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The names and affiliations of all authors are provided below, following the references.

Effect of sulphur and babool (*Prosopis juliflora*) biochar on soil properties of sesame (*Sesamum indicum* L.) grown in loamy sand soil

Brijesh Kumar Bajiya¹, KK Sharma², Kiran Doodhawal³, Vikas Kumar Singhal⁴, Binja Ram⁵, Chhatrapal Bagara⁶, Rakesh Kumawat⁷, Dharmendra Bhadala⁸, Kamlesh Gora⁹

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ABSTRACT

A field experiment was conducted at the Instructional Farm, S.K.N. College of Agriculture, Jobner (Rajasthan), during kharif 2025 to study the effect of sulphur and babool (*Prosopis juliflora* L.) biochar on soil properties under sesame (*Sesamum indicum* L., cv. RT-351). The experiment comprised four levels of sulphur (0, 20, 40 and 60 kg ha⁻¹) and four levels of babool biochar (0, 3, 6 and 9 t ha⁻¹), giving 16 treatment combinations laid out in factorial randomized block design with three replications. Application of sulphur @ 60 kg ha⁻¹ significantly reduced soil pH (8.01) and electrical conductivity (0.414 dS m⁻¹) and significantly increased available sulphur (16.68 kg ha⁻¹, at par with 40 kg ha⁻¹) over the control. Sulphur had no significant effect on organic carbon, bulk density, porosity, available N, P and K, DTPA-extractable micronutrients, or soil biological properties. Babool biochar @ 9 t ha⁻¹ significantly reduced bulk density (1.48 Mg m⁻³), increased porosity (44.91%), organic carbon (0.252%), available N, P, K and S, DTPA-extractable Fe, Mn, Cu and Zn, microbial biomass carbon (115.75 mg kg⁻¹), dehydrogenase activity (16.46 µg TPF g⁻¹ soil hr⁻¹) and alkaline phosphatase activity (11.74 µg PNP g⁻¹ soil hr⁻¹).

Keywords: Babool biochar, Sulphur, Sesame, PH, EC, OC, BD, PD, Nutrient availability

Introduction

Sesame (*Sesamum indicum* L.) is one of the oldest known oilseed crops in the world, known by various regional names - Gingelly in India, Bennisseed in Africa, Benne in South America, Gengelin in Brazil, Semsem in Hebrew, and Tila in Sanskrit. It belongs to the family Pedaliaceae, comprising 60 species under 16 genera, of which *S. indicum* (2n = 26) is the principal cultivated species. The plant grows 50-250 cm tall depending on cultivar and environment, is annual and self-pollinated, and matures in 85-90 days. The crop is particularly sensitive to water deficit at the seedling, flowering and seed-filling stages, which strongly determines final yield (Fazeli *et al.*, 2006). Sesame seeds are often called "the seeds of immortality" owing to their rich content of natural antioxidants; the oil exhibits high resistance to oxidative rancidity because of endogenous antioxidants such as sesamol, sesamolinal and sesaminol (Alpaslan *et al.*, 2001) [1]. The oil (48-52%) is rich in protein (20.28%), sugars (14-15%), minerals (5-7%), vitamins, calcium (1450 mg/100 g) and phosphorus (570 mg/100 g), with micronutrients following the order Fe > Cu > Zn > Mn (Suresh *et al.*, 2013) [2], and provides 635 calories per 100 g (Kumar and Goel, 1994), making it a valuable substitute for ghee. Sesame cake, the oil-extraction residue, contains 6.0-6.2% N, 2.0-2.2% P and 1.0-1.2% K (Yadav *et al.*, 2008) [3] and is valuable both as cattle feed and organic manure.

India ranks second in the world in sesame production, with the crop cultivated on 15.24 lakh hectares, producing 9.34 lakh tonnes at an average productivity of only 613 kg ha⁻¹ (MoA&FW, GOI 2025-26) [4] well below its genetic potential. This is largely attributable to cultivation on marginal, sandy soils with low organic matter, nitrogen and sulphur status, especially in the semi-arid regions of Rajasthan.

Sulphur requirement in plants is nearly equal to that of phosphorus (Scherer, 2001) [5] and is essential for synthesis of the sulphur-containing amino acids methionine (21%), cysteine (26%) and cystine (27%), which together constitute about 90% of plant sulphur. Sulphur is also required for co-enzyme A, biotin, thiamine and glutathione synthesis, and plays a central role in chlorophyll formation, glucoside and glucosinolate (oil) biosynthesis, enzyme activation, and formation of disulphide (-S-S-) linkages responsible for drought and cold tolerance in oilseeds. In sesame, sulphur promotes floral primordium initiation, resulting in more capsules per plant, more seeds per capsule, and higher seed oil content (Hassan *et al.*, 2007) [6]. In soil, sulphur exists mainly as sulphate-S, organic-S, total-S and non-sulphate-S (Pasricha *et al.*, 2012) [7], with sulphate (SO₄²⁻) being the dominant plant-available form (Zhou *et al.*, 2005) [8]; its release depends on soil environmental conditions, source characteristics and microbial activity.

Biochar is a porous, carbon-rich material produced by heating organic matter to 300-600 °C under limited or no oxygen (Verheijen *et al.*, 2010; Zheng *et al.*, 2010) [9, 10]. Meta-analyses show biochar is most beneficial

Corresponding Author:
Brijesh Kumar Bajiya
 Department of Soil Science
 and Agricultural
 Chemistry, S.K.N.
 Agriculture University,
 Jobner-303 329, Rajasthan,
 India.

in acidic, degraded and coarse-textured soils (Crane-Droesch *et al.*, 2013) [11] typical of the sandy loam soils of semi-arid Rajasthan. Its high surface area and porosity improve water and nutrient retention, while its stable carbon structure contributes to long-term soil carbon sequestration and is regarded as one of the most effective strategies for enhancing soil biodiversity (Brussaard *et al.*, 2007) [12]. The porous structure provides habitat for soil microorganisms (Sohi *et al.*, 2009) [13], promoting microbial colonisation, reducing nitrogen losses and improving overall nutrient availability and plant productivity (Winsley, 2007) [14]. Biochar and other carbon-rich amendments can influence soil carbon dynamics by modifying carbon quality, microbial activity and the stabilization of labile and recalcitrant carbon pools (Singhal *et al.*, 2026) [15].

Prosopis juliflora (babool) is a widely spreading invasive shrub across arid and semi-arid India with limited direct economic use; converting its biomass into biochar offers a dual-purpose strategy of weed management and soil amendment production. While the individual effects of sulphur nutrition and biochar amendment on soil fertility are documented separately, information on their combined application particularly using biochar derived from *P. Juliflora* on soil physico-chemical and biological properties in loamy sand soil is limited. The present investigation was therefore undertaken to study the individual and interactive effects of sulphur and babool biochar on soil properties of sesame grown in loamy sand soil.

Material and Methods

The field experiment was conducted at the Instructional Farm, S.K.N. College of Agriculture, Jobner, Rajasthan (26°06' N latitude, 75°28' E longitude; 427 m above mean sea level) during the *kharif* season of 2025. The experimental site falls under Agro-climatic Zone III-A (Semi-arid Eastern Plain Zone) of Rajasthan. The experiment consisted of four levels of sulphur (S), viz., 0, 20, 40 and 60 kg ha⁻¹, applied in the form of elemental sulphur containing 99.5% S, and four levels of babool biochar, viz., 0, 3, 6 and 9 t ha⁻¹, resulting in 16 treatment combinations. The treatments were evaluated in a factorial randomized block design (FRBD) with three replications, comprising a total of 48 experimental plots. Each plot had a gross size of 4.0 × 3.0 m and a net plot size of 3.0 × 2.4 m. Babool stalks were subjected to pyrolysis under low-oxygen conditions to prepare the biochar, which was uniformly surface-spread and incorporated into the soil at the time of sowing. The chemical and physical characteristics of the prepared babool biochar had a pH of 8.14, electrical conductivity of 0.55 dS m⁻¹, bulk density of 0.48 Mg m⁻³, particle density of 1.37 Mg m⁻³ and porosity of 68%. It contained 1.41% total N, 0.74% total P, 1.46% total K, 0.37% total S and 70.23% total carbon with ash and moisture contents of 30.21 and 7.92%, respectively. After harvest, soil samples were collected from the 0–15 cm soil depth from each exper-

imental plot and analyzed for important physical, chemical and biological properties. The soil samples were analyzed for pH, electrical conductivity (EC), organic carbon, bulk density, particle density, porosity, available N, P, K and S, DTPA-extractable Fe, Mn, Cu and Zn, microbial biomass carbon, dehydrogenase activity and alkaline phosphatase activity using the standard analytical procedures presented in Table 1. Data were analysed by analysis of variance for factorial RBD following Panse *et al.* (1985) [16], treatment means were compared using critical difference (CD) at *P* = 0.05.

Results and Discussion

Bulk density, particle density and porosity: Sulphur had no significant effect on any of these parameters (Table 2). Biochar significantly reduced bulk density from 1.53 (BC₀) to 1.48 Mg m⁻³ (BC₃) and increased porosity from 41.24% to 44.91%, reflecting the inherently low bulk density (0.48 Mg m⁻³) and high porosity (68%) of the biochar, which physically loosens the sandy matrix. Particle density remained unaffected by either treatment. Biochar particles can also promote aggregation and improve pore-size distribution, thereby decreasing soil compaction and increasing total porosity. A global meta-analysis by (Blanco-Canqui, 2017) [17] reported that biochar application generally decreases soil bulk density and increases soil porosity, particularly in coarse-textured and degraded soils. Similarly, (Verheijen *et al.*, 2010) [9] reported that the low density and porous structure of biochar can modify soil physical properties following incorporation. Greater carbon accumulation within soil aggregates and enhanced enzyme-mediated nutrient cycling (Singhal *et al.*, 2024).

Soil pH and electrical conductivity: Sulphur application significantly and progressively reduced soil pH from 8.38 (S₀) to 8.01 (S₃) and EC from 0.426 to 0.414 dS m⁻¹ (Table 2). This decline can be attributed to microbial oxidation of elemental sulphur to sulphuric acid, releasing H⁺ ions into the soil solution a mechanism also reported by (Pasricha *et al.*, 2012) [7]. Biochar application caused a slight, statistically non-significant increase in pH (8.10 to 8.29) and EC (0.417 to 0.426 dS m⁻¹) with increasing rate, consistent with the mildly alkaline reaction of the biochar itself (pH 8.14, Table 2). Biochar effects on soil pH are highly dependent on the initial soil condition and biochar characteristics, rather than producing a uniform increase in all soils. The slight increase in EC with biochar application may be attributed to the release of soluble mineral salts and basic cations from the ash fraction of biochar (Su *et al.*, 2024) [18].

Organic carbon: Sulphur had no significant effect on organic carbon (0.224–0.230%). Biochar significantly and progressively increased organic carbon from 0.202% (BC₀) to 0.252% (BC₃) a 24.75% increase attributable to the recalcitrant aromatic carbon in biochar (70.23% total C, Table 3) which resists rapid microbial decomposition, a finding consistent with (Zheng *et al.*, 2010) [19].

Table 1. Methods used for analysis of post-harvest soil properties

S. No.	Soil property	Method used & Reference
1	Soil pH	Potentiometric method using soil:water suspension (1:2.5); Jackson (1973)
2	Electrical conductivity (EC) (dS m^{-1})	Conductivity meter using soil:water extract (1:2.5); Jackson (1973)
3	Organic carbon (%)	Walkley and Black wet oxidation method; Walkley & Black (1934)
4	Bulk density (Mg m^{-3})	Core sampler method; Blake & Hartge (1986)
5	Particle density (Mg m^{-3})	Pycnometer method; Blake & Hartge (1986)
6	Porosity (%)	Calculated from bulk and particle density; Richards (1954)
7	Available nitrogen (N) (kg ha^{-1})	Alkaline KMnO_4 method; Subbiah & Asija (1956)
8	Available phosphorus (P) (kg ha^{-1})	Olsen's sodium bicarbonate extraction method; Olsen <i>et al.</i> , (1954)
9	Available potassium (K) (kg ha^{-1})	Neutral normal NH_4OAc extraction followed by flame photometry; Hanway & Heidel (1952)
10	Available sulphur (S) (kg ha^{-1})	0.15% CaCl_2 extraction and turbidimetric determination; Williams & Steinbergs (1959)
11	DTPA-extractable Fe, Mn, Cu & Zn (mg kg^{-1})	DTPA extraction followed by atomic absorption spectrophotometry; Lindsay & Norvell (1978)
12	Microbial biomass carbon (MBC) ($\mu\text{g C g}^{-1}$ soil)	Chloroform fumigation–extraction method; Vance <i>et al.</i> , (1987)
13	Dehydrogenase activity ($\mu\text{g TPF g}^{-1}$ soil h^{-1})	Triphenyl tetrazolium chloride (TTC) reduction method; Casida <i>et al.</i> , (1964)
14	Alkaline phosphatase activity ($\mu\text{g PNP g}^{-1}$ soil h^{-1})	<i>p</i> -Nitrophenyl phosphate (pNPP) method; Tabatabai & Bremner (1969)

Available macronutrients: Sulphur increased available N, P and K numerically, but not significantly (Table 6), while significantly increasing available S from 13.28 to 16.68 kg ha^{-1} , with S_3 at par with S_2 . Biochar significantly increased available N (+17.12%), P_2O_5 (+16.05%), K_2O (+15.97%) and S (+11.59%) at 9 t ha^{-1} over control, likely due to both direct nutrient contribution from the biochar (Table 2) and improved retention of nutrients on its charged surfaces in this coarse-textured soil, consistent with (Sohi *et al.*, 2009) [13].

DTPA-extractable micronutrients: Sulphur had no significant effect on Fe, Mn, Cu or Zn (Table 2). Biochar significantly increased all four: Fe (+7.18%), Mn (+14.90%), Cu (+15.09%) and Zn (+26.09%) at 9 t ha^{-1} , possibly due to release of micronutrients from the ash fraction of biochar (30.21%, Table 3) and improved moisture retention favouring micronutrient solubility. The positive response observed in the present study may therefore be related to the particular characteristics of babool biochar, its relatively high ash content and the properties of the experimental soil. In addition, the porous structure of biochar can improve soil water retention, particularly in coarse-textured soils, which may facilitate nutrient diffusion and maintain micronutrients in plant-available forms (Schmidt *et al.*, 2021) [20].

Soil biological properties: Sulphur did not significantly affect microbial biomass carbon (MBC), dehydrogenase (DHA) or alkaline phos-

phatase activity (Table 2), though all three increased numerically with sulphur rate. Biochar significantly enhanced all three: MBC (+21.94%), DHA (+25.27%) and alkaline phosphatase activity (+13.12%) at 9 t ha^{-1} , supporting the view that the porous structure of biochar provides a favourable habitat for microbial colonisation while its labile carbon fraction supplies an energy source for microbial growth (Winsley, 2007; Sohi *et al.*, 2009) [14, 13]. Enhancing carbon stabilization and strengthening the association between soil organic carbon and enzyme activities, particularly in degraded semi-arid soils (Singhal *et al.*, 2025).

Conclusion

Under loamy sand soil conditions of semi-arid Rajasthan, sulphur application (40–60 kg ha^{-1}) significantly improved soil sulphur status and reduced pH/EC, while babool biochar (particularly 9 t ha^{-1}) produced broad improvements in soil physical structure, nutrient availability and microbial/enzymatic activity. Both inputs independently and significantly increased sesame seed yield, and their integrated application is recommended for enhancing sesame productivity while simultaneously improving soil health and valorising invasive *P. juliflora* biomass in semi-arid sandy soils.

Table 3. Effect of sulphur and babool biochar on soil properties

Tr.	BD (Mg m ⁻³)	PD (Mg m ⁻³)	Porosity (%)	pH	EC (dS m ⁻¹)	OC (%)	N (kg ha ⁻¹)	P ₂ O ₅ (kg ha ⁻¹)	K ₂ O (kg ha ⁻¹)	S (kg ha ⁻¹)	Fe (g kg ⁻¹)	Mn (g kg ⁻¹)	Cu (g kg ⁻¹)	Zn (g kg ⁻¹)	MBC (mg kg ⁻¹)	DHA (µg TPF g ⁻¹ soil hr ⁻¹)	Alkaline phos-phatase (µg PNP g ⁻¹ soil hr ⁻¹)
S ₀	1.50	2.62	42.70	8.38	0.426	0.224	133.54	19.09	152.79	13.28	4.15	2.20	0.247	0.51	104.33	14.66	10.77
S ₁	1.50	2.62	43.27	8.27	0.422	0.226	136.10	19.47	153.96	14.83	4.17	2.22	0.249	0.52	105.58	14.89	10.98
S ₂	1.49	2.61	43.60	8.14	0.419	0.228	137.90	19.55	155.29	16.28	4.20	2.25	0.250	0.53	107.08	14.99	11.06
S ₃	1.49	2.61	43.91	8.01	0.414	0.230	139.14	19.76	156.04	16.68	4.24	2.27	0.253	0.53	107.75	15.08	11.19
SEm±	0.013	0.02	0.82	0.119	0.004	0.004	2.09	0.274	2.43	0.159	0.058	0.030	0.003	0.009	1.463	0.230	0.173
CD (0.05)	NS	NS	NS	0.34	0.102	NS	NS	NS	NS	0.460	NS	NS	NS	NS	NS	NS	NS
BC ₀	1.53	2.61	41.24	8.10	0.417	0.202	125.60	17.94	142.92	14.41	4.04	2.08	0.232	0.46	94.92	13.14	10.29
BC ₁	1.50	2.62	43.26	8.17	0.419	0.218	133.50	19.09	151.00	15.02	4.14	2.19	0.245	0.51	103.33	14.53	10.77
BC ₂	1.49	2.62	44.06	8.24	0.422	0.235	140.60	20.02	158.42	15.56	4.24	2.29	0.256	0.54	110.75	15.49	11.20
BC ₃	1.48	2.61	44.91	8.29	0.426	0.252	147.10	20.82	165.75	16.08	4.33	2.39	0.267	0.58	115.75	16.46	11.74
SEm±	0.013	0.02	0.82	0.119	0.004	0.004	2.09	0.274	2.43	0.159	0.058	0.030	0.003	0.009	1.463	0.230	0.173
CD (0.05)	0.04	NS	2.36	NS	NS	0.011	6.03	0.79	7.02	0.460	0.17	0.086	0.009	0.026	4.23	0.66	0.50

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Department of Soil Science and Agricultural Chemistry, S.K.N. Agriculture University, Jobner

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Authors

Brijesh Kumar Bajiya

Department of Soil Science and Agricultural Chemistry, S.K.N. Agriculture University, Jobner-303 329, Rajasthan, India.

KK Sharma

Department of Soil Science and Agricultural Chemistry, S.K.N. Agriculture University, Jobner-303 329, Rajasthan, India.

Kiran Doodhawal

Department of Soil Science and Agricultural Chemistry, S.K.N. Agriculture University, Jobner-303 329, Rajasthan, India.

Vikas Kumar Singhal

Rani Lakshmi Bai Central Agricultural University, Jhansi-284 003, Uttar Pradesh, India.

Binja Ram

Department of Soil Science and Agricultural Chemistry, S.K.N. Agriculture University, Jobner-303 329, Rajasthan, India.

Chhatrapal Bagara

Department of Soil Science and Agricultural Chemistry, S.K.N. Agriculture University, Jobner-303 329, Rajasthan, India.

Rakesh Kumawat

Department of Soil Science and Agricultural Chemistry, S.K.N. Agriculture University, Jobner-303 329, Rajasthan, India.

Dharmendra Bhadala

School of Agricultural Sciences, Dhanalakshmi Srinivasan University, Trichy-621 112, Tamilnadu, India.

Kamlesh Gora

Suresh Gyan Vihar University, Jaipur-302 017, Rajasthan, India.