram strip intercropping with blackgram, greengram and groundnut strips are most suitable, which gave higher redgram grain yield, crop equivalent yield with highest land equivalent ratio. Under even distribution of monsoon, redgram can be intercropped with blackgram, greengram, groundnut and cotton strips which gave higher crop equivalent yield. In addition, among these strip intercropping systems, redgram intercropped with blackgram, greengram and groundnut showed higher stability in PC1Vs PC2 interaction stability analysis, leading to increased dry matter production, number of pods per plant and redgram grain yield. Among the various land configurations, ridges and furrow sowing is the most effective for maximizing productivity in as trip intercropping system, while compartmental bunding is best suited for regions receiving more than 700 mm rainfall, ensuring maximum system yield.

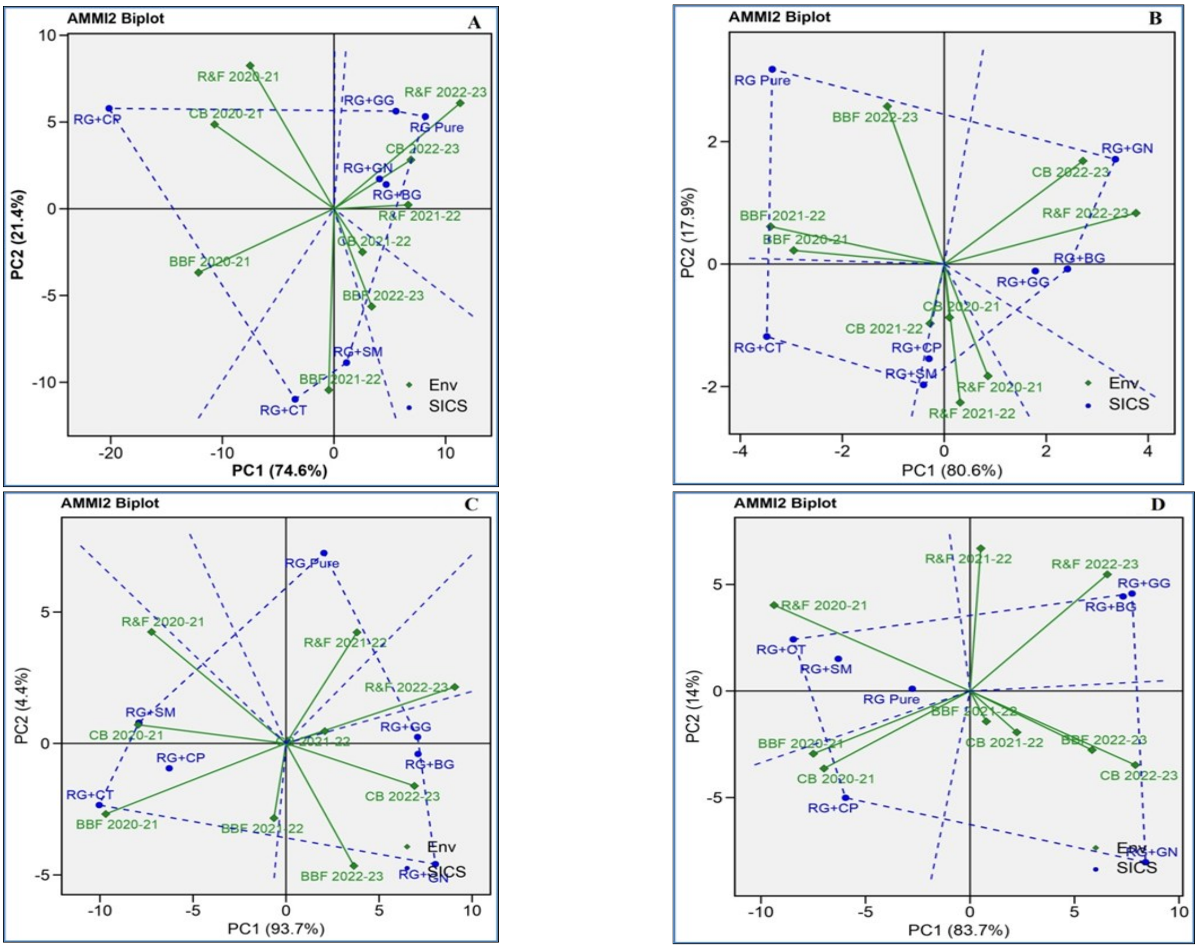

Fig. 10. The biplot 'AMMI 2' depicted the first 2 principal components (PC1 and PC2) response of strip intercropping system plus system environment interaction response of 7 strip intercropping system under 3 land configurations and 3 cropping period for (A) dry matter production (DMP), (B) number of pods (NP), (C) redgram grain yield (GY), (D) crop equivalent yield (CEY).

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Authors' contributions

AV conducted the experiment, carried out all observations and wrote the first draft of the paper. CJ conceptualized this research through adding necessary factors to make it more meaningful and justifiable. KA reviewed and edited the research paper holistically. ES, PS and MU reviewed the paper and shared their inputs for upscaling through using appropriate analysis and interpretation of the findings.

Compliance with ethical standards

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

Ethical issues: None

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