Indian Journal of Agronomy (1st International Farming Systems Conference 2025, Special Issue) **70**: S84–S91
DOI: 10.59797/ija.v70.spl.5567

Designing climate resilient legume-oilseed based cropping systems for rainfed Alfisols of South India

V. VISHA KUMARI[1], B. SUNITHA[2], K.A. GOPINATH[3], S. SUVANA[4], MANORANJAN KUMAR[5], M.A. SARATH CHANDRAN[6], ARUN K. SHANKER[7], B.M.K. RAJU[8], SAVITHA SANTOSH[9], SUBRATA BAG[6], G.K. PRASANNA[6], K. SRIRAM[12], M.S. RAO[13] AND V.K. SINGH[14]

ICAR-Central Research Institute for Dryland Agriculture, Hyderabad, Telangana 500 059

Received: January 2025; Revised accepted: February 2025

ABSTRACT

This study explores the development of climate resilient legume-oilseed cropping systems aimed at enhancing productivity and sustainability in dryland regions. Dryland agriculture, often limited by mono-cropping practices and erratic rainfall, necessitates innovative approaches for crop intensification and sustainability for the future. The integration of legumes and oilseeds into double cropping systems offers a viable solution for optimizing land use and improving productivity under precipitation-limited conditions. The experiment was conducted at the Gungal Research Farm during 2022-23 and 2023-24 to evaluate six pulse-oilseed cropping systems with and without rainwater management against existing intercropping system of sorghum+ pigeonpea (2:1). Double cropping system of cowpea and sesame with rainwater management showed promising results, offering substantial yield attributes, black gram equivalent yield and uptake of nutrients. Cowpea-sesame system emerged as a promising double cropping system in both the years, exhibiting higher equivalent yield (1758 kg/ha) compared to other systems. Rainwater management significantly influenced crop performance in both the years. Apart from the yield, the price of both cowpea and sesame resulted in higher crop equivalent yield with and without rainwater management. Overall, the study emphasizes that cowpea- sesame system with rainwater management is the best system that resulted in higher black gram equivalent yield (1758 kg/ha).

Key words: Double crop, Equivalent Yield, Legume-oilseed system, Rainwater management, SDDI

Mono-cropping is the predominant production practice in the dry land and rainfed tracts of India, leading to low cropping intensity and farm profitability (Chary *et al.,* 2024). Farmers typically grow crops during the monsoon season, leaving the fields fallow during the post-monsoon seasons especially in Alfisols. On contrary, in Vertisols, growers often conserve rainwater during the monsoon to support a post-monsoon crop.

With shrinking per capita agricultural land and rising food demands, there is an urgent need to intensify crops both temporally and spatially. The selection of a suitable cropping system depends on several factors, including climate, soil type, socio-economic conditions, and critical considerations like crop selection, cultivars, crop duration, and genotypes (Meena *et al.,* 2024). Traditional mono-cropping systems in drylands, characterized by limited water resources and erratic rainfall, present significant challenges, such as moisture stress and soil degradation. Double cropping systems, especially those involving legumes and oilseeds, can address these challenges effectively. These systems promote crop diversification, enhance nutrient cycling, and improve water-use efficiency. Replacing long-duration crops with short-duration, high-yielding varieties can enable the adoption of efficient double cropping systems (Meena *et al.,* 2023).

Early planting and timely harvesting of *kharif* crops allow for the rapid establishment of *rabi* crops, ensuring the success of double cropping even under variable climatic conditions. Integrating legumes and oilseeds within such systems offers sustainable strategies to maximize land productivity, enhance soil fertility, and improve food and economic security in dryland areas (Zentner *et al.,* 2001). Legumes, such as cowpea, black gram, and green gram, are particularly valuable in double cropping systems due to their ability to fix atmospheric nitrogen. This reduces reliance on synthetic fertilizers while increasing soil organic matter, thereby improving soil health and fertility (Kell, 2011; Kumar *et al.,* 2023; Kumari *et al.,* 2024a). Legumes also serve as an essential source of protein, con-

Corresponding author's Email: visha.venugopal@gmail.com
[1,6]Senior Scientist; [2,12]Senior Research Fellow; [3,5,7,8]Pricnipal Scientist; [4,9]Sceintsit; [6]Research Scholar; [13]Head Division of Crop Sciences, [14]Director, ICAR-Centrail Research Institute for Dryland Agriculture, Santoshnagar (P.O), Hyderabad 500 059, Telangana

tributing to food security and nutrition in dryland regions (Saikia *et al.,* 2024). Meanwhile, oilseed crops like safflower and sesame complement legumes by diversifying crop rotations and providing higher farm incomes through valuable oil production. Successfully implementing double cropping systems with legumes and oilseeds require a comprehensive understanding of agronomic practices, cropping calendars, and region-specific environmental conditions (Nithinkumar *et al.,* 2024). Scientific research plays a pivotal role in optimizing these systems by addressing challenges such as crop selection, pest and disease management, and water conservation strategies tailored to dryland environments (Wang *et al.,* 2003). Effective rainwater management, particularly the harvesting and utilization of monsoon rainfall, is crucial for ensuring the success of *rabi* crops in rainfed areas. Hence, it was hypothesized that inclusion of double cropping along with rainwater harvesting is a profitable and climate robust production practice in the dryland region of India. This study focuses on identifying a climate-resilient double cropping system involving legumes and oilseeds specifically to Alfisols. Since water is the most important resource in drylands rainwater management was considered an important sustainable agricultural practice.

MATERIALS AND METHODS

The study was carried out at the Gungal Research Farm of ICAR-Central Research Institute for Dryland Agriculture (17^{o}05' N, 78^{o}39' E) during 2022-2023 and 2023-24. Six different pulse- oilseed cropping systems were studied with and without rainwater management. For a better comparison these systems were compared with the existing cropping system of sorghum+ pigeonpea (2:1) ratio.

The legumes were sown during the *kharif* and the oilseed crops were sown after the harvest of the pulse crop (October). The crops under rainwater management were given 2 supplementary irrigations (3 mm) in 2022 and 3 supplementary irrigations (5 mm) in 2023 from the water harvested during *kharif* season. The soil of the experimental field was sandy loamy with a pH of 6.04 and EC 0.12 dS/m, low in available nitrogen (215.48 kg/ha) medium in available phosphorus (26.73 kg/ha) and available potassium (218.34 kg/ha). The experiment was laid out in a randomized block design and replicated thrice. The fertilizers were applied as per the recommendation. The treatments are presented in Table 1. The variety seed rate, spacing, fertilizers, sowing time and harvesting time are mentioned in Table 2.

As different crops were studied, after the harvest of the crops, blackgram equivalent yield (BGEY) of all other crops was calculated using the following formula:

$$\text{BGEY (kg/ha)} = \frac{\text{Yield of crop} \times \text{Price of crop}}{\text{Price of black gram}}$$

The data collected of different parameters were sub-

Table 1. Details of treatments/cropping systems

Abbreviation	Treatment
S+PP	Sorghum+ pigeonpea (2:1)
BG-SS+	Blackgram followed by sesame with rainwater management
BG-SS-	Blackgram followed by sesame without rainwater management
BG-SF+	Blackgram followed by safflower with rainwater management
BG-SF-	Blackgram followed by safflower without rainwater management
CP-SS+	Cowpea followed by sesame with rainwater management
CP-SS-	Cowpea followed by sesame without rainwater management
CP-SF+	Cowpea followed by safflower with rainwater management
CP-SF-	Cowpea followed by safflower without rainwater management
GG-SS+	Greengram followed by sesame with rainwater management
GG-SS-	Greengram followed by sesame without rainwater management
GG-SF+	Greengram followed by safflower with rainwater management
GG-SF-	Greengram followed by safflower without rainwater management

Table 2. Management practices of crops under study

Crop	Variety	Seed rate/ha	Spacing (cm)	Fertilizer (kg/ha)	Sowing	Harvesting
Green gram	WGG37	10-15	30×10	20:50:0	27 June	13 September
Cowpea	TPTC29	20-25	40×20	20:40:0	27 June	19 September
Black gram	JS9305	20-25	30×10	20:50:0	27 June	19 September
Sorghum	CSV23	12-15	45×10	80:40:0	27 June	8 November
Pigeon pea	PRG176	10-12	90×20	80:40:0	27 June	10 January
Safflower	ISF-764	12-15	45×20	40:25:20	8 October	13 February
Sesame	Shweta *til*	5-7	45×20	40:20:20	8 October	9 January

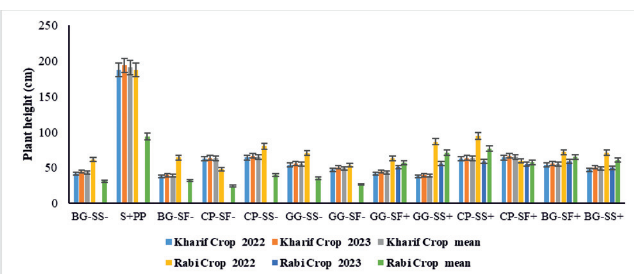
jected to appropriate statistical analysis under randomized complete block design by following the procedure of ANOVA analysis of variance. Significance of difference between means was tested through 'F' test and the least significant difference (LSD) was worked out where variance ratio was found significant for treatment effect.

$$EUE = \frac{\text{Energy output (MJ/ha)}}{\text{Energy intput (MJ/ha)}}$$

RESULTS AND DISCUSSION

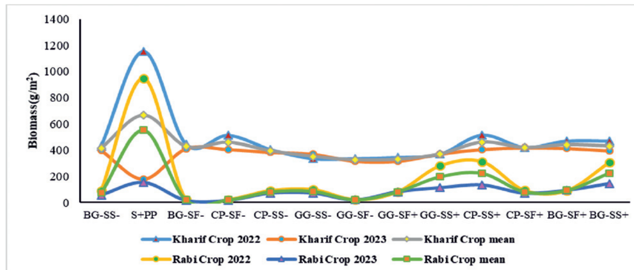
Growth attributes

The plant height varied significantly among treatments due to the inclusion of different crops, which inherently possess distinct growth patterns. However, the influence of rainwater management strategies was evident. With 2–3 supplementary irrigations, both oilseed crops exhibited greater plant heights compared to treatments without irrigation. Among the *kharif* crops, cowpea recorded the tallest plants in both 2022 and 2023, with an average height of 65.3 cm (Fig. 1). For the *rabi* crops, sesame demonstrated superior growth, achieving the tallest plants with a mean height of 76.8 cm across both years. The cowpea-sesame cropping system, when coupled with rainwater management, resulted in taller plants in both years, demonstrating the importance of effective moisture management in enhancing plant growth. These findings align with the work of Kumar and Thakur (2006), who reported improved plant height in sesame grown within intercropping systems compared to monoculture. Furthermore, cowpea exhibited higher biomass production during the *kharif* season, with a 16.4% increase under rainwater management across both years. Similarly, sesame recorded the highest biomass among *rabi* crops, averaging 226.1 g/m² over the two years (Fig. 2). The sorghum + pigeonpea (2:1) intercropping system also achieved substantial biomass, measuring 665.2 g/m² and 551.9 g/m² in 2022 and 2023, respectively. This notable biomass could be attributed to the rapid canopy development and superior ground coverage of these crops, which optimize light interception and resource utilization.



S+PP: Sorghum+ pigeonpea (2:1); BG-SS+: Blackgram followed by sesame with rainwater management; BG-SS-: Blackgram followed by sesame without rainwater management; BG-SF+: Blackgram followed by safflower with rainwater management; BG-SF-: Blackgram followed by safflower without rainwater management; CP-SS+: Cowpea followed by sesame with rainwater management; CP-SS-: Cowpea followed by sesame without rainwater management; CP-SF+: Cowpea followed by safflower with rainwater management; CP-SF-: Cowpea followed by safflower without rainwater management; GG-SS+: Greengram followed by sesame with rainwater management; GG-SS-: Greengram followed by sesame without rainwater management; GG-SF+: Greengram followed by safflower with rainwater management; GG-SF-: Greengram followed by safflower without rainwater management. Error bar represents the CD at 0.05% level of significance.

Fig. 1. Plant height of different cropping systems in the two growing seasons of year 2022 and 2023



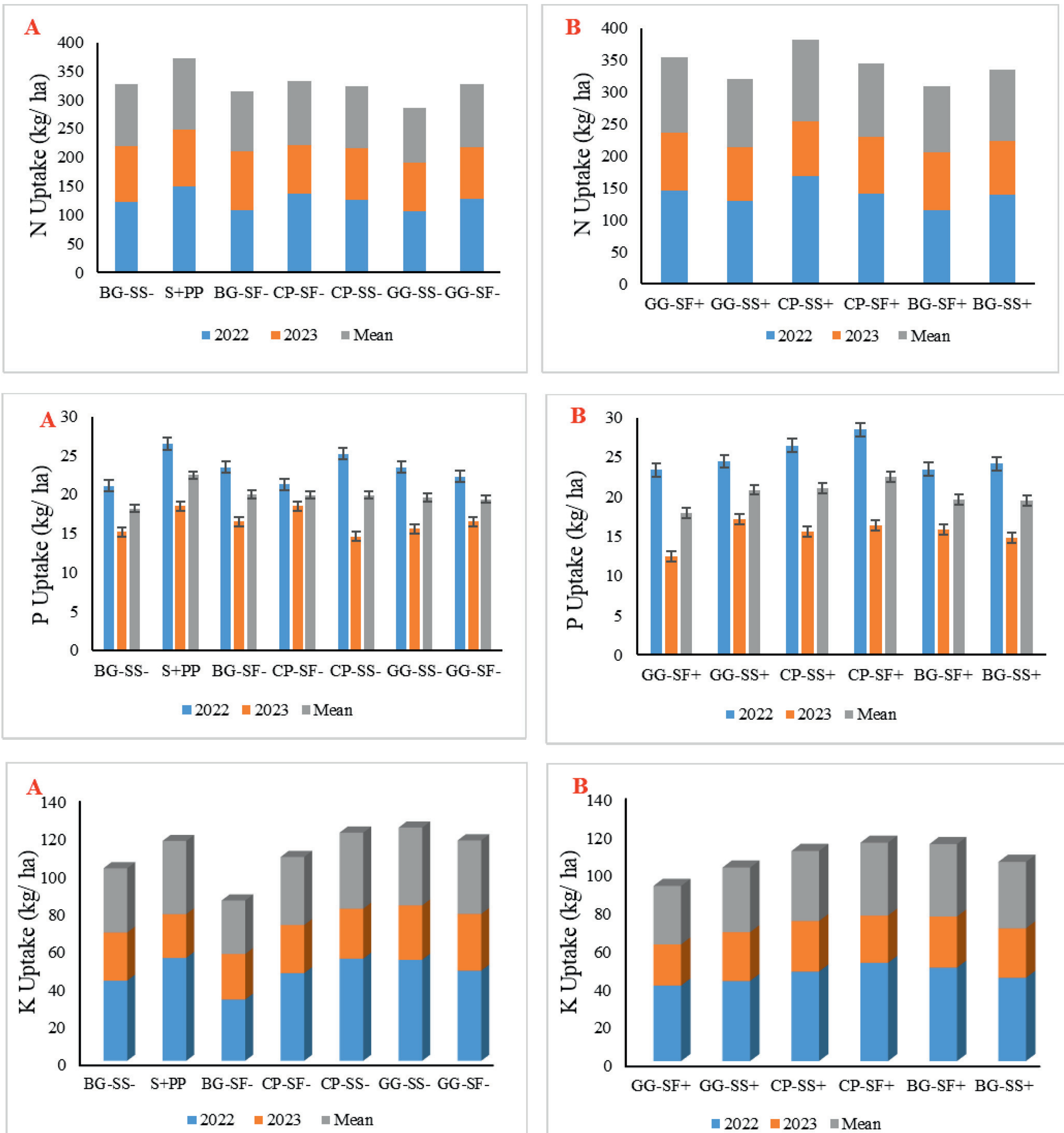
S+PP: Sorghum+ pigeonpea (2:1); BG-SS+: Blackgram followed by sesame with rainwater management; BG-SS-: Blackgram followed by sesame without rainwater management; BG-SF+: Blackgram followed by safflower with rainwater management; BG-SF-: Blackgram followed by safflower without rainwater management; CP-SS+: Cowpea followed by sesame with rainwater management; CP-SS-: Cowpea followed by sesame without rainwater management; CP-SF+: Cowpea followed by safflower with rainwater management; CP-SF-: Cowpea followed by safflower without rainwater management; GG-SS+: Greengram followed by sesame with rainwater management; GG-SS-: Greengram followed by sesame without rainwater management; GG-SF+: Greengram followed by safflower with rainwater management; GG-SF-: Greengram followed by safflower without rainwater management

Fig. 2. Biomass of different cropping systems in the two growing seasons of year 2022 and 2023

The improved growth and biomass production under these systems can be partially explained by the nitrogen fixation capabilities of cowpea, which likely enhanced soil fertility and benefited the subsequent sesame crop. This observation aligns with El-Taher *et al.* (2021). Additionally, cowpea's rapid water uptake and competitive ability against weeds and other crops (Lightfoot *et al.,* 1987; Hattlendorf *et al.,* 1988) further contributed to its superior performance. These results reaffirm findings by Kumari *et al.* (2024b), which suggest that diverse crops adopt unique growth strategies to maximize yield and resource use efficiency.

Nutrient uptake

Double cropping systems with and without rainwater management had significant impact on the nutrient uptake



S+PP: Sorghum+ pigeonpea (2:1); BG-SS+: Blackgram followed by sesame with rainwater management; BG-SS-: Blackgram followed by sesame without rainwater management; BG-SF+: Blackgram followed by safflower with rainwater management; BG-SF-: Blackgram followed by safflower without rainwater management; CP-SS+: Cowpea followed by sesame with rainwater management; CP-SS-: Cowpea followed by sesame without rainwater management; CP-SF+: Cowpea followed by safflower with rainwater management; CP-SF-: Cowpea followed by safflower without rainwater management; GG-SS+: Greengram followed by sesame with rainwater management; GG-SS-: Greengram followed by sesame without rainwater management; GG-SF+: Greengram followed by safflower with rainwater management; GG-SF-: Greengram followed by safflower without rainwater management

Fig. 3. N, P and K uptake (Kg/ha) of various double cropping systems without rain water management (A) and with rain water management (B) in the year 2022 and 2023

as shown in Fig. 3. Among the cropping systems, cowpea-sesame with rainwater management increased the N uptake as 18% compared to without rainwater management in both the years. Whereas, cowpea-safflower with rainwater management improved the P uptake (22.5 kg/ha) than without rainwater management. However, greengram -sesame without rainwater management (41.3 kg/ha) reported the highest K uptake and it is closely followed by cowpea-sesame without rainwater management (40.4 kg/ ha) (Fig. 3). This can be attributed due to the ability of cowpea to fix atmospheric nitrogen might have enriched the soil nitrogen, promoting increased nutrient availability for subsequent crops. Meena *et al.,* 2018 and Stagnari *et al.,* 2017 highlighted that in addition to providing the fixed nitrogen in the cropping system and also aid in solubilizing insoluble phosphorus (P) in the soil.

Stress Degree Days Index

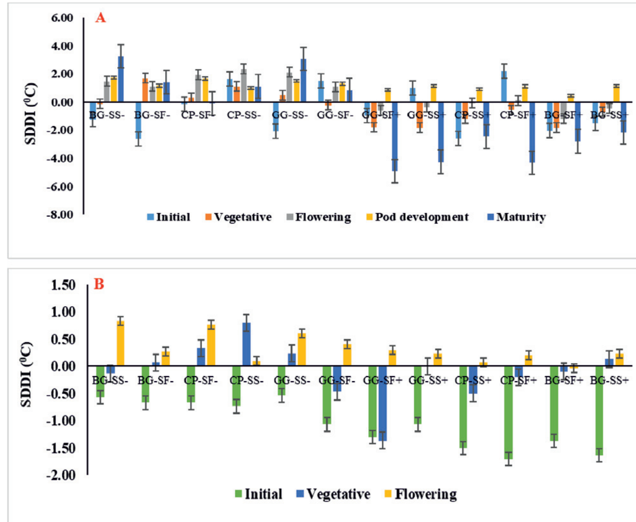
Stress Degree Days Index (SDDI) is commonly used to identify crop stress, which is crucial for understanding plant-water status at specific phenophases of crops. During the later stages of both sesame and safflower crops, the mean air temperature was higher than the early stages, which accelerated the phenological development, particularly during flower initiation and early pod development. Since both sesame and safflower are indeterminate crops, they continue to produce flowers as long as the source-sink relationship is maintained. The first-year crop exhibited lower canopy temperatures compared to the second-year crop. In contrast, crops without rainwater management in the first-year experienced significant heat stress, as indicated by positive values in the later stages of growth (Fig 4). A temperature variation of 2-3°C was observed at different growth stages, and this increase in canopy temperature led to stress, causing sesame in the second year to complete its life cycle about 20 days earlier than in the first year.

The safflower crop failed due to this heat stress. This reduction in the duration of the phenophase negatively impacted both the crop yield and quality (Venugopalan *et al.,* 2021). The SDDI index at various stages is shown in the Fig 4.

Yield attributes

The mean data of yield-attributing traits revealed significant variations in the number of pods per plant and seeds per pod for both *kharif* and *rabi* crops across different cropping systems (Table 3). Among the legumes during the *kharif* season, cowpea recorded the highest number of pods per plant (15), followed by green gram and black gram. Similarly, in the *rabi* season, sesame stood out among the oilseeds, producing the highest number of pods per plant (22) under rainwater management compared to the non-managed plots in both years (Table 3). This trend was consistent for the number of seeds per pod. In both 2022 and 2023, cowpea exhibited the highest number of seeds per pod among legumes, with a mean value of 16, followed by black gram.

Among the oilseed crops, sesame grown under rainwater management in the cowpea-sesame system recorded the highest seeds per pod (67), followed by sesame in the greengram-sesame system (65). This highlights the positive impact of rainwater management on reproductive performance (Kumari *et al.,* 2024a). However, without rainwater management, the second-year crop failed due to insufficient rainfall, underscoring the importance of supplemental irrigation in sustaining productivity in rainfed conditions. The 100-seed weight did not exhibit significant differences in *kharif* crops between rainwater-managed and non-managed systems. However, among the *rabi* crops, sesame achieved the highest 100-seed weight (4.0 g) under rainwater management in both years, indicating improved seed quality and resource utilization when moisture was adequately supplied.



S+PP: Sorghum+ pigeonpea (2:1); BG-SS+: Blackgram followed by sesame with rainwater management; BG-SS-: Blackgram followed by sesame without rainwater management; BG-SF+: Blackgram followed by safflower with rainwater management; BG-SF-: Blackgram followed by safflower without rainwater management; CP-SS+: Cowpea followed by sesame with rainwater management; CP-SS-: Cowpea followed by sesame without rainwater management; CP-SF+: Cowpea followed by safflower with rainwater management; CP-SF-: Cowpea followed by safflower without rainwater management; GG-SS+: Greengram followed by sesame with rainwater management; GG-SS-: Greengram followed by sesame without rainwater management; GG-SF+: Greengram followed by safflower with rainwater management; GG-SF-: Greengram followed by safflower without rainwater management

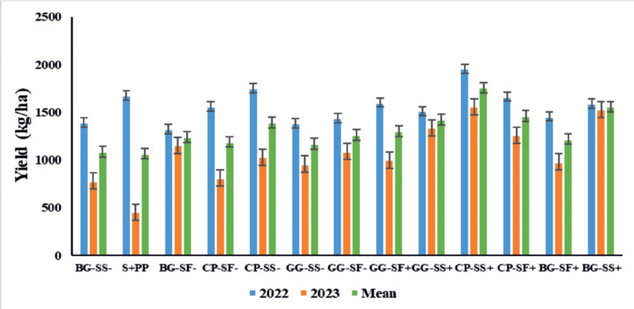
Fig. 4. SDDI at different phenological stages of various double cropping systems in the year 2022 (A) and 2023(B)

Black gram equivalent yield

The study evaluated the performance of different double cropping systems based on black gram equivalent yield. The results showed that the cowpea-sesame system with rainwater management achieved the highest equivalent yield across both 2022 and 2023, with an average yield of 1758 kg/ha. The test crop system of sorghum + pigeonpea (2:1) intercropping system recorded a BGEY of

Table 3. Yield attributing characters of double cropping systems with and without rainwater management in the years 2022 and 2023

Treatments	*Without rainwater management*																	
	Pods/plant						Seeds/pod						100 seed weight					
	Kharif crop			*Rabi* Crop			*Kharif* crop			*Rabi* Crop			*Kharif* crop			*Rabi* Crop		
	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean
BG-SS-	7	8	8	18	6	12	8	8	8	70	0	35	5.6	5.3	5.5	0.4	0.0	0.2
S+PP	24	15	19	22	11	17	1194	727	960	4	4	4	2.7	2.4	2.6	10.5	7.5	9.0
BG-SF-	8	8	8	20	0	10	8	8	8	10	0	5	23.4	5.1	14.3	2.6	0.0	1.3
CP-SF-	15	13	14	13	0	7	16	16	16	13	0	7	14.8	16.8	15.8	3.2	0.0	1.6
CP-SS-	16	14	15	19	6	12	16	16	16	68	0	34	15.9	16.3	16.1	0.4	0.0	0.2
GG-SS-	6	9	8	19	4	12	7	12	10	67	0	33	4.3	3.4	3.9	0.4	0.0	0.2
GG-SF-	4	8	6	16	0	8	7	12	9	15	0	8	4.1	3.3	3.7	2.5	0.0	1.3
SE(m)	0.92	0.68	0.82	0.77	2.19	1.14	79.88	31.76	51.97	1.07	0.22	0.57	6.53	0.28	3.21	0.12	0.62	0.33
CD	2.85	2.11	2.54	2.39	6.84	3.55	248.88	98.96	161.92	3.32	0.68	1.78	NS	0.87	10.01	0.37	1.91	1.04
	With rainwater management																	
GG-SF+	7	8	8	20	13	17	8	8	8	23	17	20	5.6	5.3	5.5	4.1	3.0	3.6
GG-SS+	8	8	8	25	19	22	8	8	8	76	53	65	23.4	5.1	14.3	0.5	0.4	0.5
CP-SS+	15	13	14	24	18	21	16	16	16	77	57	67	14.8	16.8	15.8	0.6	0.4	0.5
CP-SF+	16	14	15	20	13	17	16	16	16	21	17	19	15.9	16.3	16.1	4.3	3.6	4.0
BG-SF+	6	9	8	27	13	20	7	12	10	10	17	17	4.3	3.4	3.9	4.0	3.6	3.8
BG-SS+	7	8	8	24	17	21	7	12	9	32	52	64	4.1	3.3	3.7	0.6	0.4	0.5
SE(m)	0.87	0.54	0.69	0.77	0.46	0.55	0.83	0.93	0.79	9.93	1.92	5.18	7.04	0.27	3.47	0.08	0.16	0.09
CD	2.77	1.74	2.21	2.47	1.47	1.77	2.64	2.95	2.54	31.68	6.12	16.54	NS	0.87	NS	0.24	0.53	0.27



S+PP: Sorghum+ pigeonpea (2:1); BG-SS+: Blackgram followed by sesame with rainwater management; BG-SS-: Blackgram followed by sesame without rainwater management; BG-SF+: Blackgram followed by safflower with rainwater management; BG-SF-: Blackgram followed by safflower without rainwater management; CP-SS+: Cowpea followed by sesame with rainwater management; CP-SS-: Cowpea followed by sesame without rainwater management; CP-SF+: Cowpea followed by safflower with rainwater management; CP-SF-: Cowpea followed by safflower without rainwater management; GG-SS+: Greengram followed by sesame with rainwater management; GG-SS-: Greengram followed by sesame without rainwater management; GG-SF+: Greengram followed by safflower with rainwater management; GG-SF-: Greengram followed by safflower without rainwater management

Fig. 5. Blackgram equivalent yield of various double cropping systems in the year 2022 and 2023

1064 kg/ha (Fig. 5). This system was followed by the black gram-sesame system with rainwater management (1560 kg/ha). The lowest equivalent yields were recorded in the black gram-sesame system without rainwater management yielded 1086 kg/ha (Fig. 5).

In both the years of experiment, the superior performance of cowpea-sesame system can be attributed to cowpea's deep root system, that might have enhanced soil structure and moisture retention, facilitating better root penetration and nutrient uptake by subsequent crops (Singh *et al.,* 2019; Bijarnia *et al.,* 2024). Additionally, drought tolerance of sesame due to its extensive root system, shorter duration of three months compared to safflower's four months, and higher market price. This resulted in higher BGEY of sesamum. The importance of rainwater management in enhancing crop yields is also evident from the results of the year 2023, as yields were achieved with rainwater management compared to systems without it that is completely failed (Kang *et al.,* 2000). Moreover, cowpea's ability to suppress weeds and its role in breaking pest and disease cycles further contribute to improved crop productivity in following seasons (Kaur *et al.,* 2023).

The findings from two years indicate that the cowpea-sesame double cropping systems, particularly with rainwater management, showed strong potential for increased productivity, sustainability, nutrient uptake, and substantial yields.

REFERENCES

Bijarnia, A., Tetarwal, J.P., Yadav, R.K., Bijrania, A.L., Singh, D. and Saini, Y. 2024. Effect of fertility levels and stress mitigating chemicals on nutrient content, uptake, intercropping advantage and competition effect in cowpea-baby corn intercropping. *Heliyon* **10**(19): e38194.

Chary, G.R. Singh VK, Ramamurthy V., Gopinath K. A., Bhargavi B., Singh, R. and Babu, S. 2024. Crop Diversification Opportunities in Rainfed Farming: Approaches and Strategies. In: Babu, S., Singh, R., Rathore, S.S., Das, A., Singh, V.K. (eds) Agricultural Diversification for Sustainable Food Production. Sustainability Sciences in Asia and Africa. Springer, Singapore. https://doi.org/10.1007/978-981-97-7517-0_13

El-Taher, A. M., Abd El-Raouf, H. S., Osman, N. A., Azoz, S. N., Omar, M. A., Elkelish, A., and Abd El-Hady, M. A. 2021. Effect of salt stress and foliar application of salicylic acid on morphological, biochemical, anatomical, and productivity characteristics of cowpea (*Vigna unguiculata* L.) plants. *Plants* **11**(1): 115.

Hattlendorf, M.J., Redelfs, M.S., Amos, B., Stone, L.R. and Gwin, R.E. 1998. Comparative water uses characteristics of six row crops. *Agronomy Journal* **80**: 80–85.

Kang, S., Zhang, L., Liang, Y., Hu, X., Cai, H. and Gu, B. 2000. Effects of limited irrigation on yield and water use efficiency of winter wheat in the Loess Plateau of China. *Agricultural Water Management* **55**(3): 203–216.

Kaur, J., Saini, k. and Singh, T. 2023. Production potential of pulse- and oilseed-based climate-resilient alternative cropping systems for diversification of rice (Oryza sativa)–wheat (*Triticum aestivum*) in North-western Indo-Gangetic Plains. *Indian Journal of Agronomy* **68**(3): 246–252.

Kell, D.B. 2011. Breeding crop plants with deep roots: Their role in sustainable carbon, nutrient and water sequestration. *Annals of Botany* **108**(3): 407–418.

Kumar, A. and Thakur, K.S. 2006. Production potential and economic feasibility of sesame (*Sesamum indicum*)-based intercropping with legumes under rainfed conditions. *Indian journal of Agricultural Sciences* **76**(3): 183–189.

Kumar, S., Gopinath, K.A., Sheoran, S., Meena, R.S., Srinivasarao, C., Bedwal, S., Jangir, C.K., Mrunalini, K., Jat, R. and Praharaj, C.S. 2023. Pulse-based cropping systems for soil health restoration, resources conservation, and nutritional and environmental security in rainfed agroecosystems. *Frontiers in Microbiology* **13**: 1041,124.

Kumari V.V., K.A. Gopinath, Suvana S., Kumar M, Chandran M.A.S., Shankar A.K., Raju B.M.K., N. Jyothilakshmi, G. Venkatesh, G. Gayethri, K. Sriram, B. Sunitha, G.K. Prasanna, Bag S., Rao M.S. and Singh V.K. 2024a. Double cropping systems for sustainability and livelihood security in Rainfed Alfisols. *Indian journal of Dryland Agricultural Research and Development* **39**(1): 46–50.

Kumari, V.V., Balloli, S.S., Kumar, M., Ramana, D.B.V., Prabhakar, M., Osman, M., Indoria, A.K., Manjunath, M., Maruthi, V., Chary, G.R. and Chandran, M.S. 2024b. Diversified cropping systems for reducing soil erosion and nutrient loss and for increasing crop productivity and profitability in rainfed environments. *Agricultural Systems* **217**: 103,919.

Lightfoot, C.W.F., Dear, K.B.G. and Mead, R. 1987. Intercropping sorghum with cowpea in dryland farming systems in Botswana. II. Comparative stability of alternative cropping systems. *Experimental Agriculture* **23**: 435–442.

Meena, B. P., Fagodiya, R. K., Prajapat, K., Dotaniya, M., Kaledhonkar, M., Sharma, P., et al. 2018. Legume green manuring: an option for soil sustainability, in Legumes for Soil Health and Sustainable Management, eds R. Meena, A. Das, G. Yadav, R. Lal (Singapore: Springer), 387–408. doi: 10.1007/978-981-13-0253-4_12

Meena, L.R., Meena, S.L., Kumar, L., Pillai, N.S. and Ram, T. 2023.Evaluation of food and fodder based cropping systems for sustaining productivity, resource use efficiency and profitability in western plain zone of Uttar Pradesh. *Indian Journal of Agronomy* **68**(4): 398–403.: https://doi.org/10.59797/ija.v68i4.5462

Meena, S.N., Meena, L.K., Yadav, S., Jadon, C.K., Dhakad, U., Lal, M., Verma, H.P., Gupta, V., Singh P., 2024. Chickpea (*Cicer arietinum*)-based intercropping systems in Rajasthan's Hadoti region: Productivity and economic viability. *Indian Journal of Agronomy* **69**(1): 54–60 DOI: 10.59797/ija.v69i1.5482

Nithinkumar, K., Saikia, N., Bagrecha, S., Nymisha, A., Ali, S.K.A. 2024. Harnessing Below and Above-ground Interaction in Diversified Cropping for Sustainable Food Production. In: Babu, S., Singh, R., Rathore, S.S., Das, A., Singh, V.K. (eds) Agricultural Diversification for Sustainable Food Production. Sustainability Sciences in Asia and Africa. Springer, Singapore. https://doi.org/10.1007/978-981-97-7517-0_12

Saikia, N., Nithinkumar, K., Bagrecha, S., Ali, S.K.A., Jena, T., Kumari, M., Pooniya, V., Govindasamy, P., Raj, R., Lakhena, K.K., Barman, A., Singh, M.K and Babu, S 2024. Crop diversification with legume for sustainable production and environmental gain. In: Babu, S., Singh, R., Rathore, S.S., Das, A., Singh, V.K. (eds) Agricultural Diversification for Sustainable Food Production. Sustainability Sciences in Asia and Africa. Springer, Singapore. https://doi.org/10.1007/978-981-97-7517-0_9

Singh, A.K., Jat, M.L. and Kumar, S. 2019. Cowpea (*Vigna unguiculata*) intercropping: an agronomic approach for integrated pest and weed management in cereals. *Indian Journal of Agricultural Sciences* **89**(6): 1017-1023

Stagnari, F., Maggio, A., Galieni, A. and Pisante, M. 2017. Multiple benefits of legumes for agriculture sustainability: an overview. *Chemical and Biological Technologies in Agriculture* **4**: 1–13.

Venugopalan, V.K., Nath, R., Sengupta, K., Nalia, A., Banerjee, S., Chandran, M.A.S., Ibrahimova, U., Dessoky, E.S., Attia, A.O., Hassan, M.M. and Hossain, A. 2021. The response of lentil (*Lens culinaris* Medik.) to soil moisture and heat stress under different dates of sowing and foliar application of micronutrients. *Frontiers in plant science* **12**: 679,469.

Wang, W., Vinocur, B. and Altman, A. 2003. Plant responses to drought, salinity and extreme temperatures: towards genetic engineering for stress tolerance. *Planta* **218**(1): 1–14.

Zentner, R.P., Basnyat, P. and Lafond, GP. 2001. Double cropping systems for spring wheat production in the northern Great Plains. *Agronomy Journal* **93**(2): 261–226.