



Effect of Integrated Application of Biochar, Sulphur and Recommended Fertilizer on Growth, Yield and Quality of Groundnut Grown in an Alfisol

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

A field experiment was conducted during the rabi seasons of 2024–25 and 2025–26 at Krishi Vigyan Kendra (KVK), Palem, Nagarkurnool, Telangana, to evaluate the integrated effects of the recommended fertiliser dose (RDF), biochar and sulphur on groundnut cv. TAG 24 grown on an Alfisol. The experiment comprised 13 treatments arranged in a randomised block design (RBD) with three replications, involving 75 and 100% RDF, biochar at 2 and 4 t ha⁻¹, and sulphur at 40 kg ha⁻¹, applied alone or in combinations. Pooled analysis revealed significant treatment effects on dry matter accumulation and yield, but not on the measured quality parameters. The highest pooled dry matter accumulation was recorded with 100% RDF + biochar at 4 t ha⁻¹ + sulphur at 40 kg ha⁻¹, with values of 2976.6, 4461.9 and 5114.7 kg ha⁻¹ at 30, 60 and 90 DAS, respectively. This treatment also recorded the highest haulm (3743.2 kg ha⁻¹), pod (2938.6 kg ha⁻¹) and kernel (1970.7 kg ha⁻¹) yields, which were not significantly different from those obtained with 100% RDF + biochar at 2 t ha⁻¹ + sulphur at 40 kg ha⁻¹ and 75% RDF + biochar at 4 t ha⁻¹ + sulphur at 40 kg ha⁻¹. Protein, oil and oleic acid contents were not significantly affected by the treatments, although 100% RDF + biochar at 4 t ha⁻¹ + sulphur at 40 kg ha⁻¹ recorded the highest numerical pooled values of 26.23%, 48.55% and 46.17%, respectively. The results indicate that integrating RDF with biochar and sulphur improved groundnut growth and yield under the conditions of the study, while quality parameters showed only numerical variation.

Keywords: Biochar; sulphur; groundnut; Alfisol; recommended fertiliser dose.

1. Introduction

Sustainable nutrient management is essential for maintaining crop productivity while protecting soil health. Excessive or imbalanced use of mineral fertilisers can reduce nutrient-use efficiency and contribute to deterioration of soil quality. Biochar has received considerable attention as a soil amendment because its carbon-rich, porous structure can influence nutrient retention, soil physical properties and carbon storage. Its agronomic effects, however, vary with feedstock, pyrolysis conditions, application rate, soil properties, crop species and climate.

Biochar is a carbon-rich, porous material produced through the thermochemical conversion of biomass under limited oxygen, commonly at temperatures of about 350–600 °C (Amonette & Joseph, 2012). Field and meta-analytical evidence indicate that biochar can improve crop productivity under suitable soil and management conditions, partly through changes in soil water relations, nutrient retention and soil reaction (Liu *et al.*, 2013; Vaccari *et al.*, 2011). Biochar also provides a productive pathway for recycling biomass residues that might otherwise be burned or disposed of, while contributing to longer-term carbon storage in soil (McHenry, 2009). A systematic review of sandy-textured soils found that biochar amendments can influence nutrient cycling and crop yield, although responses vary with soil and management conditions (Bekchanova *et al.*, 2024).

Groundnut (*Arachis hypogaea* L.) is an important oilseed and food legume valued for its edible oil, protein and economic importance. The crop is widely cultivated in India, including Gujarat, Rajasthan, Andhra Pradesh, Tamil Nadu, Karnataka, Telangana and Maharashtra. Groundnut performs best in well-drained soils under balanced nutrient supply. Its geocarpic growth habit, in which pegs penetrate the soil and pods develop below the soil surface, makes favourable soil physical conditions particularly important for peg penetration, pod development and harvestable yield (Sowmya *et al.*, 2022). Field research on peanut has linked biochar application to changes in soil aggregation and root development, with yield responses varying among biochar treatments (Liu *et al.*, 2024).

Sulphur is an important secondary nutrient for groundnut because it participates in the synthesis of sulphur-containing amino acids, proteins and several enzymes and is closely associated with oilseed metabolism. Adequate sulphur nutrition can therefore support crop growth, kernel development and quality (Rao *et al.*, 2013). In soils with limited nutrient-retention capacity, combining sulphur and mineral fertilisers with biochar may provide complementary benefits by supplying readily available nutrients while improving their retention in the root zone. In a sulphur-deficient Inceptisol, combined application of sulphur-incubated organic amendments and recommended fertiliser was associated with higher pod and haulm yields of groundnut under the conditions evaluated (Kolape *et al.*, 2024).

The response to combined biochar and fertiliser application depends on soil texture, nutrient status, biochar characteristics and environmental conditions. Liu *et al.* (2013) showed that crop responses to biochar vary substantially with experimental conditions, with stronger responses often observed in coarse-textured or acidic soils. In a rainfed Alfisol, Pandian *et al.* (2016) reported that biochar improved soil physical and chemical properties and enhanced groundnut yield, demonstrating its potential relevance to groundnut-based production systems. A separate groundnut experiment also reported changes in crop growth and yield following the use of nanobiochar-based nitrogen and potassium fertilisers (Nagaraju *et al.*, 2024). Research on a groundnut-based cropping sequence has further examined biochar and trichocompost alongside full and reduced mineral-fertiliser doses, reporting changes in selected soil-health indicators (Younus *et al.*, 2026).

Although the individual effects of biochar and sulphur on soil fertility and crop productivity are well recognised, field evidence on their combined use with different levels of recommended fertiliser in groundnut grown on Alfisols remains limited. Therefore, the present investigation evaluated the integrated effects of biochar, sulphur and recommended fertiliser rates on the growth, yield and kernel quality of groundnut cv. TAG 24. The study was designed to identify nutrient-management combinations capable of improving groundnut productivity while assessing whether similar responses could be achieved under a reduced fertiliser level.

2. Materials and Methods

A field experiment was conducted during two consecutive Rabi seasons (2024–25 and 2025–26) at Krishi Vigyan Kendra (KVK), Palem, Nagarkurnool District, Telangana, India (16°34' N, 78°20' E; 543 m above mean sea level). The experiment was laid out in a

randomised block design (RBD) with 13 treatments and three replications during each season. The experimental soil was an Alfisol with a sandy loam texture, comprising 74.6% sand, 12.3% silt and 13.1% clay. The initial soil reaction was slightly alkaline (pH 7.55) and non-saline (EC 0.22 dS m⁻¹), with 0.42% oxidisable organic carbon. Available N, P₂O₅ and K₂O were 132.73, 14.37 and 240.12 kg ha⁻¹, respectively.

The treatments comprised 75 and 100% of the recommended fertiliser dose (RDF; 30:40:50 kg N:P₂O₅:K₂O ha⁻¹), biochar at 2 and 4 t ha⁻¹ and sulphur at 40 kg ha⁻¹, applied alone or in combinations. The treatment combinations were T1: control; T2: 100% RDF; T3: 100% RDF + 40 kg S ha⁻¹; T4: 100% RDF + biochar at 2 t ha⁻¹; T5: 100% RDF + biochar at 4 t ha⁻¹; T6: 100% RDF + biochar at 2 t ha⁻¹ + 40 kg S ha⁻¹; T7: 100% RDF + biochar at 4 t ha⁻¹ + 40 kg S ha⁻¹; T8: 75% RDF; T9: 75% RDF + 40 kg S ha⁻¹; T10: 75% RDF + biochar at 2 t ha⁻¹; T11: 75% RDF + biochar at 4 t ha⁻¹; T12: 75% RDF + biochar at 2 t ha⁻¹ + 40 kg S ha⁻¹; and T13: 75% RDF + biochar at 4 t ha⁻¹ + 40 kg S ha⁻¹. Maize-stalk biochar was produced by slow pyrolysis at 300–400 °C under limited-oxygen conditions and was incorporated into the soil one week before sowing. The biochar had a bulk density of 0.42 g cm⁻³, pH of 9.2, EC of 1.1 dS m⁻¹, organic carbon content of 68.4%, total N of 0.62%, total P of 0.38% and total K of 1.20%. Nitrogen, phosphorus and potassium were supplied through urea, single superphosphate and muriate of potash, respectively, while sulphur was supplied through bentonite sulphur according to the treatment schedule.

Groundnut cultivar TAG 24 was used as the test crop. Seeds were treated with thiram at 2 g kg⁻¹ seed, inoculated with *Rhizobium* culture at 3 g kg⁻¹ seed, and sown at a spacing of 22.5 cm × 10 cm in plots measuring 4.5 m × 3.5 m. Dry matter accumulation was recorded at 30, 60 and 90 days after sowing (DAS) and expressed as kg ha⁻¹.

At physiological maturity, the crop was harvested separately from the net plot area of each treatment. Pods were separated, dried and weighed to determine pod yield, while the remaining vegetative biomass was recorded as haulm yield. Kernel yield was determined after shelling, and pod, haulm and kernel yields were expressed as kg ha⁻¹. Kernel protein, oil and oleic acid contents were determined using a near-infrared reflectance spectroscopy (NIRS)-based grain analyser at ICRISAT and expressed as percentages. Data from each season were subjected to an analysis of variance appropriate for an RBD, followed by pooled analysis over the two seasons. Treatment means were compared using the critical difference (CD) at the 5% probability level when the F-test was significant.

3. Results and Discussion

3.1 Dry Matter Accumulation

Dry matter accumulation increased progressively from 30 to 90 DAS and was significantly influenced by nutrient-management treatments in both seasons and in the pooled analysis (Table 1). At 30 DAS, T7 recorded the highest pooled dry matter accumulation (2976.6 kg ha⁻¹), followed numerically by T6 (2778.0 kg ha⁻¹) and T13 (2733.6 kg ha⁻¹); the differences among these three treatments were within the pooled CD (312.15 kg ha⁻¹). The control recorded the lowest value (1922.8 kg ha⁻¹). A similar pattern occurred at 60 DAS, when T7 recorded 4461.9 kg ha⁻¹ and was statistically at par with T6 (4241.6 kg ha⁻¹) and T13 (4211.6 kg ha⁻¹). At 90 DAS, T7 again recorded the highest pooled value (5114.7 kg ha⁻¹) and remained statistically at par with T6 (4833.1 kg ha⁻¹) and T13 (4825.8 kg ha⁻¹), whereas the control recorded 4059.9 kg ha⁻¹.

The greater biomass production in treatments receiving RDF together with biochar and sulphur may be associated with improved nutrient supply and a more favourable rhizosphere during crop growth. Biochar has a porous structure and large surface area that can modify soil water retention, aeration and nutrient-holding capacity, thereby supporting root growth and nutrient acquisition (Sohi *et al.*, 2009). Such effects can be particularly relevant in coarse-textured soils where nutrient and water retention are comparatively limited.

Sulphur may have complemented these effects through its role in amino-acid and protein synthesis and other metabolic processes required for plant growth (Rao *et al.*, 2013). The combined supply of RDF, biochar and sulphur could therefore support sustained nutrient availability and photosynthetic growth, resulting in greater dry matter accumulation. Pandian *et al.* (2016) similarly reported improved soil conditions and groundnut productivity following biochar application in a rainfed Alfisol. Recent field evidence also indicates that sulphur levels can influence dry matter accumulation and biomass partitioning in groundnut, although the magnitude of response varies among genotypes (Monika *et al.*, 2024).

3.2 Yield Parameters

3.2.1 Haulm Yield (kg ha⁻¹)

Haulm yield was significantly influenced by the nutrient-management treatments in both seasons and in the pooled analysis (Table 2). Pooled haulm yield ranged from 2688.6 kg ha⁻¹ in the control to 3743.2 kg ha⁻¹ in T7. Although T7 recorded the highest numerical haulm yield, it was statistically at par with T6 (3612.6 kg ha⁻¹) and T13 (3445.2 kg ha⁻¹) based on the pooled CD of 412.91 kg ha⁻¹. The control recorded the lowest haulm yield.

The higher haulm yield under the integrated treatments was consistent with greater dry matter accumulation. Improved soil moisture and nutrient retention under biochar-amended conditions may have supported vegetative growth and biomass production. Biochar can enhance nutrient retention in the root zone and improve soil physical conditions (Sohi *et al.*, 2009; Pandian *et al.*, 2016), while RDF and sulphur provide readily available nutrients required for crop growth. Similar responses were reported by Gowthami and Gurumurthy (2023), who observed improved groundnut yield following combined application of biochar and chemical fertilisers in an irrigated Alfisol.

Similar responses were reported by Gowthami and Gurumurthy (2023), who observed improved groundnut yield following combined application of biochar and chemical fertilisers in an irrigated Alfisol.

3.2.2 Pod Yield (kg ha^{-1})

Pod yield differed significantly among treatments in both seasons and in the pooled analysis. The highest pooled pod yield was recorded with T7 ($2938.6 \text{ kg ha}^{-1}$), which was statistically at par with T6 ($2844.5 \text{ kg ha}^{-1}$) and T13 ($2721.5 \text{ kg ha}^{-1}$) because their differences were smaller than the pooled CD ($367.02 \text{ kg ha}^{-1}$). The control recorded the lowest pod yield ($1845.6 \text{ kg ha}^{-1}$).

The improvement in pod yield under integrated nutrient management may be associated with greater biomass production, sustained nutrient availability and effective partitioning of assimilates towards reproductive sinks (Jyothi *et al.*, 2025). Biochar-mediated improvement in soil moisture and nutrient retention can be particularly relevant to groundnut because peg penetration and pod development occur below the soil surface. Favourable soil physical conditions therefore support reproductive development in this geocarpic crop (Sowmya *et al.*, 2022).

Agegnehu *et al.* (2015) reported improved peanut yield following biochar and biochar-compost amendments, attributing the response to changes in soil properties and nutrient availability. Sulphur may further support reproductive growth through its role in protein synthesis, enzyme activity and oilseed metabolism (Rao *et al.*, 2013). The favourable response to sulphur-containing treatments is consistent with Walia *et al.* (2021), who reported improved groundnut pod yield with sulphur fertilisation, thereby demonstrating the importance of adequate S nutrition for groundnut productivity.

3.2.3 Kernel Yield (kg ha^{-1})

Kernel yield followed a pattern similar to pod yield and differed significantly among treatments. T7 recorded the highest pooled kernel yield ($1970.7 \text{ kg ha}^{-1}$) and was statistically at par with T6 ($1872.6 \text{ kg ha}^{-1}$) and T13 ($1773.7 \text{ kg ha}^{-1}$), with a pooled CD of $321.16 \text{ kg ha}^{-1}$. The control recorded the lowest kernel yield (869.2 kg ha^{-1}).

Greater kernel yield under the integrated treatments may reflect the combined effects of improved crop growth, pod production and assimilate supply during kernel development. Biochar can support nutrient and moisture availability, whereas sulphur contributes to amino-acid and protein synthesis and related metabolic processes (Rao *et al.*, 2013). Together with RDF, these inputs may have maintained a more balanced nutrient supply during reproductive growth, thereby supporting kernel formation and filling.

3.3 Quality Parameters

3.3.1 Protein Content (%)

The protein content of groundnut kernels was not significantly influenced by the treatments during either season or in the pooled analysis (Table 3). Nevertheless, numerical variation was observed. Pooled protein content ranged from 25.37% in the control to 26.23% in T7. The highest numerical value in T7 was closely followed by T13 (26.21%), T12 (26.14%) and T6 (26.12%). Because the treatment effect was non-significant, these differences should be interpreted as numerical trends rather than confirmed treatment responses.

The small numerical increase in protein content in treatments receiving sulphur with biochar and RDF could reflect the physiological role of sulphur in the formation of cysteine and methionine and its close association with nitrogen metabolism and protein synthesis (Rao *et al.*, 2013). However, the absence of statistical significance indicates that kernel protein concentration was relatively stable across the nutrient-management treatments under the conditions of this study.

3.3.2 Oil Content (%)

Pooled oil content ranged from 44.23 to 48.55%, and the treatment differences were not statistically significant. T7 recorded the highest numerical oil content (48.55%), followed by T6 (48.28%) and T5 (48.23%), whereas the control recorded the lowest value (44.23%). Among treatments receiving 75% RDF, T13 recorded 47.77% oil. These differences represent numerical trends only.

Sulphur participates in several enzymatic and metabolic processes associated with oilseed growth and quality, and adequate sulphur nutrition has been reported to influence oil content in oilseed crops (Kumar *et al.*, 2011). Aswini *et al.* (2024) also reported that sulphur nutrition, in combination with nitrogen management, influenced groundnut yield and oil content, indicating the importance of balanced N and S nutrition in determining groundnut productivity and kernel quality. Biochar may indirectly influence kernel composition through changes in soil moisture and nutrient availability. Nevertheless, because oil content did not differ significantly among treatments, the present data do not demonstrate a statistically confirmed treatment effect on oil concentration.

3.3.3 Oleic Acid Content (%)

Oleic acid content was also not significantly affected by nutrient-management treatments. Pooled values ranged from 43.79% in the control to 46.17% in T7. The highest numerical value in T7 was closely followed by T6 (46.16%) and T13 (45.73%). The relatively narrow variation in oleic acid concentration suggests that fatty-acid composition was less responsive to nutrient management than crop growth and yield. Although treatments receiving biochar and sulphur showed slightly higher numerical values in some cases, the non-significant treatment effect indicates that these differences should not be interpreted as confirmed changes in fatty-acid composition.

Table 1. Effect of integrated application of biochar, sulphur and recommended fertilizer on dry matter production of groundnut (kg ha⁻¹)

Treatments	30 DAS			60 DAS			90 DAS		
	2024–25	2025–26	Pooled	2024–25	2025–26	Pooled	2024–25	2025–26	Pooled
T ₁ – Control	1692.0	2153.6	1922.8	3236.3	3662.7	3449.5	3843.0	4276.7	4059.9
T ₂ - 100% RDF	2134.9	2506.3	2320.6	3582.7	4053.7	3818.2	4177.5	4598.9	4388.2
T ₃ - 100% RDF + 40 kg S ha ⁻¹	2226.2	2667.3	2446.8	3648.7	4015.7	3832.2	4277.3	4629.7	4453.5
T ₄ - 100% RDF + biochar @ 2 t ha ⁻¹	2308.1	2664.1	2486.1	3703.7	4142.7	3923.2	4384.1	4790.9	4587.5
T ₅ - 100% RDF + biochar @ 4 t ha ⁻¹	2426.4	2740.1	2583.3	3753.2	4156.0	3954.6	4495.3	4847.7	4671.5
T ₆ - 100% RDF + biochar @ 2 t ha ⁻¹ + 40 kg S ha ⁻¹	2473.3	3082.7	2778.0	4040.2	4443.0	4241.6	4609.1	5057.1	4833.1
T ₇ - 100% RDF + biochar @ 4 t ha ⁻¹ + 40 kg S ha ⁻¹	2801.8	3151.3	2976.6	4260.5	4663.3	4461.9	4952.0	5277.4	5114.7
T ₈ - 75% RDF	2040.0	2396.0	2218.0	3481.6	3916.0	3698.8	4144.2	4496.6	4320.4
T ₉ - 75% RDF + 40 kg S ha ⁻¹	1983.0	2339.0	2161.0	3497.5	3900.3	3698.9	4228.8	4514.4	4371.6
T ₁₀ - 75% RDF + biochar @ 2 t ha ⁻¹	1974.7	2330.7	2152.7	3583.2	3986.0	3784.6	4262.8	4600.1	4431.4
T ₁₁ - 75% RDF + biochar @ 4 t ha ⁻¹	2082.2	2417.0	2249.6	3676.9	4079.7	3878.3	4341.4	4693.7	4517.5
T ₁₂ - 75% RDF + biochar @ 2 t ha ⁻¹ + 40 kg S ha ⁻¹	2347.4	2752.3	2549.9	3785.7	4097.7	3941.7	4428.7	4712.0	4570.4
T ₁₃ - 75% RDF + biochar @ 4 t ha ⁻¹ + 40 kg S ha ⁻¹	2538.2	2929.0	2733.6	4010.2	4413.0	4211.6	4656.1	4995.5	4825.8
SEm±	109.9	114.5	106.94	159.6	161.40	159.61	149.4	169.34	156.94
SE(d)±	155.5	162.0	151.24	225.7	228.25	225.72	211.3	239.48	221.95
CD (P = 0.05)	320.9	334.3	312.15	465.8	471.08	465.87	436.0	494.27	458.08
CV (%)	8.5	7.6	7.70	7.45	6.79	7.06	5.92	6.20	5.97

Table 2. Effect of integrated application of biochar, sulphur and recommended fertilizer on haulm, pod and kernel yield of groundnut (kg ha⁻¹)

Treatments	Haulm Yield (kg ha ⁻¹)			Pod Yield (kg ha ⁻¹)			Kernel Yield (kg ha ⁻¹)		
	2024–25	2025–26	Pooled	2024–25	2025–26	Pooled	2024–25	2025–26	Pooled
T ₁ – Control	2528.5	2848.7	2688.6	1690.2	2001.0	1845.6	789.1	949.3	869.2
T ₂ - 100% RDF	3066.4	3353.3	3209.9	2225.1	2512.0	2368.6	1247.6	1493.7	1370.6
T ₃ - 100% RDF + 40 kg S ha ⁻¹	3130.4	3417.3	3273.9	2255.8	2631.7	2443.7	1334.1	1613.3	1473.7
T ₄ - 100% RDF + biochar @ 2 t ha ⁻¹	3142.7	3429.7	3286.2	2360.4	2647.3	2503.9	1361.2	1629.0	1495.1
T ₅ - 100% RDF + biochar @ 4 t ha ⁻¹	3152.8	3439.7	3296.2	2370.4	2657.3	2513.9	1426.4	1639.0	1532.7
T ₆ - 100% RDF + biochar @ 2 t ha ⁻¹ + 40 kg S ha ⁻¹	3469.1	3756.0	3612.6	2721.7	2967.3	2844.5	1782.9	1962.3	1872.6
T ₇ - 100% RDF + biochar @ 4 t ha ⁻¹ + 40 kg S ha ⁻¹	3599.8	3886.7	3743.2	2795.1	3082.0	2938.6	1864.4	2077.0	1970.7
T ₈ - 75% RDF	2967.0	3287.3	3127.2	2077.9	2416.0	2247.0	1185.1	1397.7	1291.4
T ₉ - 75% RDF + 40 kg S ha ⁻¹	3025.8	3312.7	3169.2	2226.7	2595.3	2411.0	1390.6	1577.0	1483.8
T ₁₀ - 75% RDF + biochar @ 2 t ha ⁻¹	3031.8	3318.7	3175.2	2288.1	2575.0	2431.6	1387.3	1556.7	1472.0
T ₁₁ - 75% RDF + biochar @ 4 t ha ⁻¹	3105.6	3354.3	3230.0	2317.6	2551.3	2434.5	1441.0	1533.0	1487.0
T ₁₂ - 75% RDF + biochar @ 2 t ha ⁻¹ + 40 kg S ha ⁻¹	3160.4	3447.3	3303.9	2354.4	2641.3	2497.9	1501.8	1623.0	1562.4
T ₁₃ - 75% RDF + biochar @ 4 t ha ⁻¹ + 40 kg S ha ⁻¹	3301.7	3588.7	3445.2	2578.1	2865.0	2721.5	1667.4	1880.0	1773.7
SEm±	140.8	142.6	141.46	117.7	137.4	125.74	98.8	125.4	110.03
SE(d)±	199.1	201.6	200.06	166.4	194.3	177.83	139.7	177.3	155.61
CD (P = 0.05)	411.0	416.2	412.91	343.5	401.0	367.02	288.4	366.0	321.16
CV (%)	7.8	7.2	7.48	8.8	9.1	8.79	12.1	13.5	12.61

Table 3. Effect of integrated application of biochar, sulphur and recommended fertilizer on quality parameters of groundnut (%)

Treatments	Protein Content (%)			Oil Content (%)			Oleic Acid (%)		
	2024–25	2025–26	Pooled	2024–25	2025–26	Pooled	2024–25	2025–26	Pooled
T ₁ – Control	25.29	25.45	25.37	44.40	44.05	44.23	43.76	43.81	43.79
T ₂ - 100% RDF	25.62	26.04	25.83	45.85	46.56	46.21	45.14	45.19	45.17
T ₃ - 100% RDF + 40 kg S ha ⁻¹	25.94	26.10	26.02	46.83	46.91	46.87	45.31	45.36	45.34
T ₄ - 100% RDF + biochar @ 2 t ha ⁻¹	26.03	26.10	26.07	46.94	47.02	46.98	45.32	45.37	45.35
T ₅ - 100% RDF + biochar @ 4 t ha ⁻¹	26.00	26.16	26.08	48.54	47.92	48.23	45.53	45.58	45.56
T ₆ - 100% RDF + biochar @ 2 t ha ⁻¹ + 40 kg S ha ⁻¹	26.04	26.20	26.12	47.93	48.63	48.28	46.06	46.26	46.16
T ₇ - 100% RDF + biochar @ 4 t ha ⁻¹ + 40 kg S ha ⁻¹	26.27	26.19	26.23	48.51	48.59	48.55	46.09	46.25	46.17
T ₈ - 75% RDF	25.28	26.10	25.69	45.33	44.53	44.93	44.52	45.42	44.97
T ₉ - 75% RDF + 40 kg S ha ⁻¹	25.99	26.15	26.07	46.26	46.34	46.30	44.88	44.93	44.91
T ₁₀ - 75% RDF + biochar @ 2 t ha ⁻¹	26.04	26.20	26.12	47.27	47.85	47.56	45.39	45.44	45.42
T ₁₁ - 75% RDF + biochar @ 4 t ha ⁻¹	25.97	26.13	26.05	47.76	47.84	47.80	45.41	45.46	45.44
T ₁₂ - 75% RDF + biochar @ 2 t ha ⁻¹ + 40 kg S ha ⁻¹	26.06	26.22	26.14	47.46	47.54	47.50	44.67	44.72	44.70
T ₁₃ - 75% RDF + biochar @ 4 t ha ⁻¹ + 40 kg S ha ⁻¹	26.13	26.29	26.21	47.73	47.81	47.77	45.70	45.75	45.73
SEm±	0.47	0.55	0.49	1.16	1.35	1.25	0.57	0.53	0.54
SE(d)±	0.66	0.77	0.69	1.65	1.91	1.76	0.81	0.75	0.76
CD (P = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	3.11	3.63	3.24	4.29	4.98	4.59	2.19	2.03	2.06

4. Conclusion

The field experiment conducted over the rabi seasons of 2024–25 and 2025–26 demonstrated significant differences in groundnut growth and yield among the nutrient-management treatments in the studied Alfisol. The combination of 100% recommended fertiliser dose (RDF), biochar at 4 t ha⁻¹ and sulphur at 40 kg ha⁻¹ recorded the highest pooled dry matter accumulation at 30, 60 and 90 days after sowing. The same treatment produced pooled haulm, pod and kernel yields of 3743.2, 2938.6 and 1970.7 kg ha⁻¹, respectively. However, these responses were not significantly different from those obtained with 100% RDF plus biochar at 2 t ha⁻¹ and sulphur at 40 kg ha⁻¹, or 75% RDF plus biochar at 4 t ha⁻¹ and sulphur at 40 kg ha⁻¹. The comparable performance of the latter treatment suggests that combinations involving reduced mineral fertiliser input merit additional evaluation under similar soil conditions. In contrast to the yield responses, treatment effects on kernel protein, oil and oleic acid contents were not statistically significant. Accordingly, the findings support the potential agronomic value of combining biochar and sulphur with RDF for groundnut production, without demonstrating a significant improvement in the measured kernel quality parameters.

5. Limitations

The study was conducted at one location during two consecutive rabi seasons in an Alfisol. Consequently, the observed treatment responses may not represent other soil types or seasonal conditions. Treatment combinations incorporating 75% RDF produced yields statistically comparable with those of selected treatments receiving 100% RDF, but the consistency of this response across production settings remains to be established. The absence of significant differences in kernel protein, oil and oleic acid contents limits interpretation of quality responses. Further field evaluation would help determine the wider applicability of the yield findings.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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