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Fenugreek Growth Response to Acidified Neem and Mesquite Biochars across Three Contrasting Sudanese Dryland Soil Materials

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Abstract

Dryland soils vary widely in texture, salinity, carbonate content, and phosphorus availability, and this variation shapes how crops respond to biochar. We tested fenugreek (*Trigonella foenum-graecum* L.) response to acidified biochars made from neem (*Azadirachta indica*) and mesquite (*Neltuma juliflora*) pruning residues in three contrasting Sudanese dryland soil materials, classified as Vertisol, Entisol, and Aridisol, all of them calcareous (2.3% - 3.5% $CaCO_3$). The residues were carbonized under traditional limited-oxygen conditions and then saturated with dilute phosphoric acid. Final biochar pH was 4.0 for neem and 3.5 for mesquite, with Olsen-extractable phosphorus of 1500 and 1800 mg·kg^{-1}, respectively. A 60-day completely randomized pot experiment compared the two feedstocks at 2.5% and 5% w/w against unamended controls, with three replicates per treatment and 45 pots in total. Plant height and leaf number were recorded during growth; shoot and root biomass and post-harvest available phosphorus were measured at harvest. Post-harvest pH and ECe were recorded at the treatment level. Responses differed by soil material, feedstock, rate, and trait. In the Entisol material, neem 5%, neem 2.5%, and mesquite 2.5% gave the tallest plants, neem 5% the highest shoot fresh and dry biomass, and mesquite 2.5% the highest leaf number and root fresh weight. In the Vertisol material, neem 5% produced the strongest shoot response and the highest post-harvest available phosphorus, while mesquite 2.5% again gave the highest root fresh weight. The Aridisol material responded less consistently: mesquite 5% raised shoot fresh and dry weight, but root traits did not improve significantly. Post-harvest pH stayed slightly alkaline throughout, between 7.45 and 7.72, and ECe rose only marginally under all treatments. Available phosphorus increased sharply at the 5% rate, yet higher phosphorus did not reliably produce balanced shoot and root growth. Under these pot conditions,

the performance of acidified neem and mesquite biochars was both soil-specific and trait-specific. Texture, carbonate content, initial salinity, feedstock, and application rate all warrant consideration before these amendments are recommended for dryland soils.

Keywords

Acidified Biochar, Neem Biochar, Mesquite Biochar, Fenugreek, Vertisol, Entisol, Aridisol, Olsen-P, Dryland Soils, Sudan

1. Introduction

Dryland agriculture operates under a narrow margin of soil and water security. Low organic matter, weak aggregate stability, limited water retention, salinity risk, and low nutrient availability often occur together, making plant response highly dependent on the interaction between soil texture, chemical buffering, and nutrient dynamics. These constraints are particularly relevant in Sudanese dryland systems, where crop production commonly occurs on soils that differ sharply in clay content, salinity status, sodium hazard, carbonate chemistry, and phosphorus availability. Under such conditions, locally available organic residues may provide a practical entry point for improving soil function, but their agronomic value cannot be assumed to be uniform across contrasting soil types.

Biochar is a carbon-rich solid produced when biomass is thermally converted under limited oxygen conditions. Depending on process conditions, this conversion can also yield heat, gases, and liquid fractions [1]-[4]. The biochars used here were produced from neem and mesquite woody pruning residues by traditional limited-oxygen carbonization, not by instrument-controlled pyrolysis.

Biochar has received sustained attention as a soil amendment because it can influence soil pH, electrical conductivity, cation exchange capacity, carbon persistence, nutrient retention, microbial activity, and soil-water relations. However, the agronomic effect of biochar is highly conditional. Early and recent meta-analyses consistently show that crop response varies with soil pH, soil texture, biochar feedstock, pyrolysis conditions, application rate, crop type, and whether biochar is applied alone or with nutrient inputs [5]-[10]. This means that biochar should not be treated as a universal growth promoter. It is better understood as a chemically active amendment whose effect depends on the receiving soil matrix.

The variability of biochar response is especially important in dryland soils. Sandy soils may respond differently from clay-rich soils because they have lower buffering capacity, lower nutrient retention, and different water-flow behavior. Clay-rich soils may retain nutrients more effectively, but they can also impose constraints related to sodicity, compaction, or slow root penetration. Calcareous and alkaline soils add another layer of complexity because phosphorus availability is often controlled by sorption and precipitation reactions. These interacting constraints ex-

plain why a biochar that improves growth in one soil may be neutral or even restrictive in another. Global analyses support this interpretation by showing that soil pH, soil organic carbon, clay content, and biochar C:N ratio are among the major drivers of biochar response [8]-[10].

Neem (*Azadirachta indica*) and mesquite (*Neltuma juliflora*) are common woody resources in dryland and semi-arid regions. Their pruning residues often have limited direct use and may become a management problem when they accumulate near farms, settlements, or field margins. Mesquite, in particular, is widely recognized in many dryland landscapes as a persistent woody species that can affect rangelands, biodiversity, and rural livelihoods when unmanaged. Converting these residues into biochar offers a circular use pathway that links residue management, carbon-rich soil amendments, and local crop production. This approach may be especially relevant where dryland farmers need low-input soil amendments produced from available woody biomass.

The chemical nature of the produced biochar is critical. Many woody biochars are alkaline because ash-derived basic cations and carbonates accumulate during carbonization or pyrolysis. In acidic soils, this alkalinity can be beneficial, but in neutral, alkaline, or calcareous soils it may intensify nutrient imbalance or reduce the availability of phosphorus and micronutrients. This concern has led to growing interest in modified biochars, including phosphorus-modified and acid-treated biochars. Phosphoric acid modification can lower biochar pH, enrich biochar with phosphorus, alter surface functional groups, and influence nutrient release behavior. At the same time, acidified biochar may increase soluble salts, introduce localized acidity, or create excessive phosphorus loading if the rate is not matched to soil buffering capacity. Studies on phosphorus-modified biochars show that these materials can alter root-zone chemistry and nutrient availability, but their effects depend strongly on amendment rate, soil type, and the balance between chemical enrichment and potential osmotic or ionic stress [11]-[14].

Phosphorus deserves specific attention in dryland soils because low available P can restrict early growth, nodulation, root development, and biomass accumulation. Biochar can influence soil phosphorus through several pathways. It may directly add phosphorus when the feedstock or modification process contains P, and it may indirectly alter P availability through pH shifts, ligand exchange, mineral interactions, microbial activity, and changes in sorption surfaces. Recent reviews emphasize that biochar generally tends to increase soil available phosphorus, but the magnitude of the effect differs according to feedstock, production conditions, modification method, soil properties, and application context [12] [13]. This is particularly relevant for acidified biochars prepared with phosphoric acid, where phosphorus enrichment may be large but plant response may still be limited by salinity, acidity, root-zone imbalance, or soil physical constraints.

Fenugreek (*Trigonella foenum-graecum* L.) is a short-duration leguminous crop with nutritional, medicinal, and agronomic value. Its early growth is sensitive to soil-water conditions, salinity, and nutrient availability, making it suitable for

evaluating amendment effects under controlled pot conditions. Recent fenugreek studies show that salinity can depress germination, growth, photosynthesis, and physiological performance, while nutrient and stress-mitigation treatments may partially improve plant response under adverse conditions [10] [15]-[17]. Fenugreek is therefore an appropriate test crop for examining whether acidified, phosphorus-enriched biochars can improve early growth across contrasting dryland soil matrices.

Despite the rapid expansion of biochar research, an important gap remains. Many studies report average crop responses to biochar without testing whether the same amendment behaves differently across soils that differ in texture, salinity, and carbonate content. This limits practical interpretation, especially in dryland agriculture, where these properties can control plant response more strongly than the amendment itself. The same biochar may improve shoot biomass in a clay-rich soil, stimulate root fresh biomass in another, and fail to produce balanced growth in a sandy soil. Such soil-specific behavior is especially likely when the biochar is strongly acidified and phosphorus-enriched.

The present study addresses this gap by evaluating acidified neem and mesquite biochars across three contrasting Sudanese soil materials classified as Vertisol, Entisol, and Aridisol. These soil materials differed in texture, salinity status, sodium hazard, carbonate chemistry, and baseline phosphorus availability. The study focused on fenugreek growth, shoot and root biomass, seasonal growth indices, and post-harvest available phosphorus. By comparing two woody feedstocks and two application rates within each soil material, the experiment assessed whether fenugreek response differed according to the tested soil material, biochar feedstock, application rate, and measured plant trait.

The objectives of this study were to:

1) produce acidified biochars from neem and mesquite pruning residues;

2) characterize selected physicochemical properties of the acidified biochars;

3) evaluate fenugreek response to neem and mesquite biochars at 2.5% and 5% application rates;

4) determine whether plant response differs among the tested soil materials classified as Vertisol, Entisol, and Aridisol;

5) identify practical implications for using acidified woody biochars in Sudanese dryland soils.

The working hypotheses were that:

1) neem and mesquite biochars would produce different fenugreek responses because of feedstock-specific chemistry;

2) biochar effects would depend on the tested soil material;

3) the 5% rate would not necessarily outperform the 2.5% rate across all traits and soils;

4) the tested Aridisol material would show a weaker or more selective response because of its sandy texture, lower buffering capacity, salinity risk, and limited capacity to convert phosphorus enrichment into balanced shoot-root growth.

2. Materials and Methods

2.1. Experimental Overview

A 60-day pot experiment was conducted to evaluate the response of fenugreek (*Trigonella foenum-graecum* L.) to acidified biochars produced from neem (*Azadirachta indica*) and mesquite (*Neltuma juliflora*) pruning residues (Figure 1). The experiment compared two acidified woody biochars across three contrasting Sudanese dryland soil materials, classified as Vertisol, Entisol, and Aridisol.

The experiment was arranged as a completely randomized pot experiment under controlled growing conditions. For each soil material, five treatments were tested: an unamended control, neem biochar at 2.5%, neem biochar at 5%, mesquite biochar at 2.5%, and mesquite biochar at 5%. Each treatment was replicated three times, giving 15 pots per soil material and 45 pots in total.

The measured response variables included repeated plant height, repeated leaf number, final plant height, final leaf number, shoot fresh weight, shoot dry weight, root fresh weight, root dry weight, and post-harvest available phosphorus. Seasonal plant height and leaf development were summarized descriptively using the area under the growth curve (AUGC).

Figure 1. Workflow for producing acidified neem and mesquite biochars and applying them in the fenugreek pot experiment. The steps are feedstock collection, traditional limited-oxygen carbonization, recovery of the charred material, crushing and sieving, saturation with dilute phosphoric acid, drying and storage without washing, and application to three contrasting Sudanese dryland soil materials classified as Vertisol, Entisol, and Aridisol.

2.2. Soil Collection, Preparation, and Baseline Characterization

Three soil materials were selected to represent contrasting soil conditions in Sudan: a clay-rich Vertisol, a clay-textured Entisol, and a sandy Aridisol. According to the original laboratory records, the Vertisol, Entisol, and Aridisol materials were collected from Al-Qadarif State, Al-Jarif, and West Omdurman, respectively. These soils were selected because they differ clearly in texture, salinity status, sodium hazard, carbonate chemistry, and baseline phosphorus availability. This contrast provided a suitable basis for testing whether the acidified biochar response depends on the receiving soil matrix.

Each soil order was represented by one composite soil sample collected from one location. The Vertisol, Entisol, and Aridisol used in this experiment should

therefore be interpreted as contrasting test soil materials, not as replicated representatives of all Sudanese Vertisols, Entisols, or Aridisols. The scope of inference is limited to the response of these sampled soil materials under controlled pot conditions. Broader recommendations for dryland soils require further testing across replicated field sites, seasons, and management conditions.

After collection, soil materials were air-dried under laboratory conditions, gently crushed, passed through a 2-mm sieve, and thoroughly homogenized before pot filling. Baseline physicochemical properties were determined before biochar application. The measured properties included pH, electrical conductivity of the saturated paste extract (ECe), soluble carbonate, bicarbonate, chloride, sodium, calcium plus magnesium, potassium, sodium adsorption ratio (SAR), Olsen-extractable phosphorus, calcium carbonate, particle-size distribution, texture class, bulk density, and particle density.

Texture classes were interpreted using USDA textural classification principles. Because the Entisol particle-size fractions in the original laboratory table summed to 98%, the silt fraction was adjusted to close the particle-size balance for textural interpretation. Based on 52% clay, 22% sand, and 26% silt, the Entisol was interpreted as clay-textured rather than clay loam.

The initial physicochemical properties of the three tested soil materials are summarized in Table 1.

Table 1. Initial physicochemical properties of the three tested soil materials.

Property	Unit	Vertisol	Entisol	Aridisol
pH	—	7.60	7.60	7.70
ECe	$dS \cdot m^{-1}$	2.50	1.27	3.50
CO_3^{2-}	$meq \cdot L^{-1}$	3.50	5.00	0.00
HCO_3^-	$meq \cdot L^{-1}$	6.00	7.00	3.30
Cl^-	$meq \cdot L^{-1}$	2.00	2.00	1.00
Soluble Na^+	$meq \cdot L^{-1}$	21.80	2.00	6.00
$Ca^{2+} + Mg^{2+}$	$meq \cdot L^{-1}$	8.00	3.00	5.00
K^+	$meq \cdot L^{-1}$	0.17	0.26	1.00
SAR	—	10.90	1.60	3.79
Olsen-P	$mg \cdot kg^{-1}$	0.50	2.60	0.36
$CaCO_3$	%	3.50	3.50	2.30
Clay	%	60.00	52.00	10.00
Sand	%	20.00	22.00	70.00
Silt	%	20.00	26.00	20.00
Texture class	—	Clay	Clay	Sandy loam
Bulk density	$g \cdot cm^{-3}$	1.60	1.55	1.40
Particle density	$g \cdot cm^{-3}$	2.80	2.50	2.30

Note. ECe = electrical conductivity of the saturated paste extract; SAR = sodium adsorption ratio; Olsen-P = sodium bicarbonate-extractable phosphorus.

2.3. Biochar Feedstocks and Production

Neem (*Azadirachta indica*) and mesquite (*Neltuma juliflora*) pruning residues were used as biochar feedstocks. The residues were manually cleaned to remove adhering soil and foreign materials, air-dried, and cut into small pieces before carbonization. Biochar was produced through traditional limited-oxygen carbonization. After carbonization, the charred materials were allowed to cool, crushed, passed through a 2-mm sieve to improve particle uniformity, and stored in sealed containers before acidification. The produced materials are described as traditionally carbonized woody biochars.

2.4. Biochar Acidification and Characterization

The neem and mesquite biochars were saturated with dilute phosphoric acid. The acid was added gradually with continuous mixing until the biochar was uniformly wetted. The treated material was left to react and air-dry for two days, ground, and stored in sealed containers before soil incorporation. No washing step was applied. The acidified biochars were characterized for pH, EC, and Olsen-extractable phosphorus before application to the soils.

After acidification, the final measured pH values were 4.0 for neem biochar and 3.5 for mesquite biochar, confirming that both materials were strongly acidified. Olsen-extractable phosphorus concentrations were 1500 $mg \cdot kg^{-1}$ in acidified neem biochar and 1800 $mg \cdot kg^{-1}$ in acidified mesquite biochar. The two biochars also differed in electrical conductivity, cation exchange capacity, residual carbon yield, and ash content. These properties were considered important for interpreting treatment effects because biochar performance can vary with acidity, soluble salt contribution, phosphorus enrichment, and feedstock-specific chemistry.

The selected physicochemical properties of the acidified neem and mesquite biochars are presented in Table 2.

Table 2. Selected physicochemical properties of the acidified biochars used in the pot experiment.

Property	Unit	Acidified neem biochar	Acidified mesquite biochar
pH	—	4.0	3.5
EC	$dS \cdot m^{-1}$	1.5	2.0
Olsen-extractable P	$mg \cdot kg^{-1}$	1500	1800
CEC	$cmolc \cdot kg^{-1}$	130	150
Residual carbon yield	%	42	48
Ash content	%	9	6

Note. EC = electrical conductivity; CEC = cation exchange capacity. Available phosphorus in the acidified biochars was determined as Olsen-extractable P. The biochars were not washed after phosphoric acid treatment; therefore, their effects should be interpreted as those of strongly acidified, phosphorus-enriched amendments.

2.5. Pot Establishment and Treatment Application

Each pot was filled with 2 kg of prepared soil. Biochar was thoroughly mixed with the soil before sowing. The 2.5% application rate corresponded to 50 g biochar per 2 kg soil, while the 5% application rate corresponded to 100 g biochar per 2 kg soil. Control pots received no biochar.

The two biochar application rates were selected to represent moderate and high amendment levels under controlled pot conditions. The 2.5% rate was used to evaluate the response to a lower biochar dose, while the 5% rate was used to evaluate the response to stronger phosphorus enrichment from the acidified biochars. These rates were used for comparative pot evaluation and are not presented as direct field application recommendations.

Fenugreek seeds were sown at 3 - 5 seeds per pot. After establishment, seedlings were thinned to one uniform plant per pot. The pots were maintained for 60 days in the experimental growing area under ambient light and temperature conditions. Pots were arranged in a completely randomized layout, with three replicates per treatment, and pot positions were periodically adjusted during the growth period to reduce positional effects. Pots were weighed every two days, and water was added to restore soil moisture to approximately 60% of the saturation water content, based on pot weight. No basal fertilizer, rhizobial inoculation, or seed pretreatment was applied.

The complete treatment structure and the amount of biochar added to each pot are presented in Table 3.

Table 3. Treatment structure of the pot experiment.

Soil material	Treatment	Feedstock	Rate	Biochar per 2 kg soil	Replicates
Vertisol	Control	None	0%	0 g	3
	Neem 2.5%	Neem	2.5%	50 g	
	Neem 5%		5%	100 g	
	Mesquite 2.5%	Mesquite	2.5%	50 g	
	Mesquite 5%		5%	100 g	
Entisol	Control	None	0%	0 g	
	Neem 2.5%	Neem	2.5%	50 g	
	Neem 5%		5%	100 g	
	Mesquite 2.5%	Mesquite	2.5%	50 g	
	Mesquite 5%		5%	100 g	
Aridisol	Control	None	0%	0 g	
	Neem 2.5%	Neem	2.5%	50 g	
	Neem 5%		5%	100 g	
	Mesquite 2.5%	Mesquite	2.5%	50 g	
	Mesquite 5%		5%	100 g	

Note. Each pot contained 2 kg of prepared soil. The 2.5% and 5% application rates corresponded to 50 g and 100 g biochar per pot, respectively. Control pots received no biochar.

2.6. Plant Measurements

Plant height was measured at six successive readings during the 60-day growth period. Leaf number was measured at four successive readings. At harvest, shoots and roots were separated. Shoot fresh weight and root fresh weight were recorded immediately after harvest. Shoot dry weight and root dry weight were determined after drying to constant weight.

Final plant height and final leaf number were used as endpoint growth variables. Repeated plant height and leaf number were also summarized descriptively using the area under the growth curve (AUGC), calculated according to the trapezoidal rule:

$$\mathrm{AUGC} = 0.5\mathrm{Y}_1 + \mathrm{Y}_2 + \mathrm{Y}_3 + \cdots + \mathrm{Y}_{n-1} + 0.5\mathrm{Y}_n$$

where Y_i is the measured trait value at the ith observation and n is the total number of observations. Successive observations were treated as equally spaced for calculating the descriptive AUGC index. Plant height AUGC was calculated from six readings, while leaf number AUGC was calculated from four readings. AUGC was used as a descriptive index to summarize seasonal changes in plant height and leaf number. Inferential analysis was restricted to final growth and biomass traits.

2.7. Post-Harvest Soil Chemical Determination

Post-harvest soil available phosphorus was determined using the Olsen sodium bicarbonate extraction method. This method was selected because it is widely used for neutral, alkaline, calcareous, and slightly acidic soils. Available phosphorus was expressed as $\mathrm{mg \cdot kg^{-1}}$ soil.

Olsen-extractable P was also determined in the acidified biochars.

Post-harvest soil pH and electrical conductivity of the saturated paste extract (ECe) were also measured at the end of the 60-day pot experiment. These measurements were used as supporting soil chemical indicators to help interpret acidity, salinity, and buffering-related responses after acidified biochar application.

2.8. Statistical Analysis

Statistical analyses were conducted using R version 4.6.0. One-way ANOVA was performed separately within each soil material to compare the unamended control with the four biochar treatments. This within-soil approach allowed each treatment to be evaluated against the control under the same soil condition and supported soil-specific interpretation of treatment responses.

Mean separation was performed using Tukey's honestly significant difference test at $p \leq 0.05$ only when the overall within-soil ANOVA was significant. Treatment means are reported with standard deviations. Model residuals were checked for normality and homogeneity of variance using Shapiro-Wilk and Levene's tests, respectively. Endpoint growth and biomass traits were analyzed inferentially, whereas AUGC was retained as a descriptive index of seasonal growth.

Because each soil order was represented by one composite soil material, the

study was designed as a controlled pot comparison among contrasting soil matrices rather than a replicated field survey of soil orders. The results therefore indicate how the tested Vertisol, Entisol, and Aridisol materials responded under controlled conditions. Broader recommendations for Sudanese dryland soils require additional field validation across replicated sites, seasons, and management conditions.

3. Results and Discussion

3.1. General Response Pattern across the Tested Soil Materials

Fenugreek response to acidified neem and mesquite biochars varied clearly among the tested soil materials, biochar feedstocks, application rates, and plant traits. The same biochar treatment did not produce the same growth pattern in all soil materials. The tested Entisol and Vertisol materials showed clearer treatment effects on shoot growth and biomass, whereas the tested Aridisol material showed a more selective response, mainly in shoot biomass.

Within-soil one-way ANOVA confirmed significant treatment effects on most growth variables in Entisol and Vertisol. In Entisol, final plant height, final leaf number, shoot fresh weight, shoot dry weight, root fresh weight, and post-harvest available phosphorus were significantly affected by treatment, while root dry weight was not significant. In Vertisol, all traits except root dry weight responded significantly. In Aridisol, treatment effects were significant for shoot fresh weight, shoot dry weight, and available phosphorus, while final height and leaf number were not significant at $p < 0.05$, although their p-values were close to the selected significance threshold.

Overall, fenugreek response to acidified neem and mesquite biochars was soil-specific and trait-specific. The response was clearer in shoot biomass than in root dry biomass, and post-harvest available phosphorus did not explain plant performance on its own. This pattern is consistent with previous biochar studies showing that crop response varies with soil properties, feedstock chemistry, amendment rate, nutrient status, and root-zone conditions [9] [10] [13].

3.2. Descriptive Seasonal Growth Response Based on AUGC

Seasonal plant height and leaf development were summarized using Area Under the Growth Curve (AUGC). AUGC values were used as descriptive indices of seasonal growth and were not included in inferential testing. They were therefore not passed through ANOVA or Tukey HSD. Accordingly, AUGC values were interpreted descriptively, and the resulting indices are presented in **Table 4**.

AUGC values were calculated from treatment-level mean readings and were used only to provide a descriptive summary of seasonal height and leaf development. Therefore, these values were not used for statistical ranking or treatment separation. In Entisol and Vertisol, the descriptive AUGC patterns were broadly consistent with the stronger endpoint shoot response observed under neem 5%, while Aridisol showed a less stable seasonal pattern. These trends are presented

only as supporting descriptive information, whereas treatment interpretation is based mainly on the final growth, biomass, Tukey HSD, and ANOVA results.

Table 4. Descriptive area under the growth curve indices for plant height and leaf number.

Soil material	Treatment	Height_AUGC	Leaf_AUGC
Entisol	Control	74.83	88.00
	Neem 5%	149.00	110.00
	Neem 2.5%	120.17	109.00
	Mesquite 5%	69.00	84.50
	Mesquite 2.5%	123.00	98.67
Vertisol	Control	89.67	58.00
	Neem 5%	138.83	91.00
	Neem 2.5%	94.50	91.50
	Mesquite 5%	104.66	109.00
	Mesquite 2.5%	100.33	91.50
Aridisol	Control	99.83	83.50
	Neem 5%	70.34	74.00
	Neem 2.5%	87.34	92.00
	Mesquite 5%	81.17	73.00
	Mesquite 2.5%	94.67	82.00

Note. AUGC = area under the growth curve. Values are descriptive treatment-level indices calculated from repeated plant height and leaf number readings. No inferential ANOVA or post-hoc mean separation was applied to AUGC because the indices were computed at treatment level rather than replicate level.

3.3. One-Way ANOVA within Each Tested Soil Material

The one-way ANOVA confirmed strong treatment effects in Entisol and Vertisol for most traits, but a weaker and more selective response in Aridisol (Table 5).

Table 5. One-way ANOVA results within each tested soil material.

Soil	Trait	SS treatment	SS error	MS treatment	MS error	F-value	p-value
Entisol	Height_Final	1369.73	64.67	342.43	6.47	52.95	<0.001
	Leaf_Final	438.67	26.67	109.67	2.67	41.13	<0.001
	Shoot_FW	38.63	3.01	9.66	0.30	32.12	<0.001
	Shoot_DW	3.42	0.57	0.85	0.06	15.13	<0.001
	Root_FW	0.65	0.09	0.16	0.01	18.65	<0.001
	Root_DW	0.0045	0.0185	0.0011	0.0019	0.61	0.665
	Available_P	624.26	1.77	156.07	0.18	882.56	<0.001

Continued

Vertisol	Height_Final	395.07	45.33	98.77	4.53	21.79	<0.001
	Leaf_Final	1704.27	26.67	426.07	2.67	159.78	<0.001
	Shoot_FW	14.08	1.00	3.52	0.10	35.02	<0.001
	Shoot_DW	0.76	0.19	0.19	0.02	9.93	0.002
	Root_FW	0.91	0.12	0.23	0.01	19.14	<0.001
	Root_DW	0.0114	0.0154	0.0028	0.0015	1.85	0.196
	Available_P	1005.81	1.34	251.45	0.13	1882.04	<0.001
Aridisol	Height_Final	102.93	74.67	25.73	7.47	3.45	0.051
	Leaf_Final	208.67	155.33	52.17	15.53	3.36	0.055
	Shoot_FW	13.05	0.77	3.26	0.08	42.27	<0.001
	Shoot_DW	0.59	0.05	0.15	0.01	28.57	<0.001
	Root_FW	0.09	0.13	0.02	0.01	1.76	0.213
	Root_DW	0.0023	0.0050	0.0006	0.0005	1.16	0.386
	Available_P	953.15	2.16	238.29	0.22	1103.25	<0.001

Note. Treatment df = 4 and error df = 10 for all tests. Root_DW sums of squares and mean squares are shown with additional decimal places because the values are small and would be obscured by rounding to two decimals.

In Entisol, treatment significantly affected final height, leaf number, shoot fresh weight, shoot dry weight, root fresh weight, and available phosphorus. Root dry weight was not significant. The strongest F-values were observed for available phosphorus and final height, indicating clear treatment effects on post-harvest available phosphorus and aboveground growth.

In Vertisol, treatment effects were significant for final height, leaf number, shoot fresh weight, shoot dry weight, root fresh weight, and available phosphorus. Root dry weight remained non-significant. Available phosphorus again showed the largest F-value, reflecting the strong phosphorus enrichment effect of acidified biochars.

In Aridisol, shoot fresh weight, shoot dry weight, and available phosphorus were significant. Final height was non-significant at $p = 0.051$, and leaf number was non-significant at $p = 0.055$. Root fresh weight and root dry weight were not significant. This means that Aridisol showed improved shoot biomass under selected treatments, but root growth was not statistically improved.

3.4. Tukey HSD Mean Separation

Tukey's HSD test was applied only to traits where the within-soil ANOVA was significant at $p < 0.05$. For traits with non-significant ANOVA results, treatment means were treated as descriptive values and were not interpreted as statistically separated groups. Mean separation results are presented in two tables. Table 6(a) summarizes shoot-related traits, including final plant height, final leaf number, shoot fresh weight, and shoot dry weight. Table 6(b) summarizes root fresh weight, root dry weight, and post-harvest available phosphorus. For Aridisol, final height and final leaf number were not statistically separated because their ANOVA p-

values were not significant at $p < 0.05$, although they were close to the selected significance threshold.

In Entisol, shoot response differed clearly among treatments. Neem 5%, neem 2.5%, and mesquite 2.5% formed the highest statistical group for final plant height, indicating that both neem treatments and the lower mesquite rate supported greater shoot elongation than the control and mesquite 5% (Table 6(a)). For shoot fresh weight, neem 5% produced the highest value, while neem 2.5% remained statistically close. Shoot dry weight followed a similar pattern, with neem 5% producing the strongest dry matter response, although neem 2.5% and mesquite 2.5% were not clearly separated from it. In contrast, mesquite 2.5% produced the highest root fresh weight in Entisol, showing that the lower mesquite rate favored root fresh biomass more than shoot biomass (Table 6(b)). Root dry weight did not differ significantly among treatments, indicating that the root fresh weight response was not matched by a statistically clear increase in structural root dry matter.

In Vertisol, neem 5%, mesquite 5%, and mesquite 2.5% formed the upper group for final plant height (Table 6(a)). Neem 5% produced the strongest shoot fresh and dry biomass response, confirming its superior performance for aboveground growth in this soil. Mesquite 5% produced the highest final leaf number, but it did not produce the highest shoot dry weight, suggesting that leaf production and dry matter accumulation were partly decoupled. For belowground traits, mesquite 2.5% produced the highest root fresh weight, whereas root dry weight remained statistically unchanged across treatments (Table 6(b)). This indicates that the Vertisol response was trait-specific: neem 5% favored shoot biomass, while mesquite 2.5% favored root fresh biomass.

In the tested Aridisol material, treatment effects were significant for shoot fresh weight, shoot dry weight, and available phosphorus. Final height and final leaf number were statistically non-significant at $p = 0.051$ and $p = 0.055$, respectively; therefore, the numerical differences in these two traits were interpreted descriptively and were not treated as statistically separated groups. Mesquite 5% produced the clearest shoot biomass response, but this response was not accompanied by significant improvement in root fresh or dry weight. Available phosphorus increased sharply under the 5% biochar treatments, especially neem 5% and mesquite 5%, but this increase did not produce a balanced shoot-root response.

Overall, the within-soil comparisons showed that the strongest treatment differed among the tested soil materials and plant traits. Neem 5% gave the clearest shoot biomass response in the tested Entisol and Vertisol materials. Mesquite 2.5% produced higher root fresh weight in the same two soil materials, although root dry weight was not significantly improved. In the tested Aridisol material, mesquite 5% produced the clearest shoot fresh and dry biomass response, while height and leaf number remained descriptive rather than statistically separated traits. These patterns show that acidified biochar performance should be interpreted in relation to the receiving soil material, feedstock type, application rate, and measured plant trait.

Table 6. (a) Tukey HSD mean separation for shoot growth traits of fenugreek. (b) Tukey HSD mean separation for root traits and post-harvest available phosphorus.

(a)

Soil material	Treatment	Height_Final	Leaf_Final	Shoot_FW	Shoot_DW
Entisol	Control	20.00 ± 2.00 b	45.00 ± 0.00 b	1.87 ± 0.06 d	0.45 ± 0.01 c
	Neem 5%	44.33 ± 1.53 a	45.00 ± 0.00 b	6.60 ± 0.80 a	1.75 ± 0.17 a
	Neem 2.5%	40.67 ± 0.58 a	43.00 ± 2.00 b	5.70 ± 0.10 ab	1.49 ± 0.36 a
	Mesquite 5%	25.67 ± 3.06 b	43.00 ± 1.73 b	4.20 ± 0.60 c	0.83 ± 0.15 bc
	Mesquite 2.5%	40.33 ± 4.04 a	57.33 ± 2.52 a	4.80 ± 0.70 bc	1.43 ± 0.33 ab
Vertisol	Control	31.00 ± 0.00 b	22.33 ± 1.53 c	1.63 ± 0.12 c	0.45 ± 0.04 c
	Neem 5%	40.00 ± 0.00 a	42.33 ± 2.52 b	4.50 ± 0.36 a	1.08 ± 0.13 a
	Neem 2.5%	26.67 ± 3.06 b	46.33 ± 1.53 b	3.13 ± 0.15 b	0.90 ± 0.18 ab
	Mesquite 5%	37.33 ± 3.51 a	54.00 ± 0.00 a	3.25 ± 0.58 b	0.64 ± 0.14 bc
	Mesquite 2.5%	39.00 ± 1.00 a	46.33 ± 1.53 b	3.97 ± 0.06 ab	0.92 ± 0.16 ab
Aridisol	Control	30.33 ± 1.15	35.00 ± 1.00	1.27 ± 0.21 b	0.29 ± 0.04 c
	Neem 5%	24.00 ± 3.61	33.00 ± 3.00	1.27 ± 0.38 b	0.29 ± 0.08 c
	Neem 2.5%	28.33 ± 1.15	40.67 ± 4.51	1.67 ± 0.31 b	0.51 ± 0.11 b
	Mesquite 5%	31.67 ± 4.51	43.33 ± 6.66	3.75 ± 0.25 a	0.83 ± 0.01 a
	Mesquite 2.5%	27.67 ± 1.15	38.00 ± 1.73	1.63 ± 0.21 b	0.51 ± 0.08 b

(b)

Soil material	Treatment	Root_FW	Root_DW	Available_P
Entisol	Control	0.20 ± 0.10 c	0.06 ± 0.03	2.10 ± 0.20 d
	Neem 5%	0.30 ± 0.10 bc	0.09 ± 0.02	18.40 ± 0.60 b
	Neem 2.5%	0.37 ± 0.06 bc	0.06 ± 0.03	9.37 ± 0.40 c
	Mesquite 5%	0.50 ± 0.10 b	0.04 ± 0.03	19.57 ± 0.40 a
	Mesquite 2.5%	0.80 ± 0.10 a	0.08 ± 0.08	9.75 ± 0.40 c
Vertisol	Control	0.17 ± 0.06 c	0.05 ± 0.02	0.39 ± 0.05 e
	Neem 5%	0.50 ± 0.17 b	0.09 ± 0.02	23.13 ± 0.06 a
	Neem 2.5%	0.37 ± 0.12 bc	0.09 ± 0.06	10.48 ± 0.80 c
	Mesquite 5%	0.35 ± 0.05 bc	0.06 ± 0.05	20.40 ± 0.10 b
	Mesquite 2.5%	0.90 ± 0.10 a	0.13 ± 0.02	9.42 ± 0.13 d
Aridisol	Control	0.23 ± 0.06	0.06 ± 0.02	0.30 ± 0.02 c
	Neem 5%	0.37 ± 0.21	0.04 ± 0.03	21.63 ± 0.65 a
	Neem 2.5%	0.17 ± 0.06	0.05 ± 0.01	10.25 ± 0.43 b
	Mesquite 5%	0.20 ± 0.10	0.04 ± 0.03	21.20 ± 0.60 a
	Mesquite 2.5%	0.33 ± 0.06	0.07 ± 0.01	10.27 ± 0.34 b

Note. Tukey grouping letters are shown only for traits with a significant within-soil ANOVA at $p < 0.05$. No grouping letters are presented for Aridisol final height, Aridisol final leaf number, Aridisol root fresh weight, or root dry weight in any soil material because the corresponding ANOVA results were not significant.

3.5. Final Plant Height

Final plant height responded significantly to treatment in the tested Entisol and Vertisol materials, while the response in the tested Aridisol material was not significant at $p < 0.05$ and was interpreted descriptively.

In Entisol, treatment effects were highly significant ($F = 52.95$, $p < 0.001$). Neem 5%, neem 2.5%, and mesquite 2.5% formed the highest Tukey group, with final heights of 44.33, 40.67, and 40.33 cm, respectively. The control and mesquite 5% formed the lower group. This shows that neem biochar, especially at 5%, promoted strong shoot elongation in Entisol. Mesquite 2.5% also supported height growth, but mesquite 5% did not.

In Vertisol, final height was also significantly affected by treatment ($F = 21.79$, $p < 0.001$). Neem 5%, mesquite 5%, and mesquite 2.5% formed the upper group. The control and neem 2.5% formed the lower group. This indicates that Vertisol responded positively to neem 5% and both mesquite treatments in terms of final height.

In the tested Aridisol material, final height showed a marginal treatment effect ($F = 3.45$, $p = 0.051$). Mesquite 5% recorded the highest numerical height, but treatment means were not statistically separated at $p < 0.05$. Final height in this soil material was therefore treated as a descriptive response rather than a confirmed treatment effect.

This soil-dependent height response indicates that biochar performance should not be generalized across contrasting soils without soil-specific testing. Biochar effects on plant growth are widely reported to vary with soil texture, pH, nutrient status, amendment chemistry, and rate [9] [10].

3.6. Leaf Number

Leaf number showed a response pattern that was not always aligned with plant height or biomass. The treatment effect was significant in the tested Entisol and Vertisol materials, while the response in the tested Aridisol material was not significant at $p < 0.05$ and was interpreted descriptively.

In Entisol, treatment significantly affected final leaf number ($F = 41.13$, $p < 0.001$). Mesquite 2.5% produced the highest leaf number at 57.33 leaves plant^{-1} and formed a distinct superior group. The control, neem 5%, neem 2.5%, and mesquite 5% did not differ significantly from one another. This indicates that mesquite 2.5% specifically stimulated leaf production in Entisol, even though neem 5% produced greater shoot biomass.

In Vertisol, leaf number was strongly affected by treatment ($F = 159.78$, $p < 0.001$). Mesquite 5% produced the highest leaf number at 54.00 leaves plant^{-1}. Neem 2.5%, mesquite 2.5%, and neem 5% formed an intermediate group, while the control was lowest. This shows that mesquite 5% promoted leaf formation in Vertisol, but this did not translate into the highest shoot dry weight.

In the tested Aridisol material, final leaf number was not significantly affected by treatment at $p < 0.05$. Treatment means were therefore not interpreted as sta-

tistically separated at $p < 0.05$. The numerical differences in leaf number are reported as descriptive values only.

This disconnect between leaf number and biomass is important. In this experiment, a higher leaf number did not necessarily correspond to higher shoot dry matter. Leaf number should therefore be interpreted separately from biomass accumulation.

3.7. Shoot Fresh and Dry Biomass

Shoot biomass provided the clearest evidence of treatment performance.

In Entisol, shoot fresh weight differed significantly among treatments ($F = 32.12$, $p < 0.001$). Neem 5% produced the highest shoot fresh weight at 6.60 g·plant^{-1}. Neem 2.5% partially overlapped with neem 5%, while mesquite 2.5% and mesquite 5% were lower. The control was the lowest treatment. Shoot dry weight followed a similar pattern. Neem 5% produced the highest dry biomass at 1.75 g·plant^{-1}, while neem 2.5% and mesquite 2.5% were statistically close. This indicates that neem 5% improved dry matter accumulation, not only fresh tissue weight.

In Vertisol, shoot fresh weight and shoot dry weight were also significantly affected by treatment. Neem 5% produced the highest shoot fresh weight and shoot dry weight. Mesquite 2.5% showed partial overlap with the upper group for shoot fresh weight and shoot dry weight. Mesquite 5% increased leaf number, but it did not produce the strongest shoot biomass response. This indicates that leaf formation and biomass accumulation were partly decoupled.

In the tested Aridisol material, shoot fresh weight and shoot dry weight were both significantly affected by treatment. Mesquite 5% produced the highest shoot fresh weight at 3.75 g·plant^{-1} and the highest shoot dry weight at 0.83 g·plant^{-1}. This indicates that the tested Aridisol material showed a clear shoot biomass response to mesquite 5%. However, this response was not accompanied by significant root improvement, so it should be interpreted as a partial shoot response rather than balanced plant improvement.

These biomass results indicate three clear patterns. Neem 5% was the strongest shoot-growth treatment in Entisol and Vertisol. Mesquite 5% was the strongest shoot-biomass treatment in Aridisol. Mesquite 2.5% produced a more root-oriented response in Entisol and Vertisol.

3.8. Root Fresh and Dry Biomass

Root response differed strongly from shoot response.

In the tested Entisol material, root fresh weight differed significantly among treatments ($F = 18.65$, $p < 0.001$). Mesquite 2.5% recorded the highest root fresh weight at 0.80 g·plant^{-1}, followed by mesquite 5%. Root dry weight, however, was not significantly affected ($F = 0.61$, $p = 0.665$). The root response in this soil material therefore reflects a change in root fresh weight rather than a confirmed increase in structural root dry biomass.

In the tested Vertisol material, root fresh weight was significantly affected by

treatment ($F = 19.14$, $p < 0.001$). Mesquite 2.5% recorded the highest root fresh weight at 0.90 g·plant^{-1}, while the control remained lowest. Root dry weight was not significantly affected ($F = 1.85$, $p = 0.196$). This indicates that the treatment effect was expressed in root fresh weight, not in root dry biomass.

In the tested Aridisol material, neither root fresh weight nor root dry weight was significantly affected by treatment. Although mesquite 5% increased shoot biomass, this was not matched by a significant root response. Therefore, the Aridisol response was expressed mainly in shoot biomass rather than in coordinated shoot-root development.

The difference between root fresh and root dry weight is important for interpretation. Root fresh weight includes both tissue mass and water content, while root dry weight better reflects structural biomass. In this study, root dry weight was not significantly affected in any soil material. Root-related conclusions were therefore limited to fresh-weight response and were not treated as evidence of increased structural root biomass.

3.9. Post-Harvest Available Phosphorus

Available phosphorus showed the strongest and most consistent treatment response.

In Entisol, available phosphorus was highly significant ($F = 882.56$, $p < 0.001$). Mesquite 5% produced the highest available P at 19.57 mg·kg^{-1}, followed by neem 5% at 18.40 mg·kg^{-1}. Mesquite 2.5% and neem 2.5% formed the intermediate group, while the control remained lowest.

In Vertisol, available phosphorus was also highly significant ($F = 1882.04$, $p < 0.001$). Neem 5% produced the highest value at 23.13 mg·kg^{-1}, followed by mesquite 5%, neem 2.5%, mesquite 2.5%, and the control. The separation among treatments was clear because within-treatment variability was very low.

In Aridisol, available phosphorus was again highly significant ($F = 1103.25$, $p < 0.001$). Neem 5% and mesquite 5% formed the highest group, while neem 2.5% and mesquite 2.5% formed the intermediate group. The control remained extremely low.

These results show that the acidified biochars acted as phosphorus-enriched amendments. The 5% rate consistently produced higher post-harvest available phosphorus than the 2.5% rate. Plant response, however, did not follow available phosphorus consistently. Neem 5% produced high available P in the tested Aridisol material without a corresponding shoot growth response, while mesquite 2.5% produced moderate available P but higher root fresh weight in the tested Entisol and Vertisol materials.

This agrees with biochar phosphorus literature. Biochar may increase available P directly by adding P-bearing material and indirectly through changes in sorption behavior, nutrient retention, microbial processes, and root-zone chemistry. The agronomic value of this increase depends on the receiving soil material and on other growth-limiting conditions [13] [18].

All three soil materials were calcareous, containing 2.3% to 3.5% $CaCO_3$. In calcareous soils, added phosphate reacts with calcium released from carbonate dissolution to form sparingly soluble calcium phosphate phases. This reaction limits the fraction of applied phosphorus that remains bicarbonate-extractable and maintains soil pH in the alkaline range. The tested Aridisol material had the lowest carbonate content and the lowest baseline available phosphorus of the three soils.

These patterns fit a wider literature in which biochar effects on soil fertility, nutrient transformation, and crop growth are strongly context-dependent [19]-[22], and in which recalcitrance and agronomic performance vary with feedstock and production conditions [23] [24]. Comparison across studies is constrained by how biochars and soils are characterized: proximate and charcoal-analysis procedures define the ash and fixed-carbon fractions [25] [26], bicarbonate extraction defines the available phosphorus reported here [27] [28], and soil survey conventions define the textural terms used to describe the tested materials [29]. Mesquite is of additional interest as a feedstock because *Neltuma juliflora* is both a dryland woody resource and an invasion-management concern in eastern Africa [30].

3.10. Post-Harvest Soil pH and ECe Response

Post-harvest soil pH and ECe were used as supporting chemical indicators to interpret the response of the tested soil materials to acidified biochar application. Because these measurements were available at the treatment level, they were interpreted descriptively as changes relative to the corresponding unamended control within each soil material. The chemical shift was expressed as ΔpH and ΔECe, calculated as treatment value minus the soil-specific control value.

Post-harvest pH remained slightly alkaline in all tested soil materials and treatments (**Table 7**, **Figure 2**). In the tested Vertisol material, pH decreased from 7.71 in the control to 7.65, 7.45, 7.61, and 7.62 under mesquite 2.5%, mesquite 5%, neem 2.5%, and neem 5%, respectively. In the tested Entisol material, pH decreased from 7.72 in the control to 7.68, 7.56, 7.65, and 7.59 under the same treatments. In the tested Aridisol material, pH decreased from 7.72 in the control to 7.68, 7.58, 7.61, and 7.65, respectively. The largest pH decrease was recorded under mesquite 5% in the tested Vertisol material.

Table 7. Post-harvest soil pH and ECe of the tested soil materials under the control and acidified biochar treatments.

Soil material	Treatment	pH	ΔpH vs control	ECe	ΔECe vs control
Vertisol	Control	7.71	0.00	2.52	0.00
	Mesquite 2.5%	7.65	−0.06	2.65	0.13
	Mesquite 5%	7.45	−0.26	2.79	0.27
	Neem 2.5%	7.61	−0.10	2.66	0.14
	Neem 5%	7.62	−0.09	2.98	0.46

Continued

Entisol	Control	7.72	0.00	1.29	0.00
	Mesquite 2.5%	7.68	−0.04	1.36	0.07
	Mesquite 5%	7.56	−0.16	1.42	0.13
	Neem 2.5%	7.65	−0.07	1.41	0.12
	Neem 5%	7.59	−0.13	1.56	0.27
Aridisol	Control	7.72	0.00	3.61	0.00
	Mesquite 2.5%	7.68	−0.04	3.68	0.07
	Mesquite 5%	7.58	−0.14	3.75	0.14
	Neem 2.5%	7.61	−0.11	3.72	0.11
	Neem 5%	7.65	−0.07	3.81	0.20

Note. Values represent post-harvest soil chemical conditions measured at the end of the 60-day pot experiment. ΔpH and ΔECe were calculated as the treatment value minus the corresponding unamended control within each soil material. ECe = electrical conductivity of the saturated paste extract.

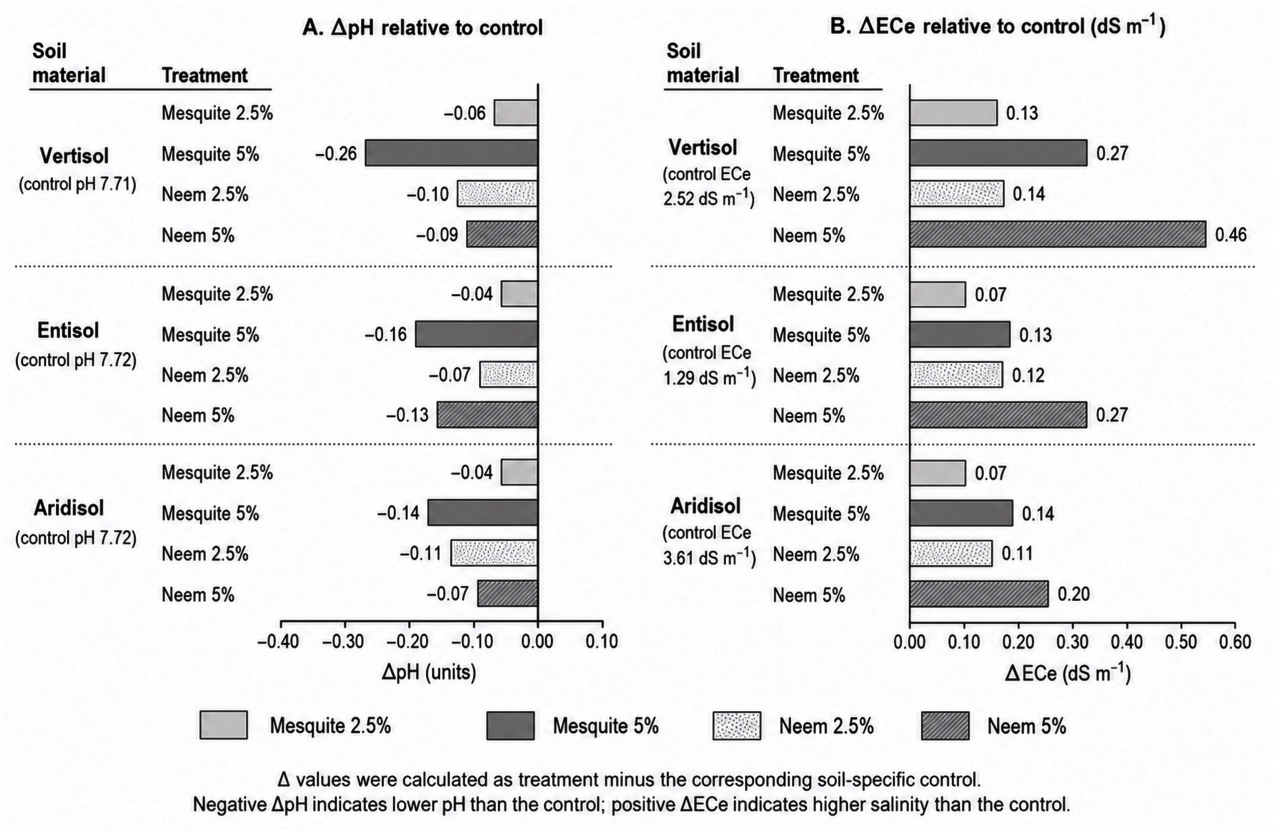

Figure 2. Changes in post-harvest soil pH (ΔpH) and electrical conductivity of the saturated paste extract (ΔECe) relative to the corresponding unamended control in the tested Vertisol, Entisol, and Aridisol materials. Values are descriptive treatment-level measurements; no inferential comparisons were applied.

Post-harvest ECe increased under all acidified biochar treatments relative to the control (Table 7, Figure 2). In the tested Vertisol material, ECe increased from

2.52 dS·m^{-1} in the control to 2.65, 2.79, 2.66, and 2.98 dS·m^{-1} under mesquite 2.5%, mesquite 5%, neem 2.5%, and neem 5%, respectively. In the tested Entisol material, ECe increased from 1.29 dS·m^{-1} in the control to 1.36, 1.42, 1.41, and 1.56 dS·m^{-1}. In the tested Aridisol material, ECe increased from 3.61 dS·m^{-1} in the control to 3.68, 3.75, 3.72, and 3.81 dS·m^{-1}. The largest ECe increase was observed under neem 5% in all three tested soil materials, while the highest absolute post-harvest ECe values occurred in the tested Aridisol material.

Figure 2 shows the post-harvest chemical shift caused by each acidified biochar treatment relative to the corresponding unamended control within each tested soil material. Negative ΔpH values indicate lower soil pH than the control, whereas positive ΔECe values indicate higher salinity than the control.

Post-harvest pH remained slightly alkaline in all soil materials and treatments. ECe increased under all biochar treatments, with shifts of 0.07 to 0.46 dS·m^{-1}. These values were measured at treatment level and are reported as descriptive observations. The tested Aridisol material was the most saline before treatment, at 3.50 dS·m^{-1}, and was also the coarsest in texture, the lowest in carbonate content, and the lowest in baseline available phosphorus.

3.11. Integrated Soil-Specific Interpretation

The results support three distinct soil-specific response patterns.

In the tested Entisol material, neem 5% gave the clearest shoot-growth response. It produced the highest final height, shoot fresh weight, and shoot dry weight. Neem 2.5% also supported shoot growth, while mesquite 2.5% recorded the highest leaf number and root fresh weight. Mesquite 5% produced the highest available phosphorus, but this was not matched by the highest shoot or root dry biomass. This pattern shows that post-harvest available phosphorus was not the only factor shaping plant response.

In the tested Vertisol material, neem 5% produced the clearest shoot response and the highest available phosphorus. Mesquite 2.5% recorded the highest root fresh weight and a strong final height response, while mesquite 5% produced the highest leaf number but not the highest biomass. The more consistent shoot response was observed under the clay-rich and comparatively buffered conditions of this soil material, although the experiment was not designed to isolate the individual effects of texture or buffering capacity. Post-harvest pH and ECe measurements showed that the tested soils remained slightly alkaline, but salinity remained highest in Aridisol. This supports the interpretation that soil texture, buffering capacity, salinity status, and phosphorus dynamics jointly shaped the observed plant response.

In the tested Aridisol material, mesquite 5% produced the clearest shoot biomass response, while root fresh and dry weights were not significantly affected. Neem 5% produced high post-harvest available phosphorus without improving shoot growth. This pattern indicates a selective shoot response rather than balanced plant development. This response pattern occurred in the sandy Aridisol

material with comparatively lower buffering potential; however, the experiment was not designed to isolate the individual effects of these soil properties. The post-harvest pH and ECe values support this interpretation at the treatment level, but replicate-level pH and ECe measurements would be needed to test treatment effects statistically and separate individual biochar effects more precisely.

3.12. Practical Implications

The results do not support a single recommendation for acidified biochar across the tested soil materials.

Under the conditions of this controlled pot experiment, neem 5% gave the clearest aboveground response in the tested Entisol and Vertisol materials. Mesquite 2.5% produced higher root fresh weight in the same two soil materials, but root dry weight was not significantly improved. In the tested Aridisol material, mesquite 5% improved shoot biomass, but this response was not accompanied by a significant root response. These results support soil-specific evaluation of acidified biochar before field recommendation.

Overall, acidified biochar should be treated as a chemically active amendment whose effect depends on feedstock, rate, soil texture, initial salinity status, buffering potential, and phosphorus dynamics. Field validation is required before converting these pot-level responses into field recommendations.

3.13. Synthesis

The results show that the response of fenugreek to acidified neem and mesquite biochars was soil-specific and trait-specific. Neem 5% gave the clearest shoot response in the tested Entisol and Vertisol materials. Mesquite 2.5% produced higher root fresh weight in these two soil materials, but this was not supported by a significant increase in root dry weight. In the tested Aridisol material, mesquite 5% improved shoot biomass, while root traits remained unchanged. Post-harvest available phosphorus increased under biochar treatments, especially at the 5% rate, but plant growth did not follow available phosphorus consistently.

Taken together, the results indicate that acidified biochar performance was strongly influenced by the receiving soil material and could not be explained by phosphorus enrichment alone. Phosphorus enrichment increased post-harvest available P, but plant growth depended on the wider soil-amendment response, including pH shift, salinity status, texture, and buffering potential. In this experiment, the clearest agronomic response occurred in the tested Entisol and Vertisol materials, while the tested Aridisol material showed a more selective shoot response.

Soil pH remained slightly alkaline across all treatments, between 7.45 and 7.72, so the acidified biochars caused only modest pH reductions over the 60 days. ECe increased under all biochar treatments relative to their controls, but the shifts were small, and the highest absolute value, 3.81 $dS \cdot m^{-1}$, was recorded in the Aridisol material, which was already the most saline soil before treatment.

This study has some important limitations. Each soil order was represented by

one composite soil material from one location, so soil order is confounded with site, texture, salinity, and carbonate content. Carbonization temperature was not monitored. Total phosphorus in the acidified biochars was not determined. Post-harvest pH and ECe were measured at treatment level. Plant tissue nutrient concentrations, phosphorus uptake, and nodulation were not measured. Micronutrients were not determined. Future studies should include controlled pyrolysis conditions, total phosphorus determination, replicate-level post-harvest soil chemistry, plant nutrient analysis, and replicated field validation.

4. Conclusions

Acidified neem and mesquite biochars produced contrasting fenugreek responses in the three soil materials tested. Both amendments were strongly acidic, at pH 4.0 for neem and 3.5 for mesquite, and both carried high Olsen-extractable phosphorus, 1500 and 1800 $mg \cdot kg^{-1}$ respectively. Phosphorus enrichment alone, however, did not govern plant performance; the response depended on the receiving soil material, the feedstock, the application rate, and the trait measured.

The Entisol and Vertisol materials gave the clearest gains. Neem at 5% was the strongest treatment for aboveground growth in both, raising final plant height, shoot fresh weight, and shoot dry weight; neem at 2.5% also supported shoot growth in the Entisol material. Mesquite at 2.5% gave the highest root fresh weight in both soils, although root dry weight did not increase significantly.

The Aridisol material behaved differently. Mesquite at 5% increased shoot fresh and dry weight without any significant gain in root fresh or dry weight, and neem at 5% raised post-harvest available phosphorus while leaving shoot growth unchanged. Higher available phosphorus, in this soil, did not translate into balanced plant development. All three soils remained slightly alkaline after treatment, and the accompanying rise in soluble salts was small.

These results do not support a single recommendation for acidified neem and mesquite biochars across contrasting dryland soils. Neem at 5% was the most promising treatment for shoot growth in the Entisol and Vertisol materials, and mesquite at 2.5% favoured root fresh weight in the same soils, though not root dry weight. In the Aridisol material, acidified biochar warrants greater caution, since phosphorus enrichment did not produce coordinated shoot and root growth. Performance appears to depend on feedstock, rate, texture, carbonate content, and initial salinity. Acidified woody biochars therefore offer a plausible route for turning pruning residues into a soil amendment in dryland agriculture, but the approach needs replicated field validation across sites, seasons, and management conditions before it can be recommended.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

J.E. contributed to conceptualization, experimental design, supervision, statistical interpretation, manuscript writing, and revision. M.A. contributed to soil and biochar preparation, pot experiment establishment, data collection, laboratory measurements, and data organization. Both authors reviewed and approved the final manuscript.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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