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Quantifying the role of regenerative agricultural practices on growth and development dynamics of Chickpea under the diverse cropping system

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Abstract

A field experiment was conducted during two consecutive years (2023–24 and 2024–25) at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, to evaluate the role of regenerative agricultural practices on the growth and developmental dynamics of Chickpea under diverse cropping systems. The experiment was laid out in a split-plot design with three cropping systems as main plots [VS1: *kharif* fallow - *rabi* Chickpea, VS2: pigeonpea (short duration) + maize (1:2) – *rabi* relay Chickpea, and VS3: *kharif* Sorghum – *rabi* Chickpea] and three regenerative agricultural practices as subplots [RA1: soil test-based fertilization (STBF), RA2: STBF + straw mulch, and RA3: STBF + straw mulch + biological consortia]. The results revealed that both cropping systems and regenerative practices had a significant effect on all growth parameters of Chickpea. Among the cropping systems, VS3 recorded significantly higher plant height (63.87 cm), number of primary (13) and secondary branches (34), dry matter accumulation (21.9 g plant⁻¹), leaf area index (3.99), and nodules per plant (45) compared to VS2 and VS1. Similarly, among regenerative agricultural practices, RA3 was found significantly superior, registering higher plant height (62.41 cm), branching, nodulation (46 nodules plant⁻¹), dry matter accumulation (19.3 g plant⁻¹), and LAI (3.74). The interaction effect was also significant, wherein the interaction of VS3 × RA3 resulted in the highest growth and physiological performance. The enhanced growth under this interaction was attributed to improved soil moisture conservation, nutrient availability, and microbial activity. Overall, the study highlights that integration of *kharif* Sorghum - *rabi* Chickpea cropping system with regenerative practices involving straw mulch and biological consortia is a promising strategy for improving Chickpea growth, soil health, and sustainability under semi-arid conditions.

Keywords: Regenerative agriculture, chickpea, cropping systems, sorghum–chickpea system

1. Introduction

Chickpea (*Cicer arietinum*) belongs to family Leguminaceae which originates from Southwest Asia. It ranks as one of the main crops cultivated across semi-arid tropics, especially in countries like India, which contributes nearly about 65-70% of global production (FAOSTAT, 2023) [3]. It is mainly cultivated in rainfed conditions during the *rabi* season and serves as a major source of dietary protein, especially in vegetarian diets (Gowda *et al.*, 2015) [6]. Although important, Chickpea yield remains relatively lower because of limitations like soil nutrient depletion, moisture stress and deteriorating soil health.

In today's context, regenerative agriculture is becoming a crucial approach to enhance crop production while restoring soil vitality and ecosystem functions. Regenerative agriculture is based on principles such as minimal soil disturbance, crop diversification, straw mulching and enhanced biological activity (Lal *et al.*, 2020; Schreefel *et al.*, 2020) [9, 20]. These practices are particularly relevant for Chickpea cultivation as soil structure, microbial activity and nutrient cycling significantly influence its growth, nodulation and overall development (Sawargaonkar, *et al.*, 2026a) [17]. Improved soil organic carbon, enhanced microbial diversity and better moisture retention under regenerative systems which can positively affect root development, nutrient uptake and ultimately yield performance in Chickpea-based systems.

Furthermore, incorporating Chickpea into regenerative systems such as conservation agriculture, intercropping and crop rotations has shown potential to improve system productivity and resilience under climate variability. The synergistic effects of legumes in such systems not only enhance soil fertility but also contribute to long-term sustainability and profitability of dryland agriculture (Varshney *et al.*, 2013) [22]. Therefore, understanding the growth dynamics and yield response of Chickpea under regenerative agricultural practices which is crucial for developing efficient, climate-resilient and resource-conserving production systems (Sawargaonkar, *et al.*, 2018) [16]. Diverse cropping systems such as intercropping, relay cropping, and crop rotations influence Chickpea performance by modifying resource availability and microclimatic conditions (Sawargaonkar, *et al.*, 2026b) [18]. When integrated with regenerative practices, these systems can enhance water-use efficiency, nutrient cycling, and overall system productivity (Sawargaonkar, *et al.*, 2026c) [19]. Practices such as residue mulching and reduced tillage improve soil moisture conservation, while organic amendments and biological inputs enhance microbial activity and nutrient availability (Rhodes, 2017; Palm *et al.*, 2014) [14, 10]. Regenerative systems have also been shown to improve soil structure, water infiltration, and yield stability under stress conditions.

In this context, the present study aims to quantify the role of regenerative agricultural practices in influencing the growth and developmental dynamics of Chickpea under diverse cropping systems in the semi-arid tropics, with a focus on improving productivity, soil health, and sustainability, and to evaluate the individual and interactive effects of cropping systems and regenerative practices.

2. Materials and Methods

2.1 Study Site and Environmental Conditions

The experiment was conducted at the research farm of the International Crops Research Institute for the Semi-Arid Tropics, Hyderabad (17.50° N latitude and 78.27° E longitude) over two consecutive years (2023–24 and 2024–25). The study area is characterized by a semi-arid climate, receiving an average annual rainfall of about 898 mm. The maximum temperature can rise up to 43 °C during May, while the minimum temperature may fall to around 5 °C in December (Patil *et al.*, 2016; Kamdi *et al.*, 2020) [11, 7]. Throughout the experimental period, daily records of rainfall as well as maximum and minimum temperatures were obtained from the agrometeorological observatory located at ICRISAT, adjacent to the experimental field. The seasonal distribution of rainfall, temperature and relative humidity for both years is presented in Figure 1 and 2. The total rainfall received during the 2023 and 2024 cropping seasons was 782.50 mm and 779.80 mm, respectively. The soil of the experimental site is classified as Vertisols.

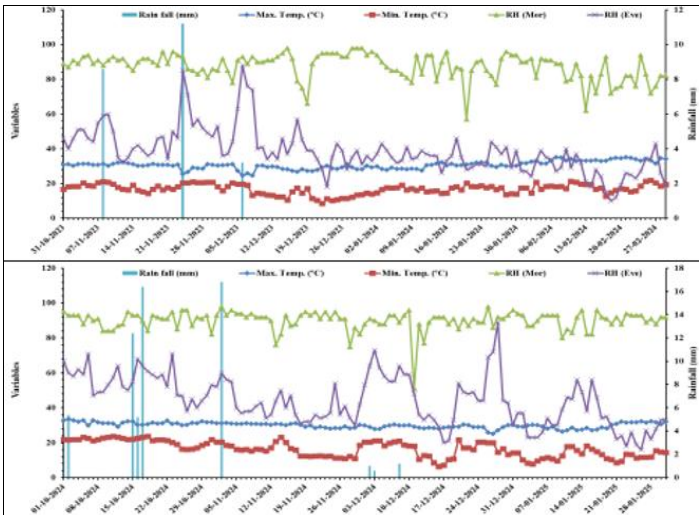


Fig 1: Weekly average weather data during both the years of the experimentation period (2023-2024 and 2024-2025)

2.2 Initial physico-chemical characteristics of soil across three depths at the experimental site.

The physico-chemical properties of the soil from 0-0.3 m depth, indicated that the soil comprised 16.69% coarse sand, 16.48% fine sand, 14.56% silt, and 52.28% clay, classifying it as clayey in texture. The mean bulk density was 1.35 g cm⁻³, with a field capacity of 37.14% and permanent wilting point of 24.54%, indicating good moisture retention capacity. Chemically, the soil was slightly alkaline with an average pH of 7.70 and low electrical conductivity (0.34 dS m⁻¹), suggesting non-saline conditions. The organic carbon content was low (0.32%). The available nutrient status showed that nitrogen was low (188.13 kg ha⁻¹), phosphorus was medium (14.80 kg ha⁻¹) and potassium was medium to high (213.73 kg ha⁻¹). Among secondary and micronutrients, Sulphur (10.61 ppm), zinc (1.60 ppm) and boron (0.80 ppm) were present in adequate ranges. Overall, the soil was clayey, slightly alkaline, low in organic carbon and nitrogen, and medium in available phosphorus and potassium. Fertilizer application in each cropping system was determined based on the cultivated area and soil test-based fertilizer (STBF) recommendations. The nutrient application strategy followed the principle of applying 25% higher than the recommended dose when nutrient levels were low, the recommended dose of fertilizer (RDF) when levels were adequate, and 25% lower when nutrient levels were high. The RDF adopted for Chickpea was 19.8–49.4–19.8 kg ha⁻¹ (N–P₂O₅–K₂O). The STBF details for both years are presented in Table 1. In the subplot treatments, fertilizers were applied as per the respective treatment specifications prior to sowing. Appropriate plant protection measures were also undertaken to manage insect pests and diseases.

Table 1: Soil test-based fertilizer application details for the cropping systems during both years of experimentation

Crops	Soil test-based fertilization (kg ha ⁻¹)		
	N	P ₂ O ₅	K ₂ O
VS1: <i>kharif</i> fallow- <i>rabi</i> Chickpea	25	49	20
VS2: <i>kharif</i> Pigeonpea (short duration) + Maize (1:2)- <i>rabi</i> relay Chickpea	161	147	80
VS3: <i>kharif</i> Sorghum- <i>rabi</i> Chickpea	99	89	50

2.3 Experimental Design and Treatments

The experiment was laid out in a split-plot design comprising 9 treatments with three replications, resulting in a total of 27 plots. Each plot measured 236.25 m² (10.5 m × 22.5 m). The main

plots consisted of three cropping systems: VS1: *kharif* fallow - *rabi* Chickpea; VS2: *kharif* pigeonpea (short duration) + maize (1:2) - *rabi* relay Chickpea and VS3: *kharif* Sorghum - *rabi* Chickpea. The subplot treatments included three regenerative

agricultural practices: RA1-soil test-based fertilization (STBF); RA2—STBF + Straw Mulch; and RA3—STBF + Straw Mulch + biological consortium.

2.4 Crop Management and Sowing

The VS1 system was established on conventionally tilled flat land prior to sowing, whereas VS2 and VS3 were implemented on broad-bed furrow (BBF) systems. The BBFs (1.5 m width and 0.15 m height) were prepared at the beginning of the experiment using a BBF maker. Sowing was carried out using a mechanized zero-till dryland multicrop planter, which enabled simultaneous sowing of different crops while maintaining

appropriate spatial arrangement. For relay sowing of Chickpea into standing pigeonpea, a hand dibbler was used. The Chickpea variety used in the study was NBeG 3, a high-yielding cultivar widely adapted to southern India. A spacing of 30 cm × 10 cm was maintained for Chickpea. The seed rate was 75 kg ha⁻¹ for sole Chickpea and 50 kg ha⁻¹ for relay Chickpea. For pigeonpea, the entire crop residue was utilized as mulch in the subsequent season. However, in the case of Sorghum and maize, top two-thirds of the biomass was removed for fodder due to its high palatability, while the remaining one-third at the base was retained and used as mulch. The quantity of mulch applied under different treatments is presented in Table 2

Table 2: Description of mulch applied under different treatments during both experimental years

Cropping Systems	Regenerative agricultural practice	2023-2024 (q ha ⁻¹)	2024-2025 (q ha ⁻¹)
VS1: <i>kharif</i> fallow- <i>rabi</i> Chickpea	Straw Mulch	-	-
	Mulch + biological consortia	-	-
VS2: <i>kharif</i> Pigeonpea (short duration) + Maize (1:2) - <i>rabi</i> relay Chickpea	Straw Mulch	59.0	61.5
	Mulch + biological consortia	60.2	62.8
VS3: <i>kharif</i> Sorghum - <i>rabi</i> Chickpea	Straw Mulch	18.1	18.8
	Mulch + biological consortia	18.5	19.2

2.5 Morpho-Physiological Observations

Plant growth and development parameters were recorded at harvest from randomly selected representative samples:

- **Morphological Characters:** Plant height (cm), number of primary and secondary branches and total number of nodules were recorded via manual counting and measurement.
- **Biomass:** Fresh weight was recorded immediately after sampling. Dry weight was determined by sun-drying samples for 48 hours, followed by oven-drying at 60 ± 5°C (or 70 °C for physiological samples) until a constant mass was achieved.
- **Photosynthetic Pigments:** Chlorophyll *a* and *b* were quantified using the spectrophotometric method following extraction with 80% acetone. (Arnon, 1949).

2.6 Growth Analysis

Leaf Area Index (LAI) was derived by dividing the total leaf area per plant by the corresponding ground area, as per the methodology of Sestak *et al.* (1971) [21]. CGR (g m⁻² day⁻¹) representing the gain in dry weight per unit of land area over a specific duration was calculated using the formula proposed by Watson (1952) [23]:

$$CGR = \frac{W2-W1}{(t2-t1)S}$$

Where, W1 and W2 = dry weight of the plant at time intervals of T₁ and T₂, respectively
S = the land area on which dry weight was observed

Absolute Growth Rate (AGR) (g plant⁻¹ day⁻¹) was expressed based on the increase in dry weight per unit of time per plant (Richards, 1969) [15]:

$$AGR = \frac{W2-W1}{(t2-t1)}$$

Where, W1 and W2 = dry weight of the plant at time intervals of

T₁ and T₂, respectively. Leaf Area Ratio (LAR) (cm² g⁻¹) was calculated as the ratio of total leaf area to total plant biomass, representing the photosynthetic surface relative to respiratory mass. Experimental data were analyzed using the analysis of variance (ANOVA) for a split-split plot design (Gomez and Gomez, 1984) [5]. Statistical significance was evaluated using the F-test at a 5% probability level (p=0.05). Critical difference (CD) values were calculated for significant effects, while non-significant differences were denoted as "NS."

3. Results and Discussion

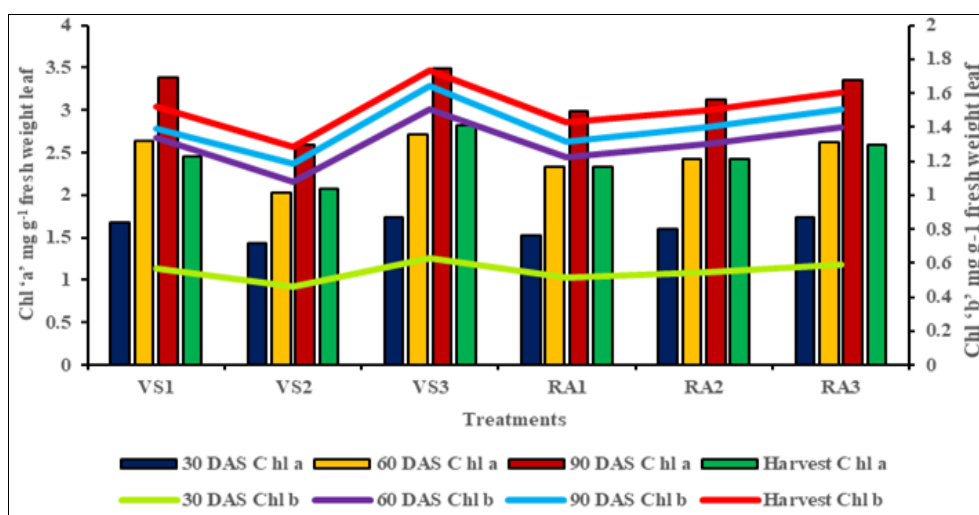
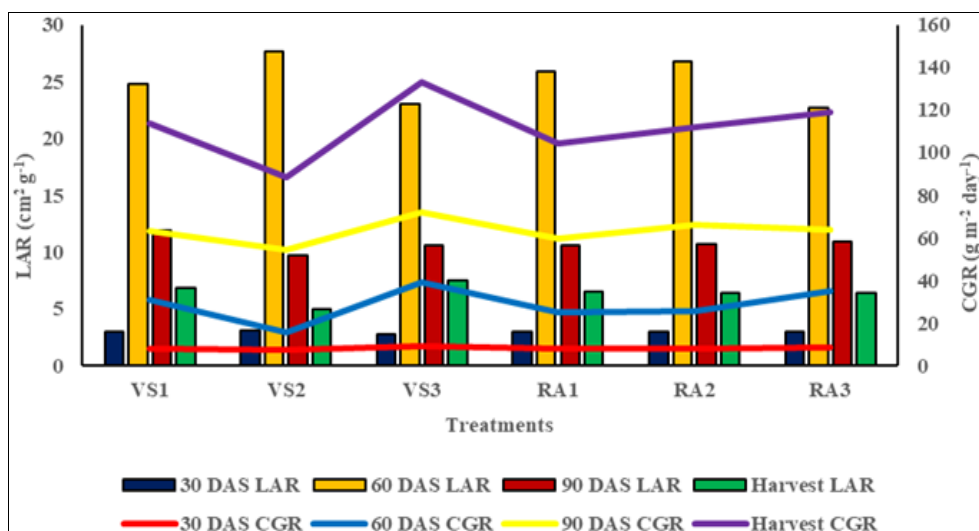
3.1 Effect of cropping system on growth and development of Chickpea

The data presented in Table 3 revealed that cropping systems had a significant effect on all growth and physiological parameters of Chickpea. Among the treatments, VS3 (Sorghum–Chickpea) recorded significantly higher plant height (63.87 cm), number of primary branches (13), number of secondary branches (34), dry weight accumulation (21.9 g plant⁻¹), fresh weight accumulation (236.2 g plant⁻¹), leaf area index (LAI) (3.99), and number of nodules per plant (45), which was superior to VS2 and comparable or higher than VS1. In addition, VS3 also recorded significantly higher chlorophyll ‘a’ and chlorophyll ‘b’ content (Fig.2), crop growth rate (CGR) (Fig. 3), absolute growth rate (AGR) (Fig.4), and leaf area ratio (LAR) (Fig. 3) compared to the other cropping systems. The lowest values for all parameters were observed under VS2. The superior performance of VS3 may be attributed to better resource-use efficiency, improved soil moisture conservation, and enhanced soil biological activity, which collectively promoted better photosynthetic efficiency and biomass accumulation (Zahoor, *et al.*, 2025; Akchaya, *et.*, 2025) [26, 1]. This is consistent with the results reported by Franke *et al.* (2018) [4] and Chen *et al.* (2021) [2], who showed that complementary utilization of resources in cereal–legume intercropping systems results in increased leaf area index (LAI) and total biomass compared to monocropping.

Table 3: Pooled effect of cropping system and regenerative agricultural practices of growth parameters of Chickpea

Treatments	Plant height (cm)	No. of primary branches plant ⁻¹	No. of secondary branches plant ⁻¹	Dry weight accumulation (g plant ⁻¹)	Fresh weight accumulation (g plant ⁻¹)	LAI	No. of nodules plant ⁻¹
Cropping system							
VS1	59.53	11	32	18.4	233.6	3.86	43
VS2	44.84	9	24	13.6	152.2	2.37	36
VS3	63.87	13	34	21.9	236.2	3.99	45
SEm (±)	0.59	0.11	0.44	0.92	2.84	0.09	0.20
CD (5%)	2.64	0.51	1.97	4.12	12.79	0.41	0.92
Regenerative Agricultural Practices							
RA1	52.06	10	27	16.6	200.8	3.11	36
RA2	53.77	10	31	18.0	207.4	3.39	41
RA3	62.41	12	33	19.3	213.7	3.74	46
Sem (±)	0.67	0.19	0.42	0.09	1.10	0.04	0.18
CD (5%)	4.08	1.19	2.56	0.56	6.66	0.27	1.11
RA at the same level of VS							
SEm (±)	1.16	0.34	0.73	0.16	2.90	20.55	0.32
CD (%)	3.92	1.14	2.46	0.54	NS	69.34	1.07
VS at the same level of RA							
SEm (±)	1.01	0.87	0.97	1.03	1.95	1.43	0.90
CD (%)	3.40	2.94	3.28	3.46	NS	4.82	3.03

VS1: *kharif* fallow - Chickpea; VS2: *kharif* Pigeonpea (short duration) + Maize (1:2) - *rabi* relay Chickpea; VS3: *kharif* Sorghum - *rabi* Sunflower; RA1: Soil test-based fertilization (STBF), RA2: STBF + Starw Mulch and RA3: STBF + Starw Mulch + Biological consortia

**Fig 2:** Pooled effect of cropping systems and regenerative agricultural practices on Chlorophyll 'a' and 'b' (mg g⁻¹ fresh weight leaf)**Fig 3:** Pooled effect of cropping systems and regenerative agricultural practices on LAR (cm² g⁻¹) and CGR (g m² day⁻¹)

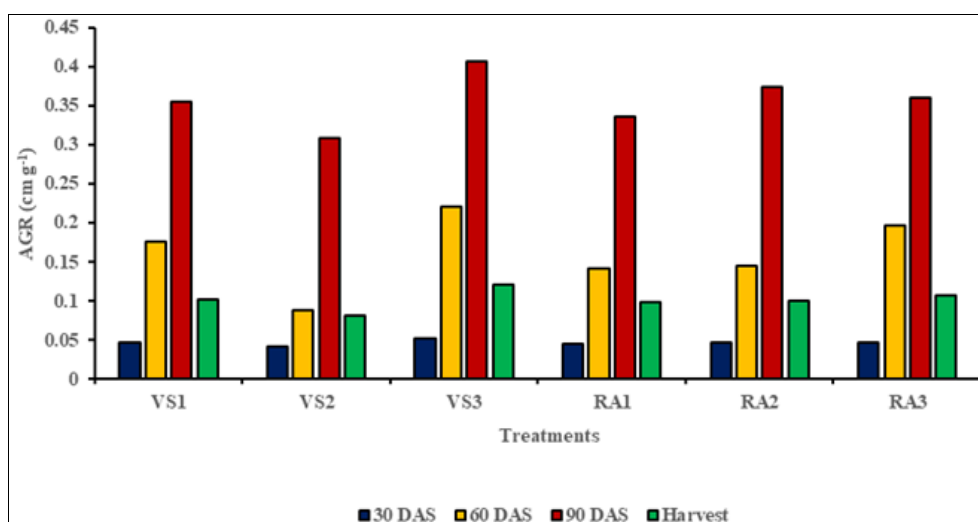


Fig 4: Pooled effect of cropping systems cropping systems and regenerative agricultural practices on AGR (g plant⁻¹ day⁻¹)

3.2 Effect of regenerative agricultural practices on growth and development of Chickpea

Regenerative agricultural practices exerted a significant influence on all growth and physiological parameters studied (Table 3). Among the treatments, RA3 (STBF + Starw Mulch + Biological Consortia) recorded significantly higher plant height (62.41 cm), number of primary branches (12), number of secondary branches (33), dry weight accumulation (19.3 g plant⁻¹), fresh weight accumulation (213.7 g plant⁻¹), LAI (3.74), and number of nodules per plant (46) compared to RA1 and RA2. Furthermore, RA3 also showed significantly higher chlorophyll 'a' and 'b' content (Fig. 2), CGR (Fig. 3), AGR (Fig. 4), and LAR (Fig. 3), indicating enhanced physiological efficiency. RA2 showed intermediate performance, while RA1 recorded the lowest values. The improved performance under RA3 may be due to better soil physical properties, increased microbial activity, enhanced nutrient availability, and improved soil moisture retention, which facilitated efficient nutrient uptake and sustained photosynthetic activity (Wei, *et al.*, 2024; Xing, *et al.*, 2025) [24, 25]. Mulching helps maintain a stable soil hydrothermal environment, thereby improving the effectiveness of biological consortia in nutrient solubilization (Pavan *et al.*, 2025) [12]. The marked improvement in growth parameters observed under N₃ is further corroborated by Kebede (2021) [8], who found that the combined application of chemical fertilizers and bio-inoculants significantly promotes vegetative growth and dry matter distribution in sorghum.

3.3 Interaction effect of cropping system and RA on growth and development of Chickpea

The interaction effect between cropping systems and regenerative agricultural practices was found to be significant for all growth and physiological parameters (figure). The interaction of VS3 with RA3 resulted in significantly higher plant height (Fig. 5), LAI (Fig. 6) and biomass accumulation (Fig. 7) compared to other treatment interactions. This clearly indicates a strong synergistic effect between an efficient cropping system and regenerative practices (Ramachandran and Biswas, 2016) [13]. The enhanced performance under this interaction may be attributed to improved rhizosphere activity, efficient nutrient cycling, better soil moisture availability, and enhanced photosynthetic efficiency, ultimately leading to maximization of crop growth and productivity (Zhang, *et al.*, 2010) [27].

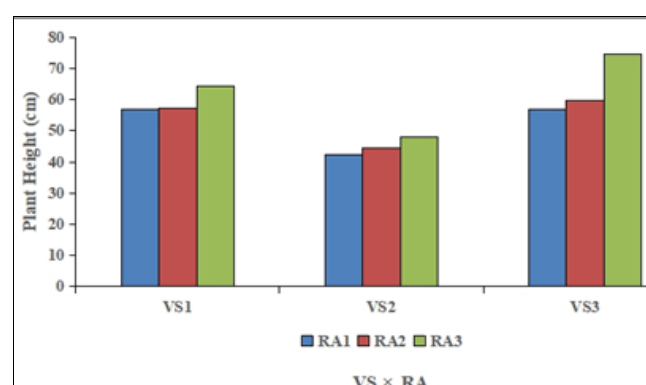


Fig 5: Interaction effect of cropping system and RA practices on plant height (cm)

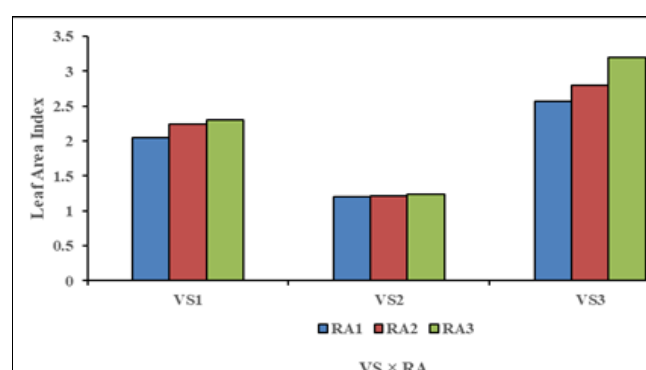


Fig 6: Interaction effect of cropping system and RA practices on Leaf Area Index

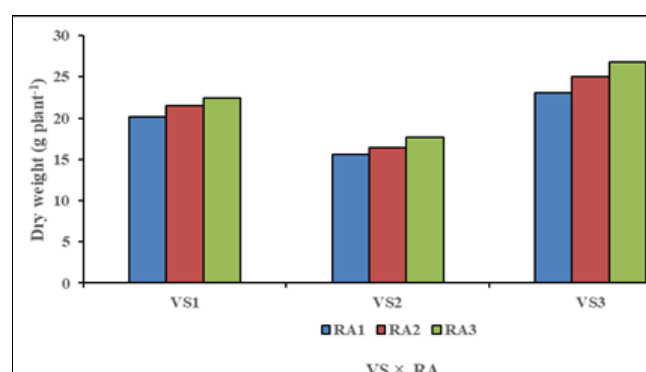


Fig 7: Interaction effect of cropping system and RA practices on dry weight (g plant⁻¹)

4. Conclusion

The present investigation clearly demonstrates that both cropping systems and regenerative agricultural practices exerted a significant influence on the growth and development of Chickpea. Among the cropping systems, VS3 (Sorghum–Chickpea) proved to be significantly superior in enhancing all growth parameters, indicating its suitability for efficient resource utilization and improved soil health. Similarly, among the regenerative practices, RA3 (STBF + Straw Mulch + Biological Consortia) recorded significantly higher values for plant growth traits, highlighting the importance of integrated nutrient management, soil moisture conservation, and biological inputs in sustaining crop performance. Furthermore, the significant interaction effect between cropping system and regenerative practices revealed that the interaction of VS3 with RA3 created a synergistic environment that maximized plant growth, biomass accumulation, nodulation, and physiological efficiency. Thus, it can be concluded that the integration of an efficient cropping system with regenerative agricultural practices is a promising approach for enhancing Chickpea growth, improving soil health, and achieving sustainable crop production under rainfed conditions.

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