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Effect of regenerative agricultural practices and biochar on growth and physiological indices of sorghum under sorghum-based cropping systems in the *vertisols* of semi-arid tropics

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Abstract

Sorghum (*Sorghum bicolor* L.) is a vital, resilient crop for semi-arid tropics, yet its productivity is often limited by declining soil fertility and moisture stress. This study was conducted to evaluate the impact of regenerative agricultural practices and biochar application on the growth dynamics and physiological indices of sorghum within different cropping sequences in the *Vertisols* of the semi-arid tropics. A field experiment was conducted over two consecutive years (2024-25 and 2025-26). The treatments included two cropping systems (*Kharif* Sorghum + Pigeonpea (2:1)- relay *rabi* greengram and Sorghum-Chickpea), three nutrient management practices (Soil test based fertilization (STBF), STBF + mulch, and STBF + mulch + biological consortia), and three biochar levels (1, 2, and 3 t ha⁻¹). Pooled data indicated that the *Kharif* Sorghum + Pigeonpea (2:1)- relay *rabi* greengram system significantly enhanced growth parameters and physiological indices of sorghum, including plant height, Leaf Area Index (LAI), Crop Growth Rate (CGR) and Net Assimilation Rate (NAR), compared to the sorghum-chickpea system. Among nutrient management practices, the integration of STBF, mulch, and biological consortia achieved the highest Chlorophyll content and SPAD values, significantly improving dry matter accumulation. Furthermore, biochar application @ 3 t ha⁻¹ acted as a superior soil conditioner, significantly increasing Absolute Growth Rate (AGR) and Biomass Duration (BMD). Significant interactions between legume-based intercropping and biochar and biological consortia indicate a synergistic effect on total biomass. The study concludes that integrating pigeonpea-sorghum intercropping with biochar (3 t ha⁻¹) and nutrient management (STBF + mulch + biological consortia) optimizes physiological efficiency and ensures sustainable sorghum productivity in semi-arid *Vertisols*.

Keywords: Biochar, Growth Dynamics, Intercropping, Physiological Indices, Regenerative Agriculture, Sorghum, *Vertisols*

1. Introduction

Sorghum (*Sorghum bicolor* L.), often referred to as “jowar,” is one of the important cereal crops ranking fifth after wheat, rice, maize, and barley globally (USDA, 2020). It is widely known as a “safe crop” in the global agricultural ecosystem because it performs consistently under climatic variability and resource constraints (Vimala Ranjan *et al.*, 2025). In India, sorghum is grown as a staple food, animal feed, fodder, and raw material for numerous industrial applications. The crop plays a vital role in sustaining dryland agriculture and supporting the livelihoods of smallholder farmers, particularly in areas with unpredictable rainfall and marginal soils (FAO, 2023). Climate change issues and erratic rainfall patterns directly impact crop yields (Sawargaonkar *et al.*, 2026a) [32].

Despite its adaptability to various constraints, sorghum productivity in India remains relatively low compared with its potential, primarily due to poor soil fertility and imbalanced nutrient management. Continuous cultivation without proper nutrient management leads to soil and land degradation, which not only declines organic carbon levels but also reduces nutrient-use

efficiency. In this context, regenerative agriculture has emerged as a new sustainable approach which primarily focuses on maintaining soil health, enhancing biodiversity and improving ecosystem resilience while sustaining crop yield by emphasizing practices such as minimal tillage, crop diversification, residue retention and the use of biologicals for rebuilding soil organic matter and improve nutrient cycling (Rhodes, 2017) [28]. Integrating regenerative approaches into sorghum-based systems is particularly relevant for Indian drylands, where soil degradation and climate variability poses significant challenges for agricultural sustainability (Samijan *et al.*, 2024) [30].

In the case of regenerative inputs, biochar has gained significant attention for its ability to improve soil properties, thereby enhancing crop productivity. Biochar, a carbon-rich product produced by pyrolysis of biomass under limited oxygen conditions, is known for its stability and ability to persist in soil for longer periods (Kumar *et al.*, 2023; Manasa *et al.*, 2024; Kumar *et al.*, 2024; Pasumarthi *et al.*, 2024; Sawargaonkar *et al.*, 2024; Lehmann and Joseph, 2024) [18, 19, 31]. Its application significantly improves soil physical properties, such as bulk density and water-holding capacity, and chemical properties, such as cation exchange capacity and nutrient retention, as well as biological activity by providing a favorable habitat for soil microorganisms (Jeffery *et al.*, 2015; Sawargaonkar *et al.*, 2026b; Sawargaonkar *et al.*, 2026c) [33, 34]. In nutrient-deficient and coarse-textured soils, biochar has been reported to reduce nutrient leaching losses and enhance fertilizer-use efficiency, thereby improving crop yields (Biederman and Harpole, 2013) [4].

In Indian soils, especially in Alfisols and Vertisols of semi-arid regions, biochar, when integrated with balanced nutrient management, offers a promising solution to address soil fertility constraints and enhance sorghum productivity (Aina and Donaldson, 2025) [1]. It plays an essential role in climate-smart and regenerative agricultural systems, as it contributes significantly to carbon sequestration and aligns with the goals of climate change mitigation (Lal, 2015; FAO, 2023) [20]. Additionally, biochar, when used in conjunction with inorganic fertilizers, can retain more nutrients in the root zone and slowly release them, thereby ensuring a steady nutrient supply during the crop growth period and improving nutrient use efficiency. Therefore, incorporating biochar within a regenerative agriculture framework shows significant potential to boost sorghum productivity, improve soil health, and ensure the long-term sustainability of dryland farming systems in India. However, site-specific research is required to optimize biochar application rates and nutrient combinations for different soil types and agro-climatic conditions, highlighting the need for further investigation in sorghum-based cropping systems.

2. Methodology

2.1 Site description

A two year experimentation (2024-25 and 2025-26, respectively) was conducted at the dryland living lab of the International Crops Research Institute for the Semi- Arid Tropics, (ICRISAT) Hyderabad, (17°0.15' N latitude and 77° 35' E longitude, at an altitude of 564m above mean sea level) to investigate the effect of nutrient management practices and biochar on the morphological growth parameters and physiological indices of sorghum crop under two sorghum based cropping systems in Vertisols. The rainfall received during the crop growth period was 882.9 mm and 888.3 mm against the average evapotranspiration of 5.12 mm and 3.43 mm, during 2024-25 and 2025-26, respectively (Fig. 1). Soil was neutral in pH with low initial organic C (0.37%), low available nitrogen

(247.43 kg ha⁻¹), medium available phosphorus (16.53 kg ha⁻¹) and medium available potassium (189.76 kg ha⁻¹).

2.2 Experimental design and treatments

The experiment was laid out in a split-split plot design (three replications) with two sorghum based cropping systems as main plots viz., CS1: *Kharif* sorghum + pigeonpea (2:1) - relay *rabi* greengram, CS2: *Kharif* sorghum- *rabi* chickpea; three nutrient management practices as sub plots: N1: Soil Test Based Fertilization (STBF), N2: STBF + mulch, N3: STBF + mulch + biological consortia and three biochar application rates as sub sub plots: B1: Biochar @ 1 t ha⁻¹, B2: Biochar @ 2 t ha⁻¹, B3: Biochar @ 3 t ha⁻¹, respectively. The plot size was 6 × 3 m². HTJH 3206 variety of sorghum was sown @ 7.5 kg ha⁻¹ at 45 cm × 15 cm geometry in terms of sole sorghum (CS2) while seed @ 5 kg ha⁻¹ at 90 cm × 15 cm was adopted for intercropped sorghum with pigeonpea (CS1).

2.3 Land preparation

The land was prepared using a Broad Bed and Furrow (BBF) maker, creating beds 1.5 meters wide and 0.15 meters high. To manage water effectively, the furrows remained open to the field edge, allowing surplus rainfall to drain into channels that fed into the farm pond. For planting, a mechanized zero-till dryland multicrop planter was used, enabling simultaneous sowing of multiple seeds while ensuring precise spatial arrangement and planting geometry.

2.4 Crop establishment

Crop water requirement was met through rainfall and no additional irrigation was provided during *kharif* period. The fertilizer application for the systems was determined by the crop's specific area and Soil Test Based Fertilizer (STBF) results. Adhering to the precision nutrient management principle, the dosage was adjusted based on soil fertility: applications were increased by 25% over the recommended dose of fertilizer (RDF) in nutrient-deficient areas, maintained at the RDF where levels were sufficient and decreased by 25% in areas with high nutrient concentrations. The RDF followed for sorghum was 59.3-39.5-29.7 kg ha⁻¹ and Pigeonpea/ Greengram/ Chickpea were: 19.8-49.4-19.8 kg ha⁻¹ (N-P₂O₅-K₂O), respectively. The details of the STBF applied in both systems during both years are tabulated in Table 1. In the subplot treatments, fertilizers were applied prior to sowing. The exception was nitrogen (N) application for sorghum: 50% was provided as a basal dose, while the remaining 50% was delivered 30 days after sowing (DAS) via fertigation through drip system. Additionally, standard plant protection protocols were followed to manage potential pest infestations and diseases.

2.5 Crop residue management and biologicals

Crop residue management varied by species: Pigeonpea was used entirely for mulch in the following seasons. In contrast, because of their high palatability, the top two-thirds of the sorghum were diverted for use as livestock fodder, with only the remaining bottom third retained as mulch. The specific amounts of mulch applied for each treatment are detailed in Table 2. Biological consortia comprising Rhizobium strain, Phosphate solubilizing bacteria, and potash solubilizing bacteria were applied @ 10 ml kg⁻¹ of seed and were mixed with the seeds before sowing of the respective treatment plots.

2.6 Biochar application

Accordingly, as per the treatments, biochar at the prescribed rate was applied to the respective sub-subplots. Pigeonpea stalk biochar was applied manually in narrow bands between the crop rows 15 days after sowing (DAS). To ensure effective incorporation, the material was mixed into the soil using hand hoes and scrapers. The pigeonpea stalk biochar is a highly porous material with a moisture content of 3.941%, a bulk density of 0.164 g cm⁻³, and a near-neutral pH of 7.08. With a total organic carbon content of 22.49% and an electrical

conductivity of 0.54 dS m⁻¹, it serves as a significant nutrient source, particularly rich in nitrogen (19,063.50 ppm), potassium (12,238 ppm), and calcium (4,712 ppm), alongside essential minerals such as magnesium, phosphorus, and sulfur. Its micronutrient profile includes notable levels of sodium, iron, and manganese, while heavy metal concentrations including arsenic, cadmium, and lead remain at negligible or undetectable levels, confirming its safety for soil application and long-term agricultural use.

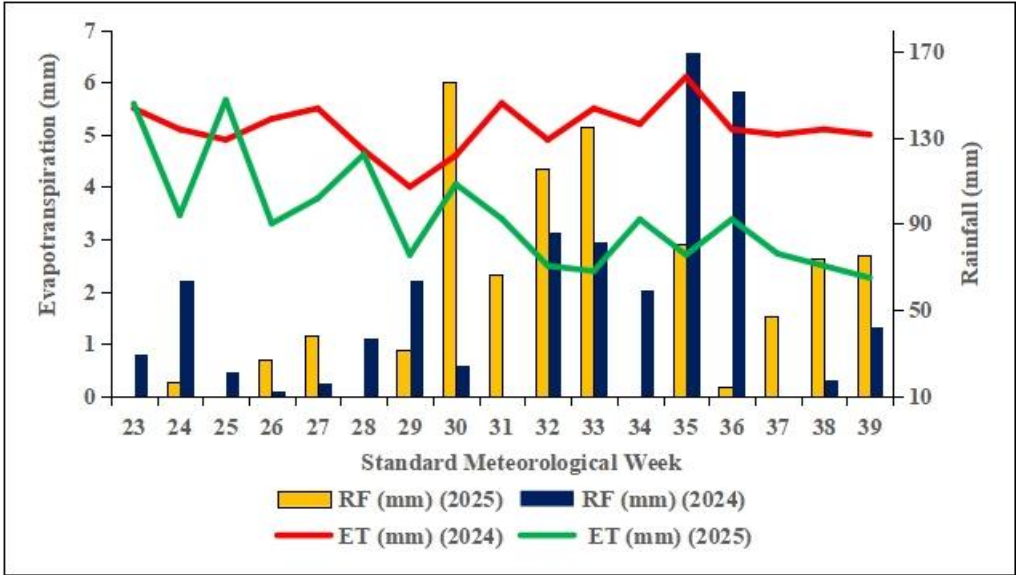


Fig 1: Total rainfall (mm) and mean evapotranspiration (mm) during the sorghum growing period across both years of experimentation

Table 1: Detailed soil test-based fertilization schedule for the cropping systems across both experimental years (2024-25 and 2025-26)

System	STBF (kg ha ⁻¹)		
	N	P ₂ O ₅	K ₂ O
CS1: Kharif sorghum + pigeonpea (2:1) - relay rabi greengram	99	124	60
CS2: Kharif sorghum- rabi chickpea	99	89	50

Table 2: Procedural details of mulch application across treatments (2024-2025 & 2025-2026)

Treatment combinations	2023-2024 (t ha ⁻¹)	2024-2025 (t ha ⁻¹)
CS1 × N2 × B1	4.41	4.56
CS1 × N2 × B2	4.69	4.83
CS1 × N2 × B3	4.90	5.08
CS1 × N3 × B1	4.65	4.77
CS1 × N3 × B2	4.84	5.02
CS1 × N3 × B3	5.06	5.23
CS2 × N2 × B1	1.40	1.81
CS2 × N2 × B2	1.50	1.96
CS2 × N2 × B3	1.54	2.04
CS2 × N3 × B1	1.42	1.86
CS2 × N3 × B2	1.52	2.01
CS2 × N3 × B3	1.58	2.07

2.7 Crop data record

Plant height was determined using a meter scale, measured from the soil surface to the tip of the folded leaf in the early stages and from the base to the ligule of the uppermost fully opened leaf after tasseling. The Leaf Area Index (LAI) was derived by dividing the total leaf area per plant by the corresponding ground area, following the methodology described by Sestak *et al.*. The fresh weights of panicles, stems, leaves and roots were measured individually from five plants, averaged, analyzed and expressed in g plant⁻¹. To determine dry matter, samples were chopped and sun-dried for 48 hours, then transferred to a hot air

oven at 60 ± 5°C until a consistent weight was achieved. Crop Growth Rate (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) [38]:

CGR = (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) ($\text{g plant}^{-1} \text{ day}^{-1}$) was expressed based on the increase in dry weight per unit of time per plant (Richards, 1969) [29]:

$$\text{AGR} = \frac{W_2 - W_1}{(t_2 - t_1)}$$

Where, W1 and W2 = dry weight of the plant at time intervals of t1 and t2, respectively.

Relative Growth Rate ($\text{g g}^{-1} \text{ day}^{-1}$) was expressed as an increase in plant material per unit of biomass per unit of time, calculated according to Fisher (1921) [9]:

$$\text{RGR} = \frac{\ln W_2 - \ln W_1}{(t_2 - t_1)}$$

Where, W1 and W2 = dry weight of the plant at time intervals of t1 and t2, respectively.

Leaf Area Ratio (LAR) ($\text{cm}^2 \text{ g}^{-1}$) was calculated as the ratio of total leaf area to total plant biomass, representing the photosynthetic surface relative to respiratory mass. Leaf area duration (LAD) (days) and Biomass duration (BD) (g days plant^{-1}) were also computed accordingly as the integral of the LAI and total dry matter, respectively, over the growth period from t1 to t2.

Net Assimilation Rate (NAR) ($\text{g m}^{-2} \text{ day}^{-1}$) was estimated based on the assimilatory efficiency of the leaves serving as a direct indicator of net photosynthesis and was calculated based on Gregory (1917) defined formula

$$\text{NAR} = \frac{(W_2 - W_1) \times (\ln L_2 - \ln L_1)}{(t_2 - t_1) \times (L_2 - L_1)}$$

Where, L1 and W1 are the leaf area and dry weight of the plant at time t1

L2 and W2 are the leaf area and dry weight of the plant at time t2

A portable SPAD-502 chlorophyll meter (Minolta Corp., Ramsey, NJ, USA) was used to non-destructively measure leaf greenness. Readings were taken from the third fully developed leaf from the apex. Measurements were recorded from the top and middle portions of 10 leaves from 5 representative plants and averaged to estimate leaf nitrogen and chlorophyll status (Ehsanzadeh *et al.*, 2009) [6]. Chlorophyll 'a' and 'b' contents in leaves were estimated following the method of Arnon (1949) [2] using 80% acetone as the extraction solvent. Leaf samples (100 mg) were macerated, extracted in 10 mL acetone, and the supernatant was obtained after centrifugation at 5000 rpm for 5 minutes. Absorbance was recorded at 645 and 663 nm against 80% acetone as blank, and chlorophyll content was calculated using standard formulae.

$$\text{Chlorophyll 'a' content} = \frac{(12.7 \times A_{663} - 2.69 \times A_{645}) \times \frac{V}{1000 \times W}}{1}$$

$$\text{Chlorophyll 'b' content} = \frac{(22.9 \times A_{645} - 4.68 \times A_{663}) \times \frac{V}{1000 \times W}}{1}$$

Experimental data were analyzed using the analysis of variance (ANOVA) for a split-split plot design (Gomez and Gomez, 1984). 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 Growth metrics

The pooled data from the two-year study on the growth and biomass of sorghum as influenced by cropping systems, nitrogen management practices, and biochar application are presented in Table 3.

The cropping systems significantly influenced all recorded growth parameters. The *kharif* sorghum + pigeonpea (2:1) - relay *rabi* greengram (CS1) system recorded significantly higher plant height (178.31 cm), number of leaves at 900 DAS (12.72) and Leaf Area Index (4.736) compared to the *kharif* sorghum - *rabi* chickpea (CS2) system. Similarly, biomass accumulation was superior in CS1, which yielded a fresh weight of 1058.03 g plant^{-1} and a dry weight of 111.10 g plant^{-1} , significantly outperforming the sole sorghum-based sequence. This improvement in the relay system may be attributed to the residual benefits of legume intercropping and better resource utilization. The significantly higher plant height, LAI and dry matter accumulation observed in the *kharif* sorghum + pigeonpea (2:1) - relay *rabi* greengram (CS1) system can be attributed to the resource-sharing mechanisms inherent in cereal-legume associations. The spatial arrangement (2:1) likely reduced intraspecific competition for sorghum while benefiting from the biological nitrogen fixation of the pigeonpea. Furthermore, the inclusion of relay greengram ensures a continuous supply of organic root exudates, which stimulates soil microbial activity. This aligns with the findings of Franke *et al.* (2018) [10] and Chen *et al.*, (2021) [5], who demonstrated that complementary resource use in cereal-legume intercrops leads to higher LAI and overall biomass compared to sole cropping systems.

Similarly, nutrient management strategies showed a progressive and significant impact on sorghum growth. The application of STBF + mulch + biological consortia (N3) emerged as the most effective treatment, recording the maximum plant height (180.43 cm), number of leaves (12.90) and LAI (4.850). The N3 treatment also recorded the highest fresh weight (1124.82 g plant^{-1}) and dry weight (118.14 g plant^{-1}), which were significantly higher than both N2 (STBF + mulch) and N1 (STBF). The integration of biological consortia with mulching likely increased nutrient availability and moisture retention, thereby promoting vegetative growth. The superior performance of the STBF + mulch + biological consortia (N3) treatment highlights the efficacy of combining inorganic fertilizers with moisture-conserving and biologically active inputs. Mulching creates a stable hydrothermal regime in the soil, which enhances the efficiency of the biological consortia in solubilizing nutrients (Pavan *et al.*, 2025) [24]. The significant increase in growth parameters under N3 is supported by Kebede (2021) [17], who reported that the integrated use of chemical fertilizers and bio-inoculants significantly enhances vegetative growth and dry matter partitioning in sorghum. The increased LAI (4.850) in this treatment indicates a higher photosynthetic surface area, directly contributing to the maximum dry weight (118.14 g plant^{-1}).

Increased biochar application levels significantly improved sorghum growth indices. The application of Biochar @ 3 t ha^{-1} (B3) resulted in significantly higher plant height (176.12 cm), leaf count at 90 DAS (12.76), and LAI (4.700) compared to the lower doses (B1) but it was statistically at par with B2. Similarly, regarding biomass, the B3 treatment achieved the

highest fresh weight (1055.07 g plant⁻¹) and dry weight (109.66 g plant⁻¹) being at par with B2. The significant improvement in growth and biomass with increasing biochar levels, reaching a peak at 3 t ha⁻¹ (B3), is likely due to enhanced soil physical properties and nutrient retention. Biochar's porous structure increases the Cation Exchange Capacity (CEC), reducing the leaching of applied nitrogen and making it available for a longer period during the crop cycle. Yin *et al.*, (2022) [39] noted that

biochar application improves crop performance by enhancing soil quality and nutrient uptake efficiency. Furthermore, the significant increase in dry weight observed in B3 (109.66 g/plant) mirrors the results of Glaser and Lehr (2019) [12], who found that higher biochar application rates lead to a linear increase in the productivity and nitrogen use efficiency of cereal crops.

Table 3: Pooled effect of cropping systems, nitrogen management practices and biochar application on plant height (cm), number of leaves at 90 DAS, leaf area index, fresh weight (g plant⁻¹) and dry weight of sorghum (g plant⁻¹)

Treatment	Plant height (cm)	No. of leaves (90 DAS)	Leaf Area Index	Fresh weight (g plant ⁻¹)	Dry weight (g plant ⁻¹)
Cropping systems (CS)					
CS1 :Kharif pigeonpea + sorghum (1:2) - relay rabi greengram	178.31	12.72	4.736	1058.03	111.10
CS2 :Kharif sorghum- rabi chickpea	168.72	11.50	4.504	1027.89	104.04
SEm±	0.32	0.18	0.001	2.67	0.50
CD (P=0.05)	1.57	0.91	0.006	13.29	2.47
Nitrogen management practices					
N ₁ : STBF	167.53	11.47	4.377	962.91	97.86
N ₂ : STBF + mulch	172.58	11.97	4.634	1041.16	106.71
N ₃ : STBF + mulch + biological consortia	180.43	12.90	4.850	1124.82	118.14
SEm ±	1.42	0.15	0.029	1.98	0.36
CD (P = 0.05)	4.61	0.50	0.095	6.47	1.19
Biochar application (B)					
B ₁ :Biochar @ 1 t ha ⁻¹	170.21	11.55	4.529	1026.91	104.08
B ₂ :Biochar @ 2 t ha ⁻¹	174.22	12.02	4.631	1046.90	108.96
B ₃ :Biochar @ 3 t ha ⁻¹	176.12	12.76	4.700	1055.07	109.66
SEm ±	0.69	0.16	0.026	2.85	0.32
CD (P = 0.05)	2.03	0.46	0.077	8.33	0.94
Interaction CD (P = 0.05)					
CS × N	NS	NS	NS	S	S
CS × B	NS	NS	NS	S	S
N × B	NS	NS	NS	S	S
CS × N × B	NS	NS	NS	NS	NS

The interaction effects between cropping systems, nutrient management, and biochar application significantly influenced fresh and dry biomass, indicating a strong synergistic relationship between these factors (CS × N, CS × B, and N × B) (Fig. 2,3,4,5,6,7). This synergy is likely driven by the improved resource use efficiency in the legume-based intercropping system (CS2), which, when combined with the enhanced nutrient retention capacity of biochar (B3) and the microbial activity from biological consortia (N3), creates a superior environment for biomass accumulation compared to any single

factor alone. As noted by Ramachandran and Biswas (2016) [27], the combined application of biochar and fertilizers yields higher productivity than individual applications, due to stabilized nutrient availability and improved soil physical properties. However, the results were at par with B2. Similarly, Ghosh *et al.* (2006) [11] observed that the interaction between intercropping and nutrient management significantly impacts total dry matter production by optimizing interspecific competition and nutrient uptake.

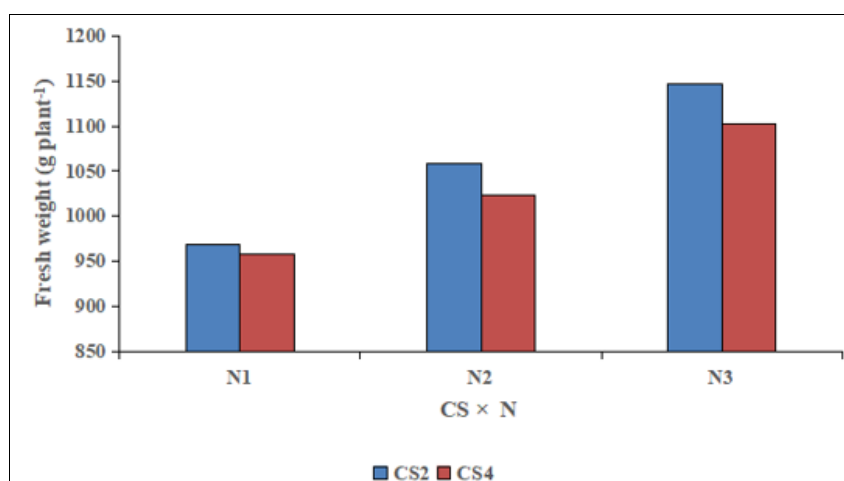


Fig 2: Pooled Interaction effect of cropping systems and nutrient management practices on fresh weight (g plant⁻¹)

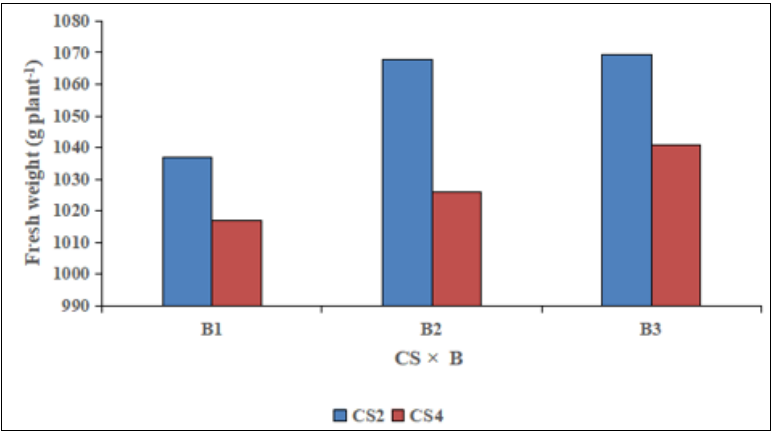


Fig 3: Pooled Interaction effect of cropping systems and biochar application rates on fresh weight (g plant⁻¹)

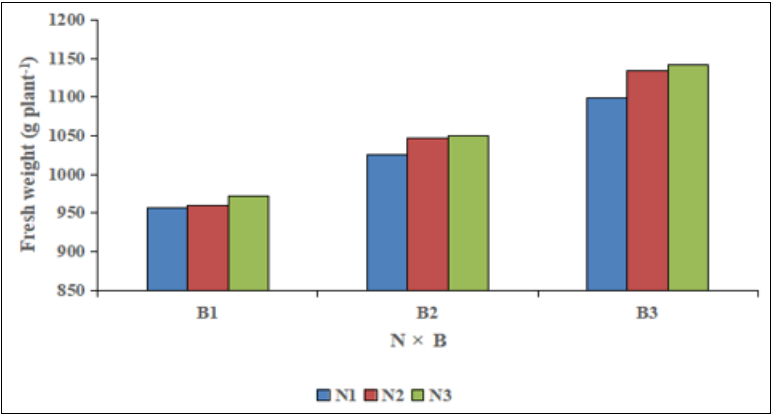


Fig 4: Pooled Interaction effect of nutrient management practices and biochar application rates on fresh weight (g plant⁻¹)

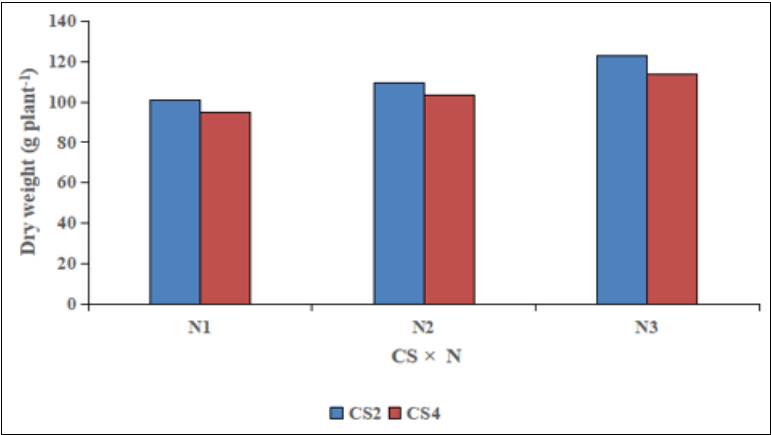


Fig 5: Pooled Interaction effect of cropping systems and nutrient management practices on dry weight (g plant⁻¹)

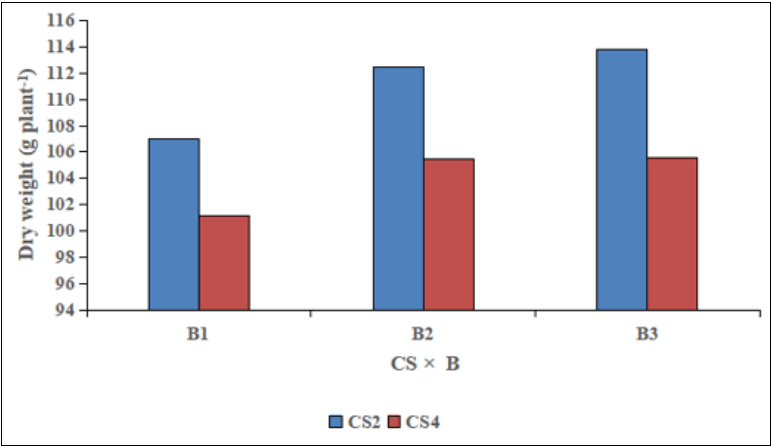


Fig 6: Pooled Interaction effect of cropping systems and biochar application rates on dry weight (g plant⁻¹)

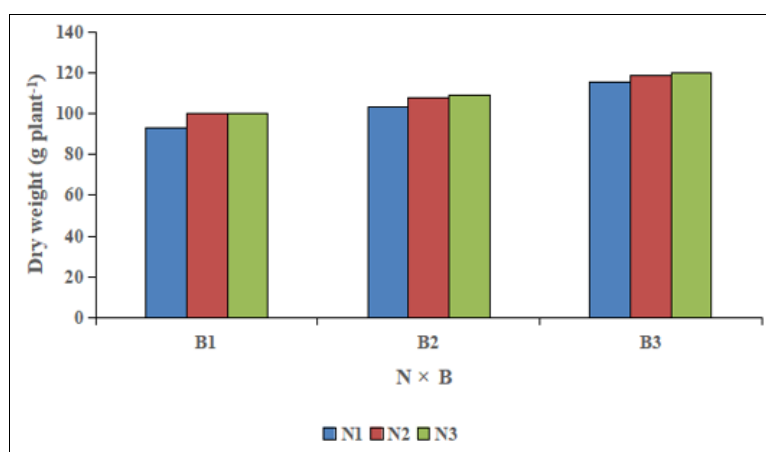


Fig 7: Pooled Interaction effect of nutrient management practices and biochar application rates on dry weight (g plant⁻¹)

3.2 Physiological Indices

The pooled analysis of two years revealed that the physiological indices, viz., absolute growth rate (AGR), relative growth rate (RGR), crop growth rate (CGR), leaf area duration (LAD), leaf area ratio (LAR) and biomass duration (BMD), exhibited distinct temporal variations across crop growth stages and were significantly influenced by cropping systems, nutrient management practices and biochar application.

At the early growth stage (30 DAS), RGR and LAR were relatively higher across treatments, while AGR and CGR remained low. This trend reflects the predominance of active cell division and leaf expansion during the initial stages of crop growth, resulting in higher assimilatory efficiency per unit biomass. Among the treatments, the diversified cropping system (CS2: *khariif* sorghum + pigeonpea (2:1) - relay *rabi* greengram) recorded higher RGR and LAR compared to the sole cropping system (CS4), indicating superior early vigour and efficient resource utilization. The enhanced performance under CS2 can be attributed to complementary interactions among component crops, particularly biological nitrogen fixation by legumes, which improves nutrient availability during early growth.

During the intermediate stage (30-60 DAS), a marked increase in AGR and CGR was observed, corresponding to rapid vegetative growth and canopy expansion. The increase in LAR during this period indicated prolonged leaf area persistence and enhanced photosynthetic surface. The superiority of CS2

continued during this phase, which may be ascribed to improved nutrient dynamics and better utilization of light, water, and nutrients.

Among nutrient management practices, STBF combined with mulch and biological consortia (N3) significantly enhanced AGR and CGR over other treatments. This could be due to improved nutrient availability, enhanced microbial activity, and moisture conservation, resulting in sustained assimilate production.

Contrarily, biochar application at higher levels (B3: 3 t ha⁻¹) further augmented growth rates by improving soil physical properties and nutrient retention capacity, but was statistically at par with 2 t ha⁻¹.

At the peak growth stage (60-90 DAS), CGR and AGR attained their maximum values, while RGR showed a declining trend. The decline in RGR with crop age is a well-established phenomenon, primarily due to the increase in structural biomass and reduced relative contribution of actively growing tissues. Significantly higher LAR and BMD were recorded under CS2, N3, and B3 treatments, indicating prolonged photosynthetic activity and better canopy maintenance during this critical period. The enhanced biomass accumulation under these treatments suggests efficient assimilation and translocation of photosynthates.

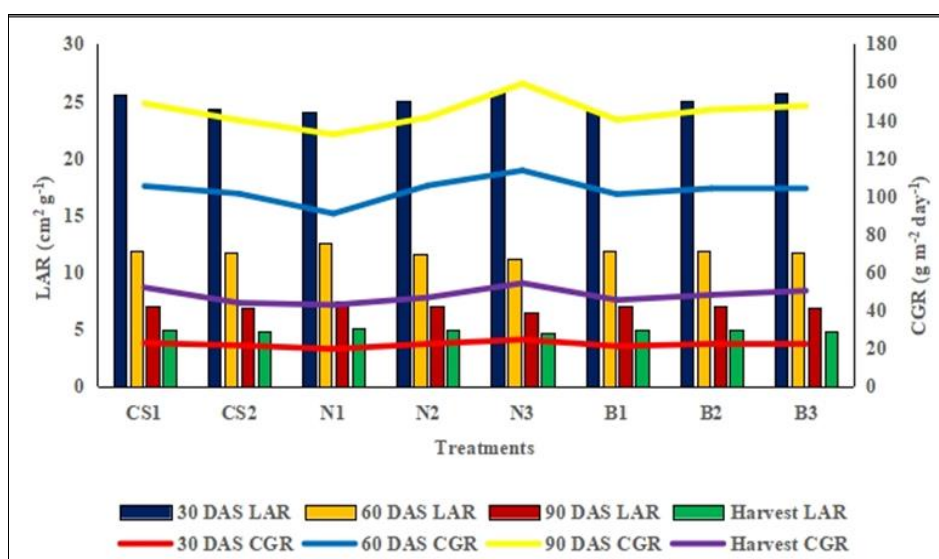


Fig 8: Pooled effect of cropping systems, nutrient management practices and biochar application rates on LAR (cm² g⁻¹) and CGR (g m² day⁻¹)

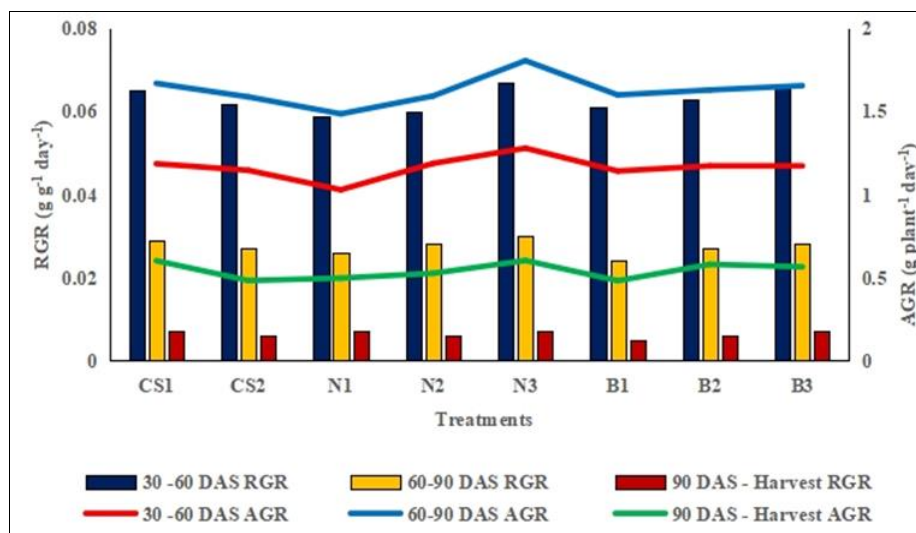


Fig 9: Pooled effect of cropping systems, nutrient management practices and biochar application rates on RGR ($\text{g g}^{-1} \text{day}^{-1}$) and AGR ($\text{g plant}^{-1} \text{day}^{-1}$)

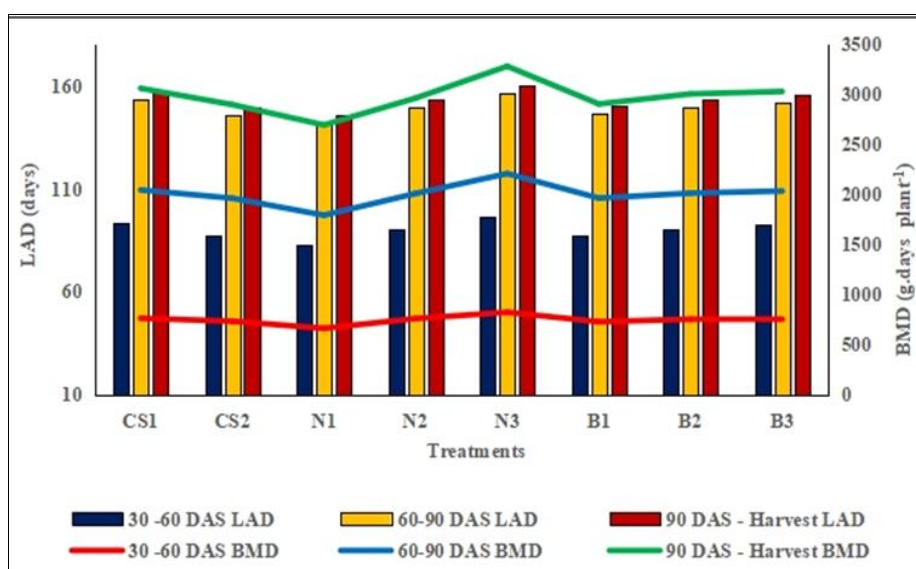


Fig 10: Pooled effect of cropping systems, nutrient management practices and biochar application rates on LAD (days) and BMD (g days plant^{-1})

At later stages (90 DAS to harvest), AGR, CGR and RGR declined across all treatments due to leaf senescence and reduced photosynthetic activity. However, LAD and BMD remained comparatively higher under CS2, N3 and B3, indicating delayed senescence and sustained physiological activity. The reduction in LAR at this stage reflects increased partitioning of assimilates towards reproductive structures. The overall improvement in growth indices under integrated treatments highlights their role in maintaining crop vigour throughout the growth period. These findings are in close agreement with the reports of Hunt (1990) [5], who emphasized the stage-wise variation in growth indices and Baligar *et al.* (2001) [3], who reported enhanced growth rates under improved nutrient management. The positive influence of biochar on biomass accumulation and growth dynamics has also been documented by Lehmann and Joseph (2024) [21]. Alternatively, the pooled results indicated that physiological parameters, namely chlorophyll 'a', chlorophyll 'b', SPAD values and net assimilation rate (NAR), followed a consistent trend across crop growth stages, with significant variation among treatments.

Chlorophyll (Chl) 'a' and 'b' contents increased progressively from the early growth stage up to 60-90 DAS, followed by a decline towards maturity. The highest chlorophyll content during the peak vegetative stage indicates maximum photosynthetic capacity at this phase. The diversified cropping system (CS2) recorded significantly higher chlorophyll content compared to sole cropping, which can be attributed to improved nitrogen availability from legume components. Nitrogen plays a crucial role in chlorophyll synthesis and its enhanced availability under intercropping systems contributes to improved photosynthetic efficiency.

Among nutrient management practices, STBF + mulch + biological consortia significantly increased chlorophyll content and SPAD values. This enhancement may be due to improved nutrient supply, particularly nitrogen, along with increased microbial activity and reduced nutrient losses. Biochar application at 3 t ha^{-1} (B3) further improved chlorophyll content by enhancing nutrient retention and root proliferation, thereby facilitating significantly higher nutrient uptake. However, it was found to be statistically at par with B2.

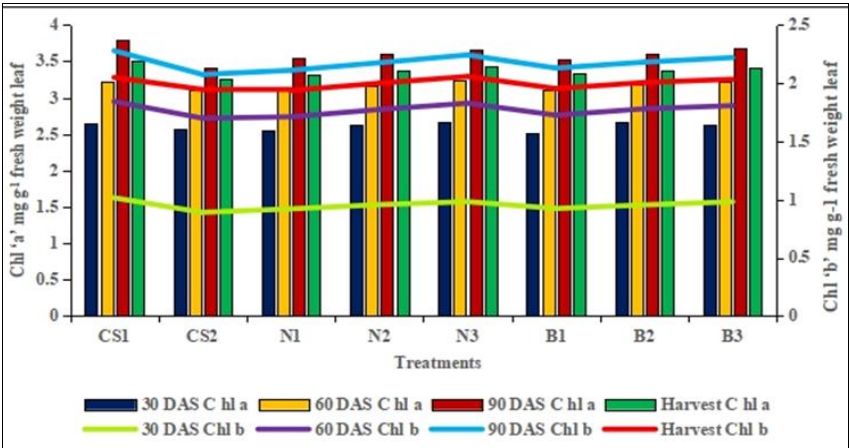


Fig 11: Pooled effect of cropping systems, nutrient management practices and biochar application rates on Chlorophyll ‘a’ and ‘b’ (mg g⁻¹ fresh weight leaf)

Moreover, SPAD values exhibited trends similar to chlorophyll content, increasing up to the peak growth stage and declining thereafter. Significantly higher SPAD readings under CS2, N3 and B3 (B3 par with B2) treatments indicated improved leaf nitrogen status and enhanced photosynthetic activity. The close association between SPAD values and chlorophyll content underscores the reliability of SPAD as a non-destructive indicator of crop nitrogen status.

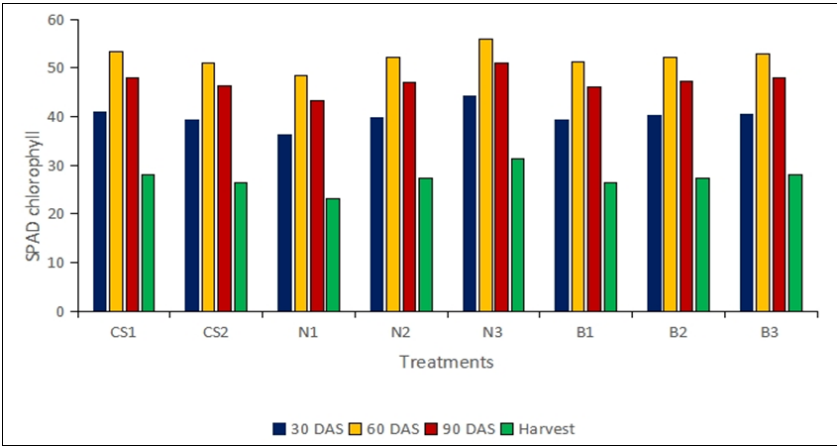


Fig 12: Pooled effect of cropping systems, nutrient management practices and biochar application rates on SPAD chlorophyll reading

Net assimilation rate (NAR) was higher during early growth stages and gradually declined with crop age. The higher NAR at initial stages reflects efficient photosynthesis per unit leaf area due to minimal shading and high metabolic activity. The decline in NAR at later stages is primarily due to mutual shading of leaves, increased respiration and senescence. Nevertheless, higher NAR values observed under CS2 and N3 treatments indicate better assimilation efficiency, which contributed to higher biomass production. These results corroborate the findings of Evans (1972)^[7], who highlighted the relationship between chlorophyll content and photosynthetic efficiency and Prakash *et al.* (2026), who reported improved chlorophyll content and SPAD values under integrated nutrient management. The beneficial effects of biochar on chlorophyll content and photosynthesis were also reported by Major *et al.* (2010)^[22] and Zhang *et al.* (2012)^[40].

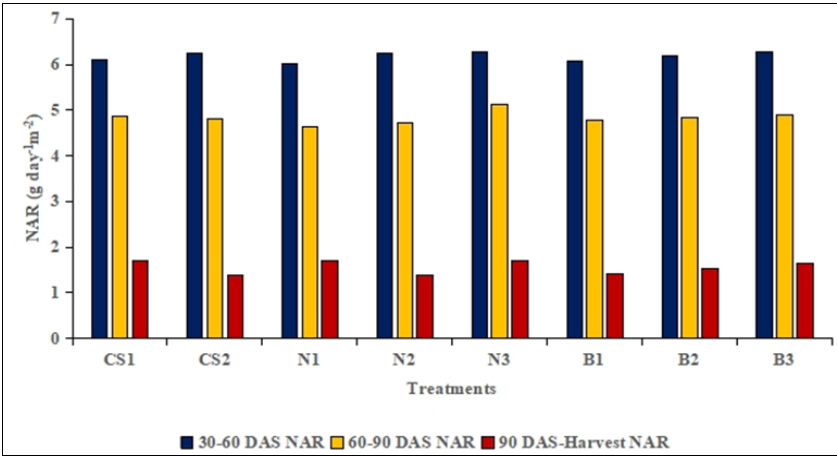


Fig 13: Pooled effect of cropping systems, nutrient management practices and biochar application rates on NAR (g day⁻¹ m⁻²)

4. Conclusion

The two-year study demonstrated that integrating regenerative agricultural practices and applying biochar significantly enhances the growth dynamics and physiological efficiency of sorghum in *Vertisols* of the semi-arid tropics. Among the cropping sequences, the *kharif* sorghum pigeonpea (2:1) - relay *rabi* greengram (CS1) system proved superior, recording significantly higher growth parameters (plant height, LAI) and physiological indices (CGR, NAR, and LAD) compared to the *kharif* sorghum-chickpea system. This confirms that legume-based relay cropping systems optimize resource use efficiency and sustain crop vigor through biological nitrogen fixation and improved soil moisture utilization. In terms of nutrient management, the application of STBF + mulch + biological consortia (N3) emerged as the most effective regenerative practice. It significantly boosted photosynthetic pigments (Chlorophyll a, b, and SPAD values) and dry matter accumulation, highlighting the synergistic role of mulching and microbial inoculants in enhancing nutrient availability and maintaining the "stay-green" trait in sorghum. Furthermore, the application of biochar @ 3 t ha⁻¹ (B3) and @ 2 t ha⁻¹ (B2) demonstrated a clear linear advantage in improving growth rates and biomass duration, acting as a critical soil conditioner for nutrient retention. The significant interaction between cropping systems, nitrogen management, and biochar for biomass production suggests that these factors work synergistically rather than in isolation. Therefore, for sustainable sorghum production in semi-arid *Vertisols*, the adoption of a sorghum + pigeonpea intercropping system combined with integrated nutrient management (including biological consortia and mulch) and biochar application at 3 t ha⁻¹ is highly recommended to maximize physiological growth and long-term productivity.

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