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Integrated effect of fertilizers and biochar on soil fertility status and nutrient uptake of groundnut crop in sandy loam soil

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ABSTRACT

A field investigation was carried out during late *kharif*, 2024 at Agricultural College Farm, Bapatla to study the influence of biochar and fertilizers on groundnut (TAG 24 variety) cultivated in sandy loam soil. The experiment consisted of eight treatments involving combinations of the recommended dose of fertilizers (30: 40: 50 kg N: P2O5: K2O ha^{-1}) and gypsum was applied commonly for all treatments except control, with cotton stalk biochar applied at 2 and 4 t ha^{-1}. The study was designed using a Randomized Block Design (RBD) with three replications. Results showed that the combined application of 100% RDF + biochar @ 4 t ha^{-1} (T6) led to the highest values for dry matter production, yield components, and nutrient uptake. Though nutrient content (N, P, and K) in plant tissues were statistically non- significant, their uptake values were notably higher in integrated treatments. Improvement in crop performance was linked to biochar's superior water holding capacity (128.6 %), organic carbon (79.2%), and porosity (33.87%). Thus integrated nutrient management using biochar and fertilizers enhanced groundnut yield and soil health, providing a promising approach for sustainable cultivation in light-textured soils.

Keywords: *Biochar, Groundnut, Integrated nutrient management. Nutrient uptake, Soil properties and Yield*

Groundnut (*Arachis hypogaea* L.) is one of the most important oilseed crop cultivated in India, especially in semi-arid and arid regions. It serves as a major source of edible oil, protein, and fodder, contributing significantly to both nutritional security and rural livelihoods. However, its productivity is often constrained by the poor fertility status of soils, especially in sandy loam soils like those found in coastal Andhra Pradesh. These soils typically have low water holding capacity, organic matter, and nutrient retention capacity, making groundnut cultivation both input-sensitive and environmentally vulnerable.

Continuous and unbalanced use of chemical fertilizers has further degraded the physical and chemical health of these soils, leading to declining crop responses and inefficiencies in nutrient use. In this context, integrated nutrient management strategies that combine organic amendments with inorganic fertilizers are gaining prominence for their ability to improve soil health and crop yield.

Biochar has emerged as a promising soil amendment in recent years. It is a carbon-rich, porous material produced through fast pyrolysis with the thermal decomposition of organic biomass under limited oxygen supply. The characteristics of biochar depend greatly on the type of feedstock and pyrolysis conditions used.

When applied to soil, biochar can influence a wide range of soil properties. Its porous structure helps improve soil aeration, reduce bulk density, and enhance moisture retention. The surface functional groups on biochar particles contribute to higher cation exchange capacity (CEC), enabling better nutrient retention and reduced leaching losses. Moreover, biochar has a long residence time in soil and is relatively resistant to microbial decomposition, contributing to long-term improvements in soil organic carbon pools and stability.

Several studies have indicated that the synergistic application of biochar with chemical fertilizers can further enhance nutrient uptake and crop yields by improving nutrient use efficiency.

The present field investigation was conducted to assess the integrated effect of fertilizers and cotton stalk biochar on the performance of groundnut (TAG

24 variety) grown in sandy loam soils under late *kharif* conditions. The study aimed to evaluate the changes in soil chemical properties, yield attributes, and nutrient uptake under various combinations of fertilizer and biochar, to identify the most effective treatment for improving groundnut productivity sustainably.

MATERIAL AND METHODS

A field experiment entitled "Integrated effect of fertilizers and biochar on performance of groundnut" was conducted during the late *kharif* season of 2024 at the Agricultural College Farm, Bapatla, to evaluate the impact of biochar and fertilizer integration on groundnut productivity and soil health. The experimental site falls under the Krishna Godavari agro- climatic zone and is characterized by sandy loam soil (77.0% sand, 6.7% silt, 16.3% clay), slightly acidic (pH 6.93), non-saline (EC 0.35 dS m^{-1}), with low oxidisable (labile) organic carbon (0.35%), medium organic carbon (0.69%), and cation exchange capacity (14.0 cmol (Pz) kg^{-1}), available nitrogen (140 kg ha^{-1}), available phosphorus P_2O_5 (17.4 kg ha^{-1}), available potassium K_2O (197 kg ha^{-1}), available sulphur (15.0 mg kg^{-1}), calcium (0.15 meq/100g), magnesium (0.08 meq/100g), copper (1.74 mg kg^{-1}), manganese (13.7 mg kg^{-1}), iron (16.8 mg kg^{-1}) and zinc (0.62 mg kg^{-1}). The test crop used was groundnut (TAG 24 variety), and the experiment was laid out in a Randomized Block Design (RBD) with eight treatments replicated three times.

The treatments were: T_1 - Control (no fertilizer or biochar); T_2 - 100% RDF (30: 40: 50 kg N: P2O5: K2O ha^{-1}); T_3 - Biochar @ 2 t ha^{-1}; T_4 - Biochar @ 4 t ha^{-1}; T_5 - 100% RDF + Biochar @ 2 t ha^{-1}; T_6 - 100% RDF + Biochar @ 4 t ha^{-1}; T_7 - 75% RDF + Biochar @ 2 t ha^{-1}; T_8 - 75% RDF + Biochar @ 4 t ha^{-1}. Cotton stalk biochar was produced via slow pyrolysis at 350-400°C under limited oxygen and was applied to the soil one week before sowing. The biochar had the following properties: bulk density- 0.41g cm^{-3}, pore space- 33.87%, pH- 8.6, EC- 0.78 dS m^{-1}, organic carbon- 79.2%, nitrogen- 0.29%, phosphorus- 0.27%, potassium-1.1%, water holding capacity-128.6 %, and conversion efficiency- 38.5%. Nutrients were supplied through urea (N), single super phosphate (P), and muriate of potash (K), applied according to the treatment schedule.

Soil samples were collected before sowing and after harvest to analyze soil macronutrients such as available nitrogen, phosphorus, potassium, sulphur, calcium, magnesium, micronutrients such as copper, manganese, iron, zinc and nutrient uptake . Crop observations at harvest included haulm yield, pod yield, kernel yield, shelling percentage and 100 kernel weight. The data were analyzed using analysis of variance (ANOVA), and treatment means were compared at the 5% level of significance. Standard statistical methods were employed to compute the Critical Difference (CD), Standard Error of Mean (SEm), and Coefficient of Variation (CV%), ensuring scientific reliability.

RESULTS AND DISCUSSION

Soil available nitrogen

The integrated effect of fertilizers and biochar on soil available nitrogen is presented in Table 1. A significant difference was observed among treatments, with the highest available nitrogen content (150 kg ha^{-1}) recorded in T_6 (100% RDF + biochar @ 4 t ha^{-1}) and the lowest (102 kg ha^{-1}) in the control (T_1). This indicates a 39.2% increase in nitrogen availability over the control. In comparison to T_2 (100% RDF - 126 kg ha^{-1}), T_6 showed a 17.3% improvement, highlighting the added benefit of incorporated biochar with fertilizer.

The combined application of biochar and RDF significantly enhanced soil nitrogen availability compared to either of the inputs used alone. While biochar itself is not a direct source of nitrogen, its porous structure and high surface area act as a microhabitat that retains added nitrogen fertilizers. This helps reduce nutrient losses through leaching and volatilization, and supports a gradual release of nitrogen throughout the crop growth period.

These results emphasize that integrating biochar with nitrogenous fertilizers enhances nutrient retention, improves nitrogen use efficiency, and contributes to sustained soil fertility for better crop productivity.

The improved nitrogen availability observed in integrated treatments might be due to biochar's interaction with soil microbial and chemical processes. This enhancement in nitrogen dynamics is supported by the findings of Nelissen *et al*. (2012), who attributed the increase in nitrogen content with biochar addition to an enhanced nitrification rate. This occurs because biochar can adsorb potential nitrification inhibitors such as monoterpenes and various

Table 1. Integrated effect of fertilizers and biochar on soil available nitrogen, phosphorus and potassium in groundnut crop

Treatments	N (kg ha^{-1})	P2O5 (kg ha^{-1})	K_2O (kg ha^{-1})
T_1 - Control	102	15.6	194
T_2 - 100% RDF (30-40-50)	126	22.1	269
T_3 - Biochar @ 2t ha^{-1}	112	19.5	258
T_4 - Biochar @ 4t ha^{-1}	115	20.8	261
T_5 - 100% RDF + Biochar @ 2t ha^{-1}	142	25.6	281
T_6 - 100% RDF + Biochar @ 4t ha^{-1}	150	27.7	310
T_7 - 75% RDF + Biochar @ 2t ha^{-1}	136	24.1	272
T_8 - 75% RDF + Biochar @ 4t ha^{-1}	139	24.7	279
SEm ±	7.01	1.77	12.8
CD @0.05	7.01	5.36	38.8
CV%	21.3	13.6	8.35

polyphenolic compounds, thereby promoting microbial activity involved in nitrogen transformations. Similarly, Shen *et al.* (2016) reported that the application of biochar enhanced soil nitrogen availability to plants. This effect is believed to result from biochar's role as a soil conditioner, which modifies the soil's chemical and microbial properties in a favourable manner. By protecting nitrogen from leaching and volatilization losses, biochar ultimately contributes to increased nitrogen availability for plant uptake.

Soil available phosphorus

The data presented in Table 1. indicated at the harvest, a significant increase in available phosphorus was observed in treatments that received both biochar and fertilizers (T_5, T_6, T_7, and T_8), compared to treatments with either of the inputs alone (T_2, T_3, T_4). Among these, the highest available phosphorus content (27.7 kg ha^{-1}) was recorded in T_6 (100% RDF + biochar @ 4 t ha^{-1}), which was statistically on par with T_5 (25.6 kg ha^{-1}), T_8 (24.7 kg ha^{-1}), and T_7 (24.1 kg ha^{-1}). Treatment T_6 exhibited a 77.6% increase over T_1 (Control: 15.6 kg ha^{-1}) and a 25.3% increase over T_2 (100% RDF: 22.1 kg ha^{-1}), clearly indicating the positive impact of biochar when combined with fertilizers.

The substantial improvement in available soil phosphorus can be attributed to the synergistic interaction between biochar and fertilizer, where biochar enhanced the retention and mobility of phosphorus in soil. The application of biochar has lead to an increased in soil pH, which in turn increases the negative charge on soil colloids. This reduced phosphate sorption and enhanced the presence of free phosphorus in the soil solution (Mukherjee *et al.,* 2013). Moreover, biochar improves microbial activity, promoting the mineralization of phosphorus into plant-available forms (Opala *et al.,* 2012). Husien *et al.* (2017) further noted that in acidic soils, biochar application improved soil reaction and increased the mobility of phosphate ions, contributing to greater phosphorus availability.

Soil available potassium

The data presented in Table 1. reveald a marked improvement in the availability of potassium in soil when biochar was applied in combination with inorganic fertilizers. Among the treatments, T_6 (100% RDF + biochar @ 4 t ha^{-1}) recorded the highest available potassium content of 310 kg ha^{-1}, which was statistically on par with T_5 (281 kg ha^{-1}), T_8 (279 kg ha^{-1}), and T_7 (272 kg ha^{-1}). The treatments T_5, T_6, T_7 and T_8 outperformed both the control and fertilizer-only treatments, demonstrating the positive synergistic effect of biochar when integrated with fertilizers. The lowest value (194 kg ha^{-1}) was observed in T_1 (control), indicating the limited potassium availability in untreated soil.

The application of 100% RDF alone (T_2) resulted in 269 kg ha^{-1} of available soil which was notably lower than the values obtained in combined treatments. Specifically, T_6 showed a 59.8 percent increase over T_1 (Control) and a 15.2 percent increase over T_2 (100% RDF alone). This clearly illustrates that the mineral fertilizers contribute to available potassium, while the addition of biochar further amplifies the effect by improving potassium retention and supply in the soil throughout the crop growth period.

The higher potassium availability in the treatments that received both biochar and fertilizers can be attributed to the direct supply of potassium through MOP (Muriate of potash) and the additional contribution from biochar itself. Biochar contains ash rich in potassium, which becomes available in soil upon application. Moreover, the enhanced retention of potassium can be linked to the high cation exchange capacity of biochar, which helps electrostatically attract and hold potassium ions. This effect is further supported by the presence of carbonate and carboxylate functional groups in biochar that assist in nutrient retention. These findings are in agreement with Bindu *et al.* (2016), who reported that biochar improved potassium retention in soil by enhancing the soil's capacity to retain exchangeable cations like Kz .

Soil available sulphur

The data presented in Table 2 revealed a significant variation in available sulphur among the treatments, particularly in plots that received a combined application of fertilizers and biochar. The highest available sulphur content was recorded in T_6 (100% RDF + biochar @ 4 t ha^{-1}) with 14.9 mg kg^{-1}, followed closely by T_5 (100% RDF + biochar @ 2 t ha^{-1}) at 14.2 mg kg^{-1}. These values were statistically superior to the T_2 treatment that received fertilizer only (12.0 mg kg^{-1}) and biochar-only treatments. In contrast, the lowest sulphur content of 10.2 mg kg^{-1} was observed in T_1 (Control).

The combined treatment T_6 showed a 46.1 percent increase over the control (T_1) and a 24.1 percent increase over T_2 (100% RDF), clearly demonstrating the positive interaction between biochar and fertilizers in enhancing sulphur availability. The increased sulphur levels in these treatments may be attributed to the direct contribution from mineral fertilizers such as single super phosphate (SSP) and to the application of gypsum @ 500 kg ha^{-1} as part of standard crop management.

Additionally, the improvement in available sulphur can be linked to the mineralisation of sulphur-bearing organic fractions within biochar. This is supported by Cheah *et al.* (2014), who observed through SEM-EDS (Scanning Electron Microscope – Energy Dispersive X-ray Spectroscopy) analysis that sulphur was distributed across the organic structure of corn stover biochar, which upon application and decomposition, contributes to soil sulphur availability.

Soil calcium content

The data presented in Table 2. showed that the application of fertilizers and biochar significantly influenced the availability of calcium in soil at the

Table 2.Integrated effect of fertilizers and biochar on soil available sulphur, calcium and magnesium in groundnut crop

Treatments	S (mg kg^{-1})	Ca (cmol (P+) kg^{-1})	Mg (cmol (P+) kg^{-1})
T_1 - Control	10.2	1.28	0.41
T_2 - 100% RDF (30-40-50)	12	1.36	0.44
T_3 - Biochar @ 2t ha^{-1}	10.7	1.42	0.47
T_4 - Biochar @ 4t ha^{-1}	11.1	1.48	0.5
T_5 - 100% RDF + Biochar @ 2t ha^{-1}	14.2	1.42	0.56
T_6 - 100% RDF + Biochar @ 4t ha^{-1}	14.9	1.8	0.65
T_7 - 75% RDF + Biochar @ 2t ha^{-1}	13.6	1.54	0.52
T_8 - 75% RDF + Biochar @ 4t ha^{-1}	13.9	1.6	0.54
SEm ±	0.43	0.06	0.04
CD @0.05	1.3	0.17	0.12
CV%	5.9	6.52	12.9

harvest stage of groundnut. The maximum calcium content was observed in T_6 (100% RDF + Biochar @ 4t ha^{-1}) with 1.80 cmol (Pz) kg^{-1}, followed by T_8 (1.60 cmol Pz kg^{-1}), T_7 (1.54 cmol Pz kg^{-1}), and T_5 (1.42 cmol Pz kg^{-1}). The lowest value was noted in T_1 (Control) with 1.28 cmol (Pz) kg^{-1}.

Application of biochar 4t ha^{-1} in combination with 100% RDF (T_6) exhibited a 40.6% increase, over control and 32.3% over T_2 which received only 100% RDF, highlighting the beneficial effect of integrating biochar with fertilizers over either amendment alone.

The enhanced calcium availability may be attributed to multiple synergistic factors. Biochar improves soil structure and increases surface area, thus enhancing the soil's capacity to retain and exchange cations like Ca^{2+}. Moreover, the presence of gypsum (Applied @ 500 kg ha^{-1}) as a general crop management practice provided a direct source of calcium, which displaced sodium and other monovalent cations from exchange sites, promoting better soil aggregation and nutrient retention.

These findings align with those of Laghari *et al.* (2015), who reported a significant increase in total calcium content in sandy soils upon biochar application. Similarly, Yusof *et al.* (2015) demonstrated that combined application of poultry manure and biochar considerably increased calcium content in sandy clay loam soils, reinforcing the role of biochar in enhancing exchangeable calcium levels.

Soil available magnesium

The data presented in table 2 shows that the application of fertilizers in combination with biochar significantly influenced the availability of magnesium in the soil at the harvest stage of the groundnut crop. The highest available magnesium content was recorded in T_6 (100% RDF + Biochar @ 4 t ha^{-1}) with 0.65 cmol (Pz) kg^{-1}, whereas the lowest value was observed in T_1 (Control) with 0.41 cmol (Pz) kg^{-1}. Compared to the control, T_6 recorded an increase of 58.5 percent, while in comparison to T_2 (100% RDF alone; 0.44 cmol (Pz) kg^{-1}), the increase was about 47.7 percent, clearly reflecting the positive impact of integrating biochar with fertilizers. Other treatments such as T_8 (0.54 cmol Pz kg^{-1}) and T_7 (0.52 cmol Pz kg^{-1}) also recorded statistically higher values than T_2, indicating the synergistic effect of biochar even at lower RDF levels.

The improved magnesium content in biochar-treated plots may be attributed to the enhancement of cation exchange capacity (CEC) by biochar, which helps retain cations like Mg^{2+} in the root zone, especially in light textured soils prone to leaching. Moreover, RDF indirectly supports better root growth and nutrient uptake, contributing to increased magnesium cycling and retention. A significant increase in available magnesium was observed in the biochar and fertilizer-applied treatments compared to the control. The improvement in T_6 and T_8 can be attributed to the enhanced nutrient retention due to the porous nature and cation exchange capacity of biochar. This might have reduced leaching losses and increased the retention of Mg^{2+} ions. Similar trends were observed by Zhang *et al.* (2012), who reported better availability of base cations with biochar addition, and by Major *et al.* (2010), who noted that the mineral ash content of biochar contributed to increased magnesium levels in the soil.

Soil available micronutrients

The results obtained on integrated effect of fertilizers and biochar on soil available micronutrients are presented in the table 3 which indicated that there was no significant influence of biochar on available Zn, Fe, Mn and Cu at harvest stage.

Available zinc

The data in the table 3. showed no significant influence of biochar on available zinc but with slightly decreased values of zinc with biochar application was found. The highest value recorded (0.69 mg kg^{-1}) in T_2 (100 % RDF) and lowest (0.50 mg kg^{-1}) in T_6 (100% RDF + Biochar @ 4t ha^{-1}) The soil available Zn content did not differ significantly among treatments at harvest.

With the addition of biochar slight reduction in soil available zinc was observed due to sorption of zinc to the biochar which form stable complex because of recalcitrant nature of biochar. Jun and Xu (2013) also reported the decreased available zinc by incorporation of biochar due to immobilization of zinc in the soil.

Available iron

Addition of biochar did not significantly influence the available iron in the soil. Marginal reduction of available iron with increased rates of

Table 3. Integrated effect of fertilizers and biochar on soil micro nutrients in groundnut crop

Micro nutrients (mg kg^{-1})				
Treatments	**Zn**	**Fe**	**Mn**	**Cu**
T_1 - Control	0.59	15.2	12.2	1.12
T_2 - 100% RDF (30-40-50)	0.69	16.8	13.9	1.33
T_3 - Biochar @ 2t ha^{-1}	0.56	13.5	11.6	1.17
T_4 - Biochar @ 4t ha^{-1}	0.56	14.4	9.96	1.12
T_5 - 100% RDF + Biochar @ 2t ha^{-1}	0.59	12.4	10.6	1.17
T_6 - 100% RDF + Biochar @ 4t ha^{-1}	0.5	12.2	10.4	1.04
T_7 - 75% RDF + Biochar @ 2t ha^{-1}	0.53	13.1	8.82	1.05
T_8 - 75% RDF + Biochar @ 4t ha^{-1}	0.53	12.6	10.7	1.01
SEm ±	0.04	0.97	0.93	0.06
CD @0.05	NS	NS	NS	NS
CV%	10.7	12.2	14.6	9.46

biochar application was found among treatments data in table 3. Relatively high soil available Fe (16.8 mg kg^{-1}) in T_2 (100% RDF) and lowest (12.2 mg kg^{-1}) in T_6 (100% RDF + Biochar @ 4t ha^{-1}) at harvest.

Available manganese

The data in Table 3. indicated that the application of biochar does not influence significantly on soil available manganese, however it showed a decreasing trend between the treatments at harvest. The highest available manganese (13.9 mg kg^{-1}) was observed in T_2 (100% RDF) and lowest (8.82 mg kg^{-1}) in T_7 (75% RDF + biochar @ 2t ha^{-1}). Decrease of available manganese was noticed in biochar applied plots, which could be due to the surface adsorption of manganese by biochar (Masto *et al.,* 2013).

Available copper

The available copper in soil decreased at harvest stage of groundnut. Lower soil available copper (1.01 mg kg^{-1}) was observed in T_8 treatment (75% RDF+ biochar@ 4 t ha^{-1}) and higher soil available Cu (1.33 mg kg^{-1}) was found in T_2 treatment (100% RDF) at harvest, with increasing rates of biochar application (2 t ha^{-1} & 4 t ha^{-1}) but non-significant reduction in soil available copper was observed.

There was no significant variation observed in soil available copper content among the treatments. This lack of response could be due to the immobilization of copper in the soil following biochar incorporation. Such behaviour aligns with the possibility that biochar may reduce the mobility of certain micronutrients like copper. Observations similar to this were also noted in previous studies, where no significant effect on available copper was reported (Namgay *et al.,* 2010), and reduced mobility of copper due to immobilization mechanisms suggested (Jun and Xu, 2013).

EFFECT OF BIOCHAR ON NUTRIENT UPTAKE

Nitrogen uptake

A significant variation in nitrogen uptake by groundnut was observed among the treatments involving inorganic fertilizers and biochar application (Table 4.). The maximum nitrogen uptake at harvest was recorded in treatment T_6 (100% RDF + biochar @ 4 t ha^{-1}), with values of 23.5/ kg/ ha^{-1} in haulm + shell and 45.9/ kg/ ha^{-1} in kernel. This was statistically on par with T_5 treatment (100% RDF + biochar @ 2 t ha^{-1}), which recorded 22.4/ kg/ ha^{-1} in haulm + shell and 44.3/ kg/ ha^{-1} in kernel.

An increase of 56.7 percent of haulm + shell and 54.5 pecent of kernel was observed in T_6 treatment when compared to T_1. The enhanced nitrogen uptake in the treatments receiving biochar and fertilizers can be attributed to the immediate availability of nitrogen from inorganic sources combined with the role of biochar in stimulating mineralization and improving

Table 4.Integrated effect of fertilizers and biochar on nitrogen uptake of groundnut

Treatments	N uptake from Haulm+Shell (kg ha^{-1})	N uptake from Kernel (kg ha-1)
T_1 - Control	15	29.7
T_2 - 100% RDF (30-40-50)	19.8	39.5
T_3 - Biochar @ 2t ha^{-1}	17.9	34.9
T_4 - Biochar @ 4t ha^{-1}	18.3	35.6
T_5 - 100% RDF + Biochar @ 2t ha^{-1}	22.4	44.3
T_6 - 100% RDF + Biochar @ 4t ha^{-1}	23.5	45.9
T_7 - 75% RDF + Biochar @ 2t ha^{-1}	21	39.7
T_8 - 75% RDF + Biochar @ 4t ha^{-1}	21.4	41.8
SEm ±	1.1	3.38
CD @0.05	3.33	10.2
CV%	9.54	7.14

nitrogen retention. Biochar's porous structure also enhances microbial activity, supporting better nutrient cycling and availability. Biochar improves nitrogen retention and reduces leaching losses, while also promoting microbial activity that enhances decomposition and nutrient cycling (Lehmann *et al.*, 2015; Xu *et al.,* 2016). Moreover, biochar's porous structure may facilitate biological nitrogen fixation (BNF) and support a more sustained nitrogen supply to crops throughout the growing season (Mukherjee and Lal, 2014).

Phosphorus uptake

Phosphorus uptake by the groundnut crop exhibited significant variation among treatments (Table 5). The maximum uptake was recorded in T_6 (100% RDF + biochar @ 4 t ha^{-1}), with 3.91 kg/ ha^{-1} in haulm + shell and 12.5 kg/ ha^{-1} in kernel. The lowest uptake was observed in T_1 (Control), with 2.19/ kg/ ha^{-1} and 8.06/ kg/ ha^{-1}, respectively. Compared to the control, treatment T_6 showed an increase of 78.5 % in haulm + shell phosphorus uptake and 55.1 % in kernel phosphorus uptake.

Table 5. Integrated effect of fertilizers and biochar on phosphorus uptake of groundnut

Treatments	P uptake from Haulm+Shell (kg ha^{-1})	P uptake from Kernel (kg ha^{-1})
T_1 - Control	2.19	8.06
T_2 - 100% RDF (30-40-50)	3.03	10
T_3 - Biochar @ 2t ha^{-1}	2.61	9.15
T_4 - Biochar @ 4t ha^{-1}	2.82	9.58
T_5 - 100% RDF + Biochar @ 2t ha^{-1}	3.56	11.8
T_6 - 100% RDF + Biochar @ 4t ha^{-1}	3.91	12.5
T_7 - 75% RDF + Biochar @ 2t ha^{-1}	3.44	10.5
T_8 - 75% RDF + Biochar @ 4t ha^{-1}	3.47	11.7
SEm ±	0.3	0.56
CD @0.05	0.92	1.69
CV%	15.5	8.48

Potassium uptake

The uptake of potassium by the groundnut crop was markedly influenced by the application of fertilizers and biochar (Table 6). The highest uptake was observed in T_6 (100% RDF + biochar @ 4 t ha^{-1}), recording 29.5 kg ha^{-1} in haulm + shell and 48.8 kg ha^{-1} in kernel, followed closely by T_5, with values of 27.3 and 47.4 kg ha^{-1}, respectively. In contrast, the control (T_1) exhibited the lowest uptake of potassium, with 17.5 kg ha{ ¹ in haulm + shell and 30.0 kg ha^{-1} in kernel. This represents a 68.57 percent increase in haulm + shell uptake and 62.67 percent increase in kernel uptake when T_6 is compared to T_1. The significant enhancement in potassium uptake in integrated treatments is likely due to the contribution of biochar's native potassium content, improved soil cation exchange capacity, and its ability to reduce nutrient leaching losses. Biochar also enhances nutrient retention in the rhizosphere by increasing soil buffering capacity and providing exchange sites (Laird *et al.,* 2010). The alkaline nature and ash content of biochar further facilitate potassium solubility and root accessibility (Yusof *et al.,* 2015). Moreover, biochar-amended soils have been shown to retain more exchangeable Kz ions, thus supporting continuous plant uptake across growth stages, as demonstrated by Uzoma *et al.* (2011) and Sohi *et al.* (2010).

The enhancement in p uptake can be explained by the dual benefit of immediate phosphorus supply from fertilizers and the role of biochar in improving phosphorus availability. The addition of biochar reduced P contribution in the soil and improved its availability, which led to higher uptake. Supporting this, Yeboah *et al.,* (2017) revealed that biochar application enhanced phosphorus uptake in maize by increasing microbial activity and reducing fixation. Similarly, Sharma *et al.,* (2020) observed improved phosphorus uptake in groundnut with biochar and inorganic fertilizers. The porous structure and high surface area of biochar also promoted root proliferation and nutrient interception zones, as described by Glaser *et al.,* (2002), facilitating efficient phosphorus absorption. Integrated effect of fertilizers and biochar on drymatter accumulation and yield parameters of groundnut

Haulm yield

The data in Table 7. shows a clear enhancement in groundnut haulm yield with integrated nutrient management practices. The highest haulm yield (2.06 t ha^{-1}) was recorded in a treatment T6 (100% RDF + biochar @ 4 t ha^{-1}), which was statistically on par with T5 (1.98 t ha^{-1}), T8 (1.93 t ha^{-1}) and T7 (1.91 t ha^{-1}). In contrast, the lowest

Table 6. Integrated effect of fertilizers and biochar on potassium uptake of groundnu

Treatments	K uptake from Haulm+Shell (kg ha^{-1})	K uptake from Kernel (kg ha^{-1})
T_1 - Control	17.5	30
T_2 - 100% RDF (30-40-50)	23.5	40.9
T_3 - Biochar @ 2t ha^{-1}	22.1	37.6
T_4 - Biochar @ 4t ha^{-1}	22.7	38.6
T_5 - 100% RDF + Biochar @ 2t ha^{-1}	27.3	47.4
T_6 - 100% RDF + Biochar @ 4t ha^{-1}	29.5	48.8
T_7 - 75% RDF + Biochar @ 2t ha^{-1}	25.8	42.2
T_8 - 75% RDF + Biochar @ 4t ha^{-1}	26.8	45.2
SEm ±	1.43	2.45
CD @0.05	4.33	7.42
CV%	10.11	10.2

yield (1.46 t ha^{-1}) was observed in T1 (Control), and T2 treatment 100% RDF alone (1.78 t ha^{-1}), both being significantly inferior to T6. When compared to the control, T6 treatment showed a 41.1percent increase in haulm yield, and even over T2, the increase was 15.7percent , highlighting the synergistic effect of biochar and RDF in promoting vegetative biomass. This improvement could be due to better nutrient availability, enhanced soil structure, and increased microbial activity associated with biochar application, which likely contributed to improved root growth and nutrient uptake, thus boosting haulm production.

Pod yield

The data in Table 7. clearly indicates that integrated nutrient management involving biochar and RDF had a significant positive effect on groundnut pod yield. The highest yield (4.03 t ha^{-1}) was recorded in T6 treatment (100% RDF + biochar @ 4 t ha^{-1}), which was statistically on par with T5 (3.92 t ha^{-1}), T8 (3.77 t ha^{-1}) and T7 (3.61 t ha^{-1}). In contrast, the lowest yield (2.88 t ha^{-1}) was observed in T1 (Control), while T2 (100% RDF alone) recorded a yield of 3.56 t ha^{-1}, both significantly lower than T6 treatment.

When compared to the control, Treatment T6 recorded a 39.9 percent increase in pod yield, and treatment T2 recorded an increase of 13.2 percent, suggesting a strong synergistic effect of combining biochar with inorganic fertilizers. This improvement can be attributed to enhanced nutrient retention, improved soil structure, and increased microbial activity due to biochar addition, which collectively promoted better crop growth and productivity under T6.

The enhanced availability of soil-bound nutrients through chelation and their uptake by the plants was the cause of the rise in pod and haulm yield following the addition of biochar. The enhanced ability of the biochar-treated soils to retain water and nutrients may be the cause of the increase in peanut output (Agegnehu *et al.,* 2016).

Kernel yield

The kernel yield data presented in Table 7. showed a marked improvement under integrated treatments involving biochar and fertilizers. The highest kernel yield (2.99 t ha^{-1}) was obtained in treatment T6 (100% RDF + biochar @ 4 t ha^{-1}), which was statistically on par with T5 (2.85 t ha^{-1}), T8 (2.82 t ha^{-1}), and T7 (2.61 t ha^{-1}) treatment. The lowest yield (1.98 t ha^{-1}) was recorded in treatment T1 (Control), while treatment T2 (100% RDF) yielded 2.54 t ha^{-1}.

An increase of 51percent of kernel yield was observed in T6 treatment when compared to control (T1), clearly indicating that the combined application of biochar and inorganic fertilizers had a synergistic effect on yield improvement. This may be attributed to enhanced nutrient uptake efficiency, better root development, and improved microbial activity stimulated by the porous structure and organic carbon content of biochar. These findings were consistent with earlier reports, where a biochar dose of 10 t ha^{-1} along with NPK significantly enhanced rice grain yield from 4.32 t ha^{-1} (Control) to 6.79 t ha^{-1} (Zaitun *et al.,* 2011), suggesting similar mechanism.

Table 7. Integrated effect of fertilizers and biochar on yield parameters of groundnut

Treatments	Haulm yield (t/ha)	Pod yield (t/ha)	Kernal yield (t/ha)	Shelling (%)	100 kernal weight (g)
T1 - Control	1.46	2.88	1.98	68.7	36.8
T2 - 100% RDF (30-40-50)	1.78	3.56	2.54	71.3	43.2
T3 - Biochar @ 2t ha^{-1}	1.74	3.39	2.42	71.4	40.7
T4 - Biochar @ 4t ha^{-1}	1.76	3.42	2.47	72.2	41.4
T5 - 100% RDF + Biochar @ 2t ha-1	1.98	3.92	2.85	72.7	44.2
T6 - 100% RDF + Biochar @ 4t ha-1	2.06	4.03	2.99	74.2	44.6
T7 - 75% RDF + Biochar @ 2t ha-1	1.91	3.61	2.61	72.3	43.2
T8 - 75% RDF + Biochar @ 4t ha-1	1.93	3.77	2.82	74.8	43.4
SEm ±	0.09	0.15	0.14	2.71	1.53
CD @0.05	0.27	0.45	0.43	NS	NS
CV%	8.56	7.13	9.39	6.5	6.27

Shelling percentage

The data on shelling percentage of groundnut present in Table 7. which indicated that there was no significant difference in shelling percentage with the application of biochar and fertilizers. However slight increase could be noticed at higher application rates of biochar. Highest shelling percentage of 74.2 percent was observed in T6 treatment (100% RDF + biochar @ 4 t ha^{-1}). Lowest shelling percentage of 68.7% was noticed in treatment T1(Control).

100 kernel weight (gm)

The data on 100 kernel weight of groundnut present in Table 7. which revealed that that highest 100 kernel weight of 44.6 g was noticed in treatment T6 (100% RDF + biochar @ 4 t ha^{-1}) and lowest 100 kernel weight of 36.8 g in treatment T1(Control). There was no significant difference in 100 kernel weight among treatments.

CONCLUSION

The study revealed that the integrated application of fertilizers and biochar significantly improved soil nutrient availability, nutrient uptake, and yield of groundnut compared to their individual use. Among the treatments, T_6 (100% RDF + biochar @ 4 t ha^{-1}) recorded the highest values of macronutrients, nutrient uptake, and yield parameters. The improvement is attributed to the synergistic effect of biochar in enhancing nutrient retention, reducing losses, and improving soil properties. However, micronutrients were not significantly influenced. Overall, the combined use of biochar and fertilizers is an effective and sustainable approach for improving soil fertility and maximizing groundnut productivity under sandy loam conditions.

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