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Application of *Leucaena leucocephala* (Lam.) and Biochar Improved the Performance and Yield of Pearl Millet (*Pennisetum glaucum* (L.) R. Br.) and Sorghum (*Sorghum bicolor* (L.) Moench) in Saline Soils While Reducing Intrinsic Biochemical Attributes

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Abstract

Soil salinity is increasingly becoming a limiting factor for crop productivity in sub-Saharan Africa. This study aimed to assess the impact of organic and inorganic soil amendments on the growth, yield, and biochemical attributes (total protein, proline, and malondialdehyde) of pearl millet and sorghum in salt-affected soils. The experiment was conducted over two consecutive cropping seasons, from June to September 2021 and January to April 2022. Pearl millet variety IP 19586 and sorghum variety ICSV-700 were exposed to five soil amendments, including a control, *Leucaena leucocephala* (a green manure applied at 5 t/ha), biochar (5 t/ha) made from palm shells, rock phosphate (2.5 t/ha), and dolomitic lime (3.3 t/ha). The experimental design used a split-plot design with randomized blocks, with crops as the primary plot factor and amendments as the subplot factor, each replicated three times. Inorganic fertilizers were applied to each plot at rates of 150 kg/ha NPK (15-15-15) and 100 kg/ha urea (46%). Results showed that different amendments significantly affected sorghum height, while pearl millet growth was not affected ($P < 0.05$). Amended plots showed a substantial improvement in pearl millet grain yield by approximately 64% (ranging from 49% to 101%) and sorghum grain yield by 159% (from 93% to 202%). Proline and MDA contents in pearl millet and sorghum were higher under the control treatment compared to other soil amendments. Leucaena and biochar were the most effective amendments in mitigating soil salinity throughout the crop growth periods. These treatments significantly improved pearl millet and sorghum grain yield and associated MDA content. It can be concluded that organic soil amendments (biochar and leucaena) significantly outperformed ($P < 0.05$) mineral soil amendments (rock phosphate and dolomite) in mitigating soil salinity. This finding holds great promise for agricultural researchers and practitioners seeking to enhance crop productivity in salt-affected soils while also reducing intrinsic biochemical attributes. However, further research is warranted to understand the seasonal dynamics of salinity under organic-based soil amendments.

Keywords

Salinity, Soil Amendments, Crop Yields, West Africa

1. Introduction

Soil degradation is a significant global concern, particularly affecting developing countries where a large portion of the population depends directly on the soil for their livelihoods [1]. Various forms of physical, chemical, and biological land degradation, such as compaction, inorganic/organic contamination, and reduced microbial activity and diversity, have arisen due to excessive human pressures over the last century. These processes have severely impacted global natural resources [2]. Climate change has exacerbated salinity challenges in the root zone, especially in shallow water tables and coastal areas [3] [4]. Soil salinization is a major degradation process, particularly in semi-arid and arid zones [5]. Globally, over one billion hectares of soil are affected by salinity [6] [7]. By 2050, soil salinization is projected to impact more than half of the world's agricultural land [8] [9]. According to the FAO [10], approximately 1.5 million hectares of cropland lose production, and 20 - 46 million hectares experience a decrease in potential production annually due to land salinization, resulting in an annual revenue loss of about $31 million.

Salinity affects 19.09 million hectares in Sub-Saharan Africa (SSA) [1], mainly in Eastern Africa, the coast of Western Africa, the Lake Chad Basin, and isolated areas of Southern Africa [10]-[12]. In Togo, salt-affected soils are documented along the lagoon from Lake Togo to the Mono River, at the edge of the Zio River valley, and in the village of Atti-Apedokoe [13] [14]. In agricultural ecosystems, soil salinity refers to the excessive accumulation of soluble salts within the root zone of plants, resulting in elevated pH (>8.5), sodium adsorption ratio (<13%), exchangeable sodium percentage (<15%), and electrical conductivity (EC > 4 dSm-1). This condition reduces crop yield and compromises soil health. In regions where soil salinity remains unaddressed, a significant portion of agricultural land is abandoned [15].

Soil salinity, arising from both natural and human-induced causes, is predominantly caused by inappropriate irrigation practices and seawater intrusion into coastal farming areas. This issue is further exacerbated by rising sea levels due to climate change and excessive groundwater extraction [9] [11] [16]. Salt-affected soils accumulate soluble salts such as NaCl, $NaHCO_3$, and Na_2CO_3 in the root zone [11] [17]-[19], leading to adverse effects on soil fertility, stability, and biodiversity [20] [21]. The elevated concentration of soluble salts, or salinity, primarily impacts plant growth and crop production by increasing the osmotic potential of the soil solution [22] [23]. Consequently, salinity poses significant challenges to agricultural production, with far-reaching implications for rural livelihoods, economic sectors, environmental sustainability, and overall development [1] [6] [21] [24]. Notably, since 75% of the population across SSA relies on subsistence farming, addressing salinity-related issues is crucial for ensuring food security and sustainable agricultural practices [25] [26].

Mitigating and preventing salinity is crucial for advancing agricultural development, particularly in SSA. This region is transitioning from traditional rain-fed agricultural systems to intensive irrigated agriculture to combat food insecurity, poverty, and climate change. To achieve these goals, proper agricultural field management and adaptation for increased productivity are essential. Additionally, efficient food supply chains are needed to support a growing population in SSA.

A comprehensive set of adaptations and mitigation measures, including the use of salt-tolerant crop varieties [27]-[29] and effective soil and water management practices [22] [25] [26] [30], is essential to address the challenges posed by salinity. Among these measures, soil amendments play a crucial role. Salt-affected soils can be rehabilitated through inorganic and organic amendments. The physical, chemical, and biological properties of soil can be improved by applying organic matter, which accelerates salt leaching, improves aggregate stability, and increases water holding capacity [31], thereby enabling better plant growth in salt-affected soils. Additionally, adding organic matter (OM) can decrease the exchangeable sodium percentage (ESP) and electrical conductivity (EC) [32]. It can also enhance both cation exchange capacity and soluble exchangeable K+, which competes with Na+ in saline sodic soil, limiting its entry at exchangeable sites [31]. This adaptation and mitigation technology is cheaper compared to saltwater drainage and small-scale irrigation technologies. Furthermore, some studies [27] [33] used chemicals such as gypsum to reclaim salt-affected soils, which release Ca2+ to replace Na+ at soil exchangeable sites, followed by leaching with a good quality water supply.

The village of Atti-Apédokoe in Togo is renowned for its high market gardening production and its suitability for cultivating cereals such as rice, millet, and sorghum. However, salt accumulation in the water and soil has negatively affected crop yields, leading to land abandonment by vegetable growers [34]. The residents of Atti-Apédokoe depend on agriculture for their livelihood, and increasing salinization threatens their income and existence. Despite the critical situation, no specific studies have been conducted to explore cropping strategies that could alleviate soil salinity. The combination of salt-tolerant crops and soil amendments under drip irrigation may be a promising strategy to address the salinity of agricultural lands in Atti-Apédokoe. This study aims to assess the effect of various organic and inorganic soil amendments on millet and sorghum growth and yields in salt-affected soils.

2. Materials and Methods

2.1. Study Site

The study was conducted during two consecutive seasons (June to September 2021 and January to April 2022) at Atti-Apedokoe. The village is located 50 km northwest of Lome in the prefecture of Ave, in the maritime region of Togo (longitude 0˚54’ E and latitude 6˚26’ N). The area experiences a tropical sub-guinea climate with a bimodal rainfall distribution, featuring two rainy and two dry seasons. The main rainy season spans from March to June, and the second from August to October. Atti-Apedokoe receives an average annual rainfall of approximately 1200 mm, with temperatures ranging from 24˚C to 33˚C. Subsistence agriculture is the primary economic activity in the village, providing employment for approximately 80% of the population.

The experiment was conducted on-farm at a location chosen specifically for testing and demonstrating agricultural technologies as part of the RESADE project (Improving Agricultural Resilience to Salinity through the development and promotion of pro-poor technologies and management strategies in saline-affected agricultural areas). The soil at the site is characterized as silty-sandy near the surface (0 - 30 cm) and silty-clay-sand at greater depths (>30 cm). The initial physicochemical parameters of the soil at the beginning of the experiment are detailed in **Table 1**. The experiment was repeated in the second season on the same plot.

Table 1. Physicochemical parameters of the topsoil (0 - 30 cm) before the experiment.

	Sand (%)	Silt (%)	Clay (%)	OM[a] (%)	N[b] (%)	P[c] (ppm)	K[d] (meq/100)	pH[e]	ECs (dS/m)	CEC (meq/100)
2021	81	8.6	10.4	2.30	0.064	5.00	0.11	6.3	2.17	13.47
2022	78	12	10	1.79	0.056	2.91	0.08	6.4	1.78	15.22

[a]Walkley and Black method as outlined by Nelson et Sommers [35]; [b]Kjeldahl method; [c]Olsen and Sommers [36]; [d]Helmke et Sparks [37]; [e]Dilution method, Jackson [38].

2.2. Plant Materials

The plant materials used comprised millet variety IP 19586 and sorghum variety ICSV-700. Genotype seeds were received from the International Center for Biosaline Agriculture (ICBA). These specific varieties were chosen for their demonstrated tolerance to saline soil and irrigation water. The characteristics of the millet and sorghum genotypes used in this study are presented in Table 2.

Table 2. Characteristics of crop genotypes used.

Crop	Variety	Origin	Race/ Biological status	Cycle duration (days)	Salinity sensitivity	Height (m)	Use	Yield potential (t/ha)
Sorghum	ICSV-700	ICRISAT	Guinea-OPV	120 - 130	Tolerant	3.0 - 3.5	Dual purpose	3
Millet	IP 19586	ICRISAT	Traditional cultivar/ Landrace	75	Tolerant	1.8	Dual purpose	2.7

OPV: Open Pollinated Varieties.

2.3. Treatments Formulation

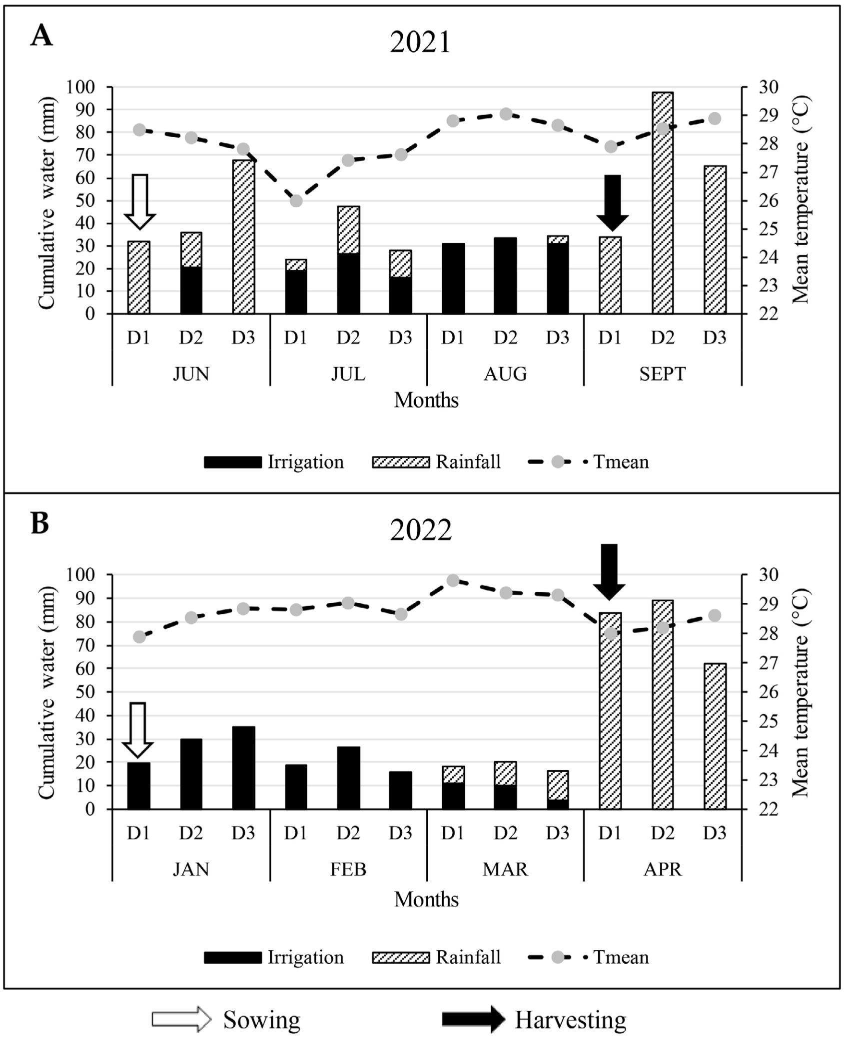
The treatment consisted of five sources of amendment, including the control (Amendment 1), green manure (*Leucaena leucocephala*, Amendment 2), biochar made from palm shells (Amendment 3), rock phosphate (Amendment 4), and lime (Amendment 5). Table 3 shows each amendment's sources and application rate according to recommendations in Togo. The amendments were applied and incorporated into the soil by plowing each year before sowing. *L. leucocephala* (Amendment 2) was air-dried in the shade for two weeks before application. Each plot received mineral fertilizer at 150 kg/ha NPK 15-15-15 and 100 kg/ha urea (46%). The mineral fertilizer rate is recommended by the Togolese Institute of Agricultural Research (ITRA) for cultivating sorghum and millet. The effect of the amendments will be assessed through the difference between the control and the other amended plots.

Table 3. Source of amendments and application rates.

Treatments	Source	Rate	
		kg/6m^2	t/ha
Amendment 1	Control (no application)	0	0
Amendment 2	*Leucaena leucocephala*	3	5
Amendment 3	Biochar (with palm shells)	3	5
Amendment 4	Togo Rock phosphate	1.5	2.5
Amendment 5	Dolomite (28% - 32% CaO) 17% - 18% (B, Cu, Zn, MgO, SO^{3-})	2	3.3

2.4. Experimental Design

A randomized complete block design (RCBD) arranged in a split plot with three replications was used. Crops (pearl millet and sorghum) were assigned to the main plots, while the amendments were assigned to the subplots. The crops were sown in elementary plots of 6 m^2 (3 m × 2 m). Sowing spacing was 80 cm × 30 cm, resulting in a plant density of 83,333 plants per hectare. Weed and pest management, disease control, and bird scaring were conducted as recommended by the Togolese Institute of Agricultural Research (ITRA).



D1: decade 1, D2: Decade 2, D3: decade 3

Figure 1. Cumulative water quantity (rainfall and irrigation) and mean temperature during the experiment in 2021 (A) and 2022 (B).

The experiment's total water input (irrigation + rainfall) amounted to 366 mm in 2021 and 283 mm in 2022. The irrigation water applied was 171 mm in 2021 and 114 mm in 2022. Irrigation was administered daily, except on rainy days, based on the water requirements of pearl millet and sorghum. Irrigation water was sourced from groundwater in the experiment area. The chemical characteristics of the irrigation water are detailed in **Table 4**, with an average EC of 5.6 dS/m, indicating moderate salinity [39], neutral pH, and moderate SAR according to Shainberg and Letey [40]. **Figure 1** illustrates the cumulative water (rain + irrigation) and mean air temperatures (Tmean) per decade during the experiment.

Table 4. Chemical characteristics of used irrigation water.

Year	pH	ECw (dS/m)	Na^+ (mg/l)	K^+ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	SAR
2021	7.33	5.46	25.63	19.3	36.0	12.4	5.2
2022	7.21	5.77	22.3	20.3	38.6	16.3	5.9

2.5. Data Collection

To assess the effect of salinity on plant growth, plant height and stem diameter measurements were taken at 30, 60, and 90 days after sowing (DAS). At physiological maturity, fifteen randomized hills from each subplot were harvested to assess grain yield (Y) and plant biomass (YB) after a controlled drying process.

To assess the plant's adaptive response to salinity, three leaves were collected randomly from each plot for laboratory determination of biochemical parameters: total protein, proline, and malondialdehyde contents, whose accumulation in the plant indicates salt stress. Total protein and proline were determined according to Bradford [41] and Bogdanov *et al.* [42], respectively, as modified and adapted for plant material analysis. The extraction and determination of malondialdehyde (MDA) were conducted following the method described by Heath and Packer [43]. These biochemical parameters were calculated using the following equations:

$$\mathrm{P}\left(\mathrm{mg/gFW}\right)=\frac{\mathrm{D}*\mathrm{R}*\mathrm{V}}{\mathrm{W}*\mathrm{Vs}} \tag{1}$$

where P is protein content; D is possible dilution; R is the value read on the spectrophotometer; V is the total volume of the extract; W is the weight of fresh material (here, leaves); Vs is the sample volume.

$$\mathrm{Pro}\left(\mu\mathrm{g/mgProtein}\right)=\frac{\left(\left(\mathrm{Ae/As}\right)*\left(\mathrm{Ws/Wf}\right)\right)}{\mathrm{Qp}} \tag{2}$$

where Pro is proline content; Ae is the absorbance of the leaf extract; As represents the absorbance of the proline standard solution; Ws is the proline weight in the standard solution (µg); Wf stands for the fresh weight of the leaf (g); Qp is the amount of protein (mg/g fresh material).

$$\mathrm{CMDA}\left(\mathrm{mg/gFW}\right)=\frac{\mathrm{Ae}}{\epsilon*\mathrm{L}} \tag{3}$$

where CMDA is the MDA concentration; Ae is the absorbance of the leaf extract; ϵ is the molar extinction coefficient; L is the width of the cell (1 cm).

The grain yield index (Gij) was calculated (Equation (4)) to evaluate the effect of amendments (leucaena, biochar, rock phosphate, and dolomite) compared to the non-application of amendments (control):

$$\mathrm{Gij} = \frac{\left(\mathrm{Yij} - \mathrm{Y1j}\right)}{\mathrm{Y1j}} \tag{4}$$

where Yij is the biomass/grain yield of crop j under amendment i (i = leucaena, biochar, rock phosphate, and dolomite); Y1j is the yield from the control treatment.

2.6. Statistical Analysis

Statistical analyses were performed using R, version 4.2.2. Data from the two years were pooled for each crop and parameter according to the randomized complete block design (RCBD). The data were subjected to analysis of variance (ANOVA). Treatment means were separated using the Least Significant Difference (LSD) at the 5% probability level.

3. Results and Discussion

3.1. Experimental Conditions

Figure 1 shows the cumulative water quantity (rainfall and irrigation) and the average air temperature during the experiments in 2021 and 2022. In 2021, a total of 366 mm of water was received, compared to 283 mm in 2022. During the first 30 days of the 2021 experiment, plants received more rainfall, reducing their exposure to pronounced salt stress. In 2022, plants received only irrigation water during the first 60 days, coinciding with the flowering and stem extension phases for millet and sorghum, respectively. As a result, the amount of salt water received during the experiment was higher in 2022. The average temperature during both years was similar, with a mean of 29˚C. Table 5 shows the nutrient content and chemical characteristics of the different amendments used.

Table 5. Chemical properties of the amendments during the evaluation of pearl millet and sorghum at Atti-Apedokoe.

	N (%)	P (ppm)	K (meq/100)	OM (%)	Na (meq/100g)	Mg (méq/100g)	Ca (méq/100g)	pH
Leuceana leucocephala	5.60	1.154	0.157	42.14	-	-	-	7.05
Biochar*	2.45	1.470	0.256	36.49	-	-	-	7.20
Rock phosphate	0.1	22.74	2.43	-	0.27	2.77	1.73	7.01
Dolomite (28% - 32% CaO) 17% - 18% (B, Cu, Zn, MgO, SO^{3-})	0.1	-	-	-		87.5	86.7	9.91

-: non determined, *Biochar is made with palm oil shells, N: nitrogen, P: available phosphorus, OM: organic matter, Mg: Magnesium, Ca: calcium.

3.2. Effects of Amendments on Sorghum and Millet Growth

- **Effect on pearl millet and sorghum height**

The impact of different amendment sources on plant height under saline soil and water conditions is shown in **Figure 2**. Millet height ranged from 29.5 cm (control treatment in 2022) to 320.0 cm with Leucaena in 2021, while sorghum height ranged from 43.3 cm (Leucaena treatment in 2022) to 386 cm (rock phosphate in 2021). Although plant height increased from tillering (30 DAS) to maturity (90 DAS) for pearl millet, the growth rate was lower than in the early growth stages (1 - 30 DAS). The growth rate for sorghum remained constant between the growth stages (**Figure 2(C)** & **Figure 2(D)**). No significant effect of amendment sources was observed on the height of both crops ($P > 0.05$), except at flowering (90 DAS) for sorghum ($P < 0.05$). Plant height was statistically similar for plots with different amendments but differed from plants under control (no amendment) at flowering. There was a significant difference in plant height at all growth stages between years ($P < 0.05$) (**Table 6**). Plants in 2022 were shorter than those in 2021 (**Figure 2**). Plant height was not affected by the interaction between amendment sources and year (**Table 6**).

Table 6. ANOVA results on pearl millet and sorghum plant height, stem diameter, protein, proline, malondialdehyde, dry biomass, and grain yield.

Crop	Source of variation	Plant height			Stem diameter			Salt stress indicators			Dry biomass	Grain yield
		30	60	90	30	60	90	Total Protein	Proline	MDA		
Millet	A	0.3668^{ns}	0.448^{ns}	0.273^{ns}	0.9326^{ns}	0.7129^{ns}	0.909^{ns}	0.827^{ns}	0.0191*	0.000434***	0.591^{ns}	0.0012**
	Y	07e−08***	1.37e−08***	3.33e−09***	1.25e−11***	3.47e−08***	1.87e−07***	0.281^{ns}	0.617^{ns}	0.233^{ns}	0.0381*	0.5315^{ns}
	M*Y	0.2908^{ns}	0.726^{ns}	0.791^{ns}	0.9778^{ns}	0.4141^{ns}	0.883^{ns}	0.742^{ns}	0.836^{ns}	0.593^{ns}	0.1973^{ns}	0.5707^{ns}
Sorghum	A	0.257^{ns}	0.413^{ns}	0.0409*	0.939^{ns}	0.515^{ns}	0.582^{ns}	0.22^{ns}	0.637^{ns}	0.00946**	0.00237**	0.0474*
	Y	1.98e−09***	9.37e−06***	2.3e−08***	9.06e−13***	2.93e−08***	1.52e−08***	0.318^{ns}	0.441^{ns}	0.152^{ns}	0.365^{ns}	0.9533^{ns}
	A*Y	0.311^{ns}	0.911^{ns}	0.2067^{ns}	0.656^{ns}	0.260^{ns}	0.345^{ns}	0.612^{ns}	0.835^{ns}	0.97^{ns}	0.278^{ns}	0.1215^{ns}

A: amendment source, MDA: Malondialdehyde, Y: year, A*Y: Amendment and year interaction, ns: not significant, *Significant at the 0.05 probability level; **Significant at the 0.01 probability level; ***Significant at the 0.001 probability level.

Salinity negatively affects plant growth by increasing soil osmotic pressure and interfering with plant nutrition [22]. In this study, we found that applying different amendments under saline conditions did not statistically affect pearl millet plant height during the vegetative growth stages (**Figure 2**). This indicates pearl millet's ability to maintain its growth rate in stressful environments, reflecting its tolerance or adaptation to salt stress. The results corroborate the work of Qaoud *et al.* [44], who demonstrated that pearl millet genotypes moderately tolerate salinity. The soil amendments used in this study appeared favorable for sorghum growth (plant height). During the 2022 cropping season, sorghum plants from the amended plots were taller than those in the control. The significant difference in effect between the control and amendment application on sorghum height at 90 DAS can be attributed to the combined effect of reduced salinity severity induced by the amendment and a decrease in cell division during abiotic stresses (salt and water) [45]. This result corroborates the findings of Punia *et al.* [46], who observed higher plant heights at later stages of crop growth in sorghum. Moreover, Benmahioul *et al.* [47] pointed out that the presence of NaCl in the culture medium leads to a significant decrease in stem length.

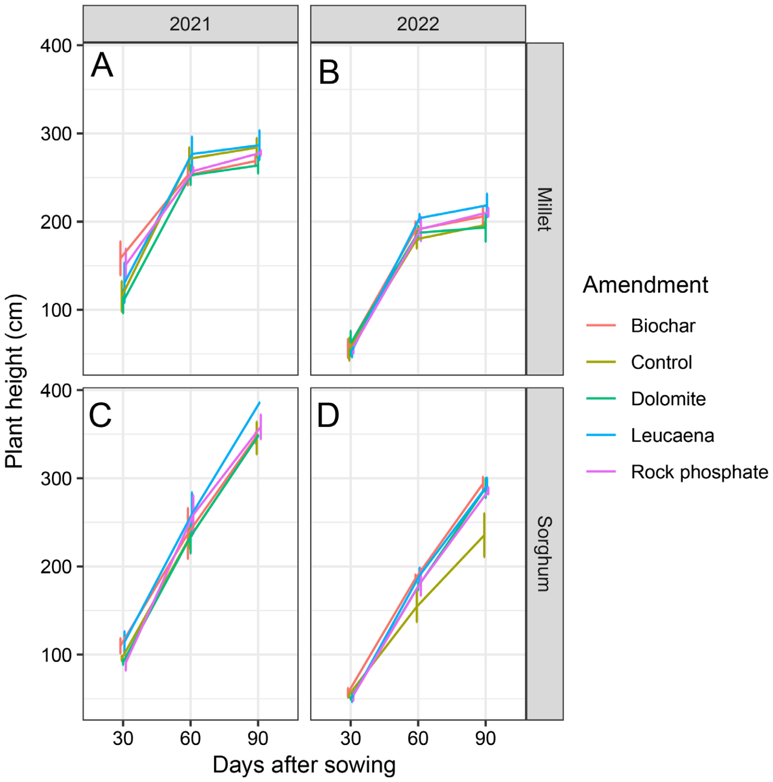


Figure 2. Plant height (cm) measurements were conducted on pearl millet (A and B) and sorghum (C and D) grown in plots amended with biochar, dolomite, leucaena, and rock phosphate at Atti-Apedokoe.

- **Effect on sorghum and millet stem diameter**

Figure 3 shows the stem diameter at all growing stages for millet and sorghum. The stem diameter ranged from 0.64 cm (control in 2022) to 2.8 cm (Biochar in 2021) for millet and from 1.46 cm (control in 2022) to 2.7 cm (Dolomite in 2021) for sorghum. A highly significant effect of the year was observed for stem diameter at all growing stages. In 2022, plants showed the smallest stem diameter at all stages for both millet and sorghum (**Figure 3(B)** & **Figure 3(D)**). Salt stress did not influence the stem diameter at different stages. Neither amendment sources nor the interaction between amendment sources and year affected the stem diameter. This result aligns with Nasri and Benmahioul [48], who found no effect of salt stress on argan stem diameter when grown in a sand and peat mixture. However, it was observed that, irrespective of amendment sources, the stem diameter increased slightly between 30 to 60 DAS and between 60 to 90 DAS in 2021 for both millet and sorghum (**Figure 3(A)** & **Figure 3(C)**). In contrast, stem diameter increased significantly between 30 to 60 DAS (on average 0.54 to 1.49 cm) and slightly between 60 to 90 DAS (on average 1.49 to 1.7 cm) (**Figure 3(D)**), except for millet, where stem diameter decreased after 60 DAS in 2022 (**Figure 3(C)**). This decrease in millet stem diameter in 2022 might be due to plant senescence and/or osmotic effects. Under saline conditions, plants find themselves in a toxic environment and face osmotic pressure [22] [49].

Several studies have reported findings on the effect of salt on plant growth. These findings vary with crops, genotypes [15] [28], experimental conditions (laboratory vs. field) [27] [28] [33] [48], and salt concentrations (low, moderate, and high concentrations) [50]-[53].

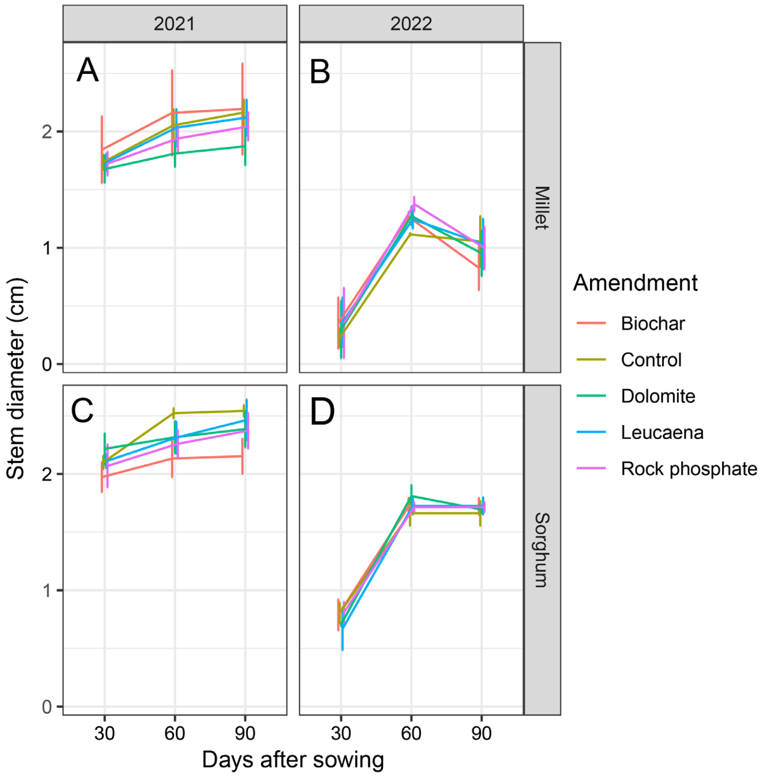
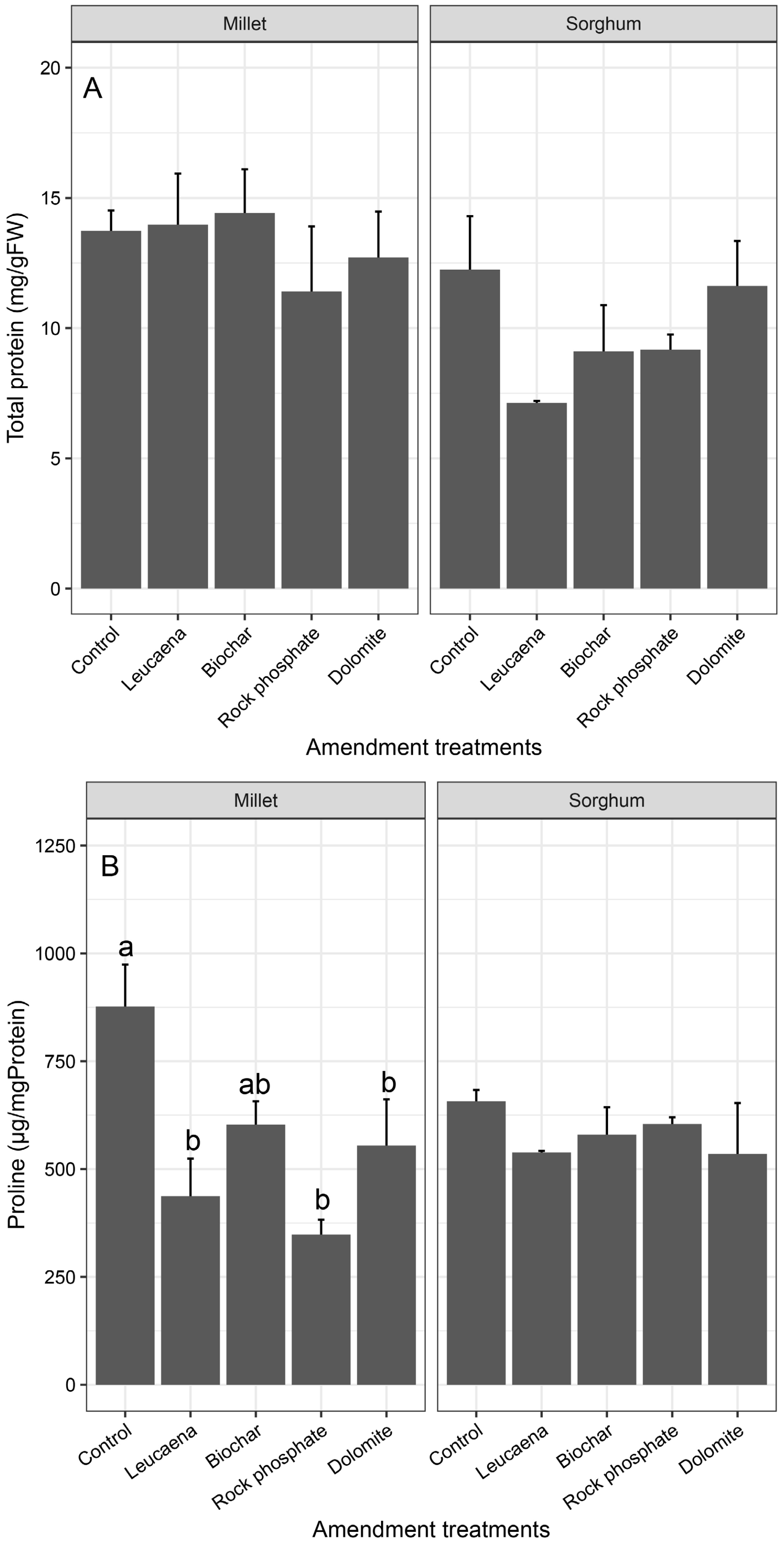
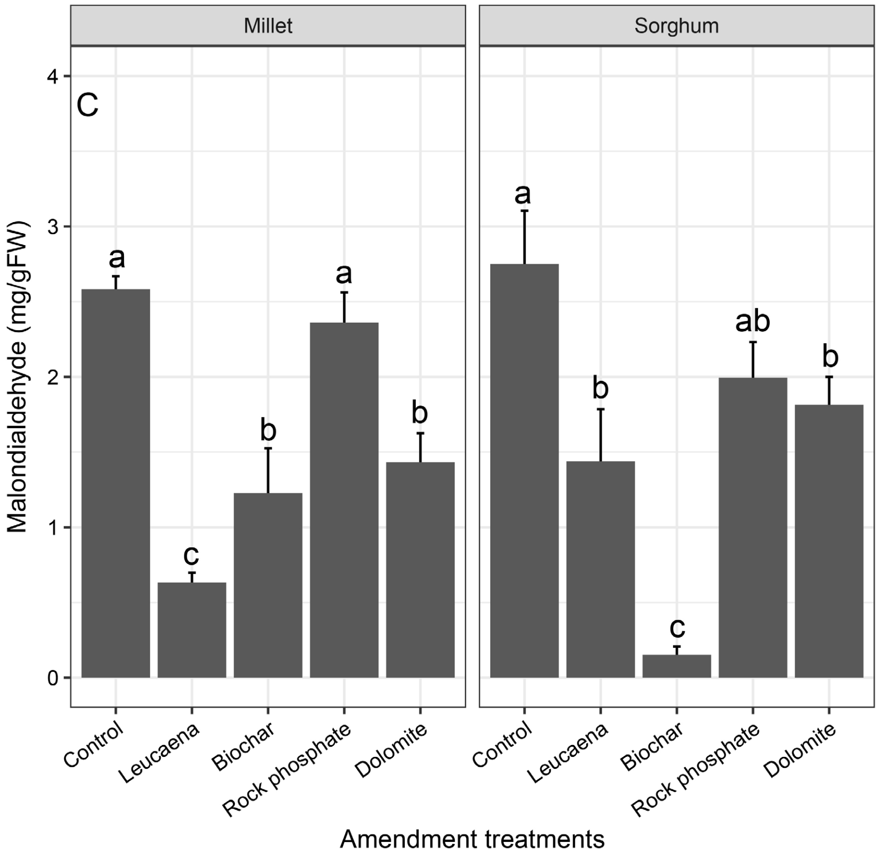


Figure 3. Plant stem diameter measurement was conducted on pearl millet (A and B) and sorghum (C and D) grown on plots amended with biochar, dolomite, leucaena, and rock phosphate at Atti-Apedokoe.

3.3. Plants' Responses to Salt Stress in Amended Soils

Sorghum leaves showed the lowest total protein content where leucaena, biochar, and rock phosphate treatments were applied (**Figure 4(A)**). However, the total protein content in the leaves of millet and sorghum did not differ statistically with the different amendments for both crops ($P > 0.05$) (**Table 6**). This indicates that soil amendments did not produce differences in the accumulation of total protein content compared to the control. Previous studies reported similar findings. Zahra *et al.* [54] reported insignificant differences between stresses (saline and non-saline pots) for protein content in roots of two maize genotypes. However, Tort and Turkyilmaz [55] found that protein content in barley leaves varied with salt concentration, with 120 mM of sodium chloride inducing higher protein content.


Millet
Sorghum
A
Total protein (mg/gFW)
0
5
10
15
20
Control
Leucaena
Biochar
Rock phosphate
Dolomite
Amendment treatments
Millet
Sorghum
B
Proline (µg/mgProtein)
0
250
500
750
1000
1250
a
b
ab
b
b
Control
Leucaena
Biochar
Rock phosphate
Dolomite
Amendment treatments



Histograms without letters are not significantly different.

Figure 4. Biochemical attributes in leaves at 30 DAS: total protein (A), proline (B), and malondialdehyde (MDA) (C).

Statistical analysis showed significant differences in millet leaves' proline content ($P < 0.05$), whereas for sorghum, there was no significant difference (**Table 6**). The proline content for millet was significantly high under control conditions, where no soil amendments were applied. This suggests that amendments influenced proline content. Plants from plots amended with rock phosphate, leucaena, and dolomite showed the lowest proline content, while those under biochar application showed intermediate proline content (**Figure 4(B)**). Plants usually accumulate proline in response to stress [56]. Treatments with lower proline content relative to the control for millet indicate that those amendments contributed less to salt stress. However, proline content has been reported to increase in plants with salt stress by Savouré *et al.* [57] and Toumi *et al.* [58]. Our results for pearl millet suggest the contrary. In sorghum leaves, proline content did not differ among amended treatments, possibly due to a higher threshold of salt stress in sorghum [58] [59]. This salt insensitivity in sorghum plants could also be attributed to the intrinsic characteristics of the genotypes, such as salt tolerance and salt sensitivity.

The MDA concentration effectively assesses oxidative stress damage to the cell membrane [60]. In this study, no difference was observed in MDA accumulation between the control and rock phosphate treatments on pearl millet. Biochar, leucaena, and dolomitic lime significantly reduced MDA in both pearl millet and sorghum leaves (**Figure 4(C)**). There was no significant difference in MDA between the control and rock phosphate treatments in pearl millet and sorghum. Millet and sorghum showed the lowest MDA accumulation under leucaena and biochar amendments, respectively. The low level of MDA accumulation indicates better protection of cell membranes against oxidative damage induced by salt accumulation in plants. Our findings align with several studies [58] [61]-[63] that reported various MDA content depending on the stress level and the genotype of sorghum, halophyte (*Atriplex halimus* L. and *Atriplex canescens* (Pursh) Nutt), pearl millet, and colza. It can be concluded that soil amendment with leucaena and biochar reduces salt accumulation in the root zone, and millet and sorghum differ in their ability to respond to salinity in their leaf cells.

3.4. Effect of Soil Amendment on Crop Yields under Saline Conditions

- **Dry biomass yield**

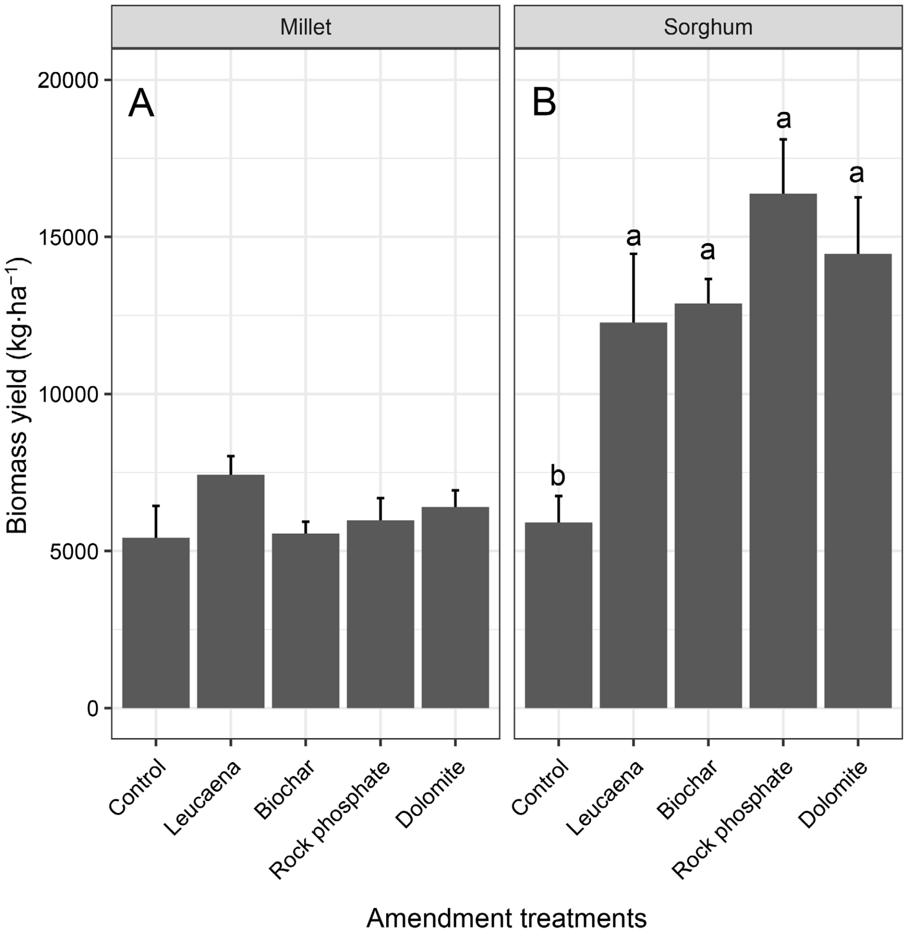


Figure 5. Effect of amendment sources on dry biomass yields measured from pearl millet (A) and sorghum (B) at Atti-Apedokoe. (Histograms without letters are not significantly different).

The results for the dry biomass yield are depicted in **Figure 5**. Average dry biomass yield varied from 5418.6 kg/ha (control) to 7424.5 kg/ha (leucaena) for millet (**Figure 5(A)**) and from 5912.5 to 16371.9 kg/ha for sorghum (**Figure 5(B)**). Amendment sources affected dry millet and sorghum biomass differently. Notably, there was a significant effect only on the dry biomass yield of sorghum ($P < 0.01$) (**Table 6**). The lowest average dry biomass yield was obtained from the control treatment, while the application of amendments induced high biomass production. Application of rock phosphate showed the highest dry biomass; however, this was not significantly different from the biomass recorded from leucaena, dolomite, and biochar applications (**Figure 5**). In general, the application of soil amendments increased dry biomass by 106 to 177%. Furthermore, there was a significant difference between years only for millet dry biomass, with 2021 showing the highest biomass. The amendment-year interaction was not statistically significant for dry biomass yield for both millet and sorghum ($P > 0.05$) (**Table 6**). Rekaby *et al.* [64] reported similar findings, observing that applying organic amendments (biochar, humic acid, and compost) significantly increased the dry biomass yield of barley compared to a control treatment.

- **Grain yield**

The results showed that neither year nor amendment-year interaction significantly affects grain yield for millet and sorghum. However, soil amendments significantly affected grain yields ($P < 0.05$) (**Table 6**). For millet, the lowest grain yield (1100.3 kg/ha) was observed under the control (without amendment application), followed by rock phosphate (1640.8 kg/ha), biochar (1681.4 kg/ha), and dolomite (1691.7 kg/ha), which were statistically not different. The leucaena treatment showed the highest grain yield for millet (2214 kg/ha) (**Figure 6(A)**). The application of amendments improved grain yields for millet by 49% - 101%, with an average increase of 64%. For sorghum, the application of biochar and leucaena showed the highest grain yields (1153.3 and 1158 kg/ha, respectively), followed by rock phosphate (946.9 kg/ha) and dolomite (737.3 kg/ha), whereas the control showed the lowest grain yield (381.3 kg/ha) (**Figure 6(B)**). The application of amendments improved grain yields by 93% to 202% (an average increase of 159%) for sorghum. Applying amendments, regardless of the crop, resulted in better grain yields than not applying them, which is the farmers' usual practice in the area. Millet performed better than sorghum, and grain yield responses to amendments under saline conditions varied slightly depending on the amendment source. Organic amendments (biochar and leucaena) responded better to salinity than chemical amendments (rock phosphate and dolomite), which produced intermediate grain yields for millet and sorghum. Leucaena, in particular, outperformed all other amendment sources (**Figure 6**). The amendments significantly improved salt-affected soil conditions by reducing salinity and sodicity, enhancing soil structure, and increasing nutrient availability. Organic amendments like leucaena and biochar likely improved the soil's physical properties, water retention, and microbial activity more effectively than inorganic amendments like dolomite and rock phosphate. Increasing water infiltration and drainage helps leach out excess salts.

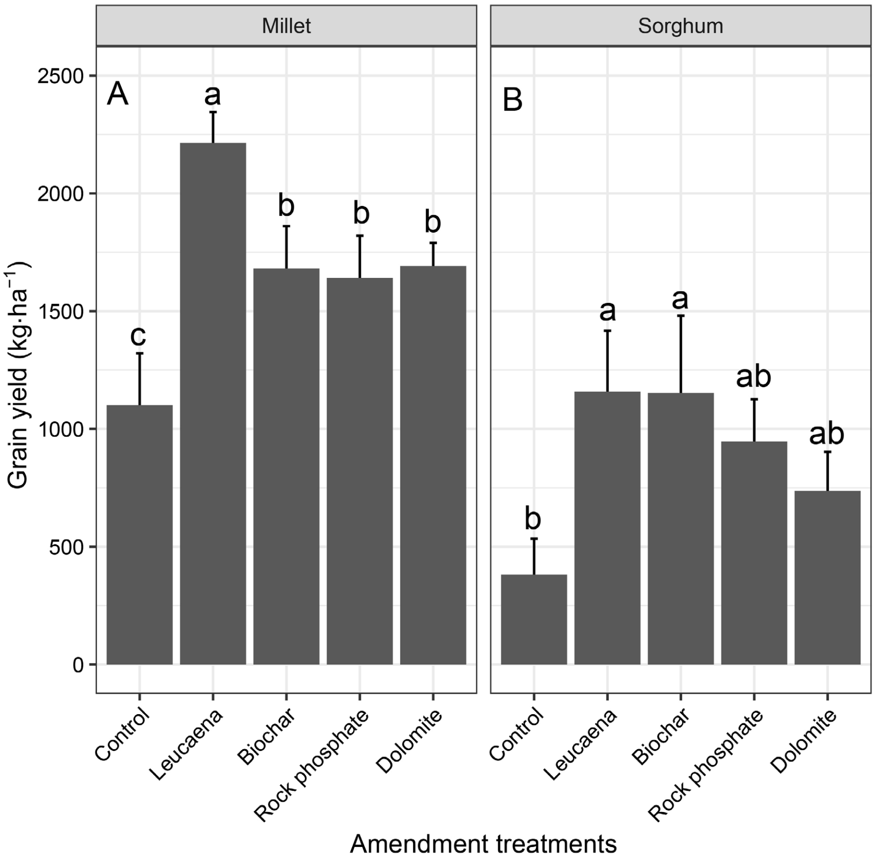


Figure 6. Effect of amendment sources on grain yields measured from pearl millet and sorghum at Atti-Apedokoe. (Histograms with the same letter are not significantly different).

Organic matter (OM) improves the mineral nutrient status and growth of plants in saline soils by supplying nutrients, particularly N, P, and K [32] [65]. Moreover, mulching benefits saline soils by reducing evaporation from the soil surface and encouraging a downward flow of soil water [49]. The response of crops to amendments under saline conditions depends on the type of amendment (organic vs. mineral) and the type of organic matter (leucaena vs. biochar) (**Table 5**). The characteristics of each amendment used in the study were compared. Leucaena and biochar showed high OM and N content, making them crucial for improving soil structure, supporting plant nutrient provision, and limiting soil water evaporation. Amendment with dolomite did not perform as well as leucaena and biochar. However, this amendment contains calcium and magnesium, reducing soil sodium levels and increasing calcium and sulfur provision to plants. The low performance of dolomite compared to the organic amendments might be due to the timing of application (one day before sowing). There was likely insufficient time for reactions to occur in the soil. Our findings align with Litardo *et al.* [66], who found that the application of mineral and organic amendments on rice affects its reproductive growth. Among all their treatments, compost, sugarcane filter cake, and leonardite showed the highest yield values compared to control under saline conditions. However, the authors observed that the application of the amendments did not affect vegetative growth (plant height, tiller number, and straw dry mass weight). Other authors, such as Choudhary *et al.* [67], showed that in the case of saline-sodic irrigation, sugar yield from sugarcane under farmyard manure treatment was comparable to the combination of gypsum and farmyard manure treatment but was significantly higher than that of gypsum alone.

Additionally, the significant increase in millet grain yield with leucaena and sorghum yield with biochar and leucaena was associated with the plant's MDA content. Treatments with lower MDA content produced more yield, likely due to better cell membrane protection from oxidative damage, which might influence photosynthesis and the accumulation of assimilates. Toderich *et al.* [63] found similar results for pearl millet in response to different soil salinity levels, with yield decreasing as salinity increases. Few studies have reported on the benefits of biochar and leucaena for plants under saline conditions. In a critical review, Ali *et al.* [68] noted that biochar application increased plant growth, biomass, and yield under saline conditions. Ibrahim *et al.* [69] found that biochar soil amendment effectively alleviated the effects of salinity on sorghum seedling growth. Among all biochar levels tested, a 5% biochar level had a significant impact on mitigating salt stress. Kul *et al.* [70] also found that biochar amendments at 5% and 10% (v/v) significantly decreased malondialdehyde (MDA) and proline contents while improving tomato plant performance, including plant height, leaf area, shoot fresh and dry weight, number of leaves, and root fresh and dry weight under saline conditions. *L. leucocephala* showed promise for afforestation of sodic soils due to its potential to produce higher biomass and improve the fertility of these soils [71].

The experimental conditions impacted the results. Crop response to the application of amendments was more positive in 2021 than in 2022 (**Figure 2** and **Figure 3**). This can be explained by the experiment being conducted during the short dry season in 2021, which was not completely dry. The crops benefited from rain and probably leaching, which likely reduced the severity of salinity. However, the analysis of variance for the amendments and year interaction was not significant for all parameters measured. Therefore, the plants reacted similarly to the amendments during both years.

4. Conclusion

The findings of this study have potential implications for agricultural practitioners and professionals in soil science and crop production. The differential impact of amendments on the growth of pearl millet and sorghum in saline conditions, with sorghum showing positive effects and pearl millet showing no significant impact, suggests the need for crop-specific approaches to soil salinity management. The study also revealed that both pearl millet and sorghum experienced osmotic and oxidative stresses, as indicated by elevated proline and MDA levels in the control group compared to the amended plants. The application of amendments led to a substantial improvement in grain yield, with an increase of up to 101% (averaging 64%) for pearl millet and up to 202% (averaging 159%) for sorghum. Among the various amendments tested, leucaena and biochar were identified as the most effective in mitigating soil salinity. These treatments significantly enhanced the grain yield of both pearl millet and sorghum and were correlated with MDA content. Notably, the organic amendments, specifically biochar and leucaena, outperformed the mineral amendments, such as rock phosphate and dolomite, in mitigating soil salinity.

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Conflicts of Interest

The authors declare no conflicts of interest. The funders had no role in the study's design, data collection, analysis, interpretation, manuscript writing, or decision to publish the results.

References

[1] Tully, K., Sullivan, C., Weil, R. and Sanchez, P. (2015) The State of Soil Degradation in Sub-Saharan Africa: Baselines, Trajectories, and Solutions. *Sustainability*, **7**, 6523-6552. https://doi.org/10.3390/su7066523

[2] Ondrasek, G., Rengel, Z. and Veres, S. (2011) Soil Salinisation and Salt Stress in Crop Production. In: *Abiotic Stress in Plants-Mechanisms and Adaptations*, InTech, 171-190. https://doi.org/10.5772/22248

[3] Mukhopadhyay, R., Sarkar, B., Jat, H.S., Sharma, P.C. and Bolan, N.S. (2021) Soil Salinity under Climate Change: Challenges for Sustainable Agriculture and Food Security. *Journal of Environmental Management*, **280**, Article 111736. https://doi.org/10.1016/j.jenvman.2020.111736

[4] Corwin, D.L. (2021) Climate Change Impacts on Soil Salinity in Agricultural Areas. *European Journal of Soil Science*, **72**, 842-862. https://doi.org/10.1111/ejss.13010

[5] Zhou, Y., Chen, S., Hu, B., Ji, W., Li, S., Hong, Y., *et al.* (2022) Global Soil Salinity Prediction by Open Soil Vis-NIR Spectral Library. *Remote Sensing*, **14**, Article 5627. https://doi.org/10.3390/rs14215627

[6] Hassani, A., Azapagic, A. and Shokri, N. (2020) Predicting Long-Term Dynamics of Soil Salinity and Sodicity on a Global Scale. *Proceedings of the National Academy of Sciences*, **117**, 33017-33027. https://doi.org/10.1073/pnas.2013771117

[7] Ivushkin, K., Bartholomeus, H., Bregt, A.K., Pulatov, A., Bui, E.N. and Wilford, J.

(2018) Soil Salinity Assessment through Satellite Thermography for Different Irrigated and Rainfed Crops. *International Journal of Applied Earth Observation and Geoinformation*, **68**, 230-237. https://doi.org/10.1016/j.jag.2018.02.004

[8] Shrivastava, P. and Kumar, R. (2015) Soil Salinity: A Serious Environmental Issue and Plant Growth Promoting Bacteria as One of the Tools for Its Alleviation. *Saudi Journal of Biological Sciences*, **22**, 123-131. https://doi.org/10.1016/j.sjbs.2014.12.001

[9] Ullah, A., Bano, A. and Khan, N. (2021) Climate Change and Salinity Effects on Crops and Chemical Communication between Plants and Plant Growth-Promoting Microorganisms under Stress. *Frontiers in Sustainable Food Systems*, **5**, Article 618092. https://doi.org/10.3389/fsufs.2021.618092

[10] FAO (2021) The State of the World's Land and Water Resources for Food and Agriculture.

[11] FAO (2021) Global Map of Salt-Affected Soils: GSASmap V1.0.

[12] Szabolcs, I. (1989) Salt-Affected Soils. CRC Press.

[13] Harper, R.J., Dell, B., Ruprecht, J.K., Sochacki, S.J. and Smettem, K.R.J. (2021) Salinity and the Reclamation of Salinized Lands. In: *Soils and Landscape Restoration*, Elsevier, 193-208. https://doi.org/10.1016/b978-0-12-813193-0.00007-2

[14] Khamidov, M., Ishchanov, J., Hamidov, A., Donmez, C. and Djumaboev, K. (2022) Assessment of Soil Salinity Changes under the Climate Change in the Khorezm Region, Uzbekistan. *International Journal of Environmental Research and Public Health*, **19**, Article 8794. https://doi.org/10.3390/ijerph19148794

[15] Ashraf, M. and Waheed, A. (1993) Responses of Some Local/exotic Accessions of Lentil (*Lens culinaris* Medic.) to Salt Stress. *Journal of Agronomy and Crop Science*, **170**, 103-112. https://doi.org/10.1111/j.1439-037x.1993.tb01063.x

[16] Jamil, A., Riaz, S., Ashraf, M. and Foolad, M.R. (2011) Gene Expression Profiling of Plants under Salt Stress. *Critical Reviews in Plant Sciences*, **30**, 435-458. https://doi.org/10.1080/07352689.2011.605739

[17] Jhariya, M.K. and Raj, A. (2013) Effect of Salinity on Plant Growth and Their Management. In: Sharma, H. and Sabalpa, A.N., Eds., *Terminology of Plant Pathology*, Publisher, 19-21.

[18] Daliakopoulos, I.N., Tsanis, I.K., Koutroulis, A., Kourgialas, N.N., Varouchakis, A.E., Karatzas, G.P., *et al.* (2016) The Threat of Soil Salinity: A European Scale Review. *Science of the Total Environment*, **573**, 727-739. https://doi.org/10.1016/j.scitotenv.2016.08.177

[19] Tessema, N., Yadeta, D., Kebede, A. and Ayele, G.T. (2023) Soil and Irrigation Water Salinity, and Its Consequences for Agriculture in Ethiopia: A Systematic Review. *Agriculture*, **13**, Article 109. https://doi.org/10.3390/agriculture13010109

[20] Abbasi, H., Jamil, M., Haq, A., Ali, S., Ahmad, R., Malik, Z., *et al.* (2016) Salt Stress Manifestation on Plants, Mechanism of Salt Tolerance and Potassium Role in Alleviating It: A Review. *Zemdirbyste-Agriculture*, **103**, 229-238. https://doi.org/10.13080/z-a.2016.103.030

[21] Carter, D.L. (2018) Salinity and Plant Productivity. In: Rechcigl, M., Ed., *Handbook of Agricultural Productivity*, CRC Press, 117-133.

[22] Machado, R.M.A. and Serralheiro, R.P. (2017) Soil Salinity: Effect on Vegetable Crop Growth. Management Practices to Prevent and Mitigate Soil Salinization. *Horticulturae*, **3**, Article 30. https://doi.org/10.3390/horticulturae3020030

[23] Sanchez, P., Palm, C., Sachs, J., Denning, G., Flor, R., Harawa, R., *et al.* (2007) The

African Millennium Villages. *Proceedings of the National Academy of Sciences*, **104**, 16775-16780. https://doi.org/10.1073/pnas.0700423104

[24] Toenniessen, G., Adesina, A. and DeVries, J. (2008) Building an Alliance for a Green Revolution in Africa. *Annals of the New York Academy of Sciences*, **1136**, 233-242. https://doi.org/10.1196/annals.1425.028

[25] Yoshida, S. (1981) Fundamentals of Rice Crop Science. International Rice Research Institute.

[26] Cuevas, J., Daliakopoulos, I.N., del Moral, F., Hueso, J.J. and Tsanis, I.K. (2019) A Review of Soil-Improving Cropping Systems for Soil Salinization. *Agronomy*, **9**, 295. https://doi.org/10.3390/agronomy9060295

[27] Gharaibeh, M.A., Eltaif, N.I. and Albalasmeh, A.A. (2011) Reclamation of Highly Calcareous Saline Sodic Soil Usingatriplex Halimusand By-Product Gypsum. *International Journal of Phytoremediation*, **13**, 873-883. https://doi.org/10.1080/15226514.2011.573821

[28] Hamrouni, L., Abdallah, F.B., Abdelly, C. and Ghorbel, A. (2008) La Culture *in Vitro*: Un Moyen Rapide et Efficace Pour Sélectionner des Génotypes de Vigne Tolérant La Salinité. *Biologies*, **331**, 152-163. https://doi.org/10.1016/j.crvi.2007.11.002

[29] Reddy, B., Ashok Kumar, A., Reddy, P., Ibrahim, M., Ramaiah, B., Dakheel, A., Ramesh, S. and Krishnamurthy, L. (2010) Cultivar Options for Salinity Tolerance in Sorghum. *Journal of SAT Agricultural Research*, **8**, 1-5.

[30] Zalidis, G. (1998) Management of River Water for Irrigation to Mitigate Soil Salinization on a Coastal Wetland. *Journal of Environmental Management*, **54**, 161-167. https://doi.org/10.1006/jema.1998.0226

[31] Walker, D.J. and Bernal, M.P. (2008) The Effects of Olive Mill Waste Compost and Poultry Manure on the Availability and Plant Uptake of Nutrients in a Highly Saline Soil. *Bioresource Technology*, **99**, 396-403. https://doi.org/10.1016/j.biortech.2006.12.006

[32] Qadir, M., Ghafoor, A. and Murtaza, G. (2001) Use of Saline-Sodic Waters through Phytoremediation of Calcareous Saline-Sodic Soils. *Agricultural Water Management*, **50**, 197-210. https://doi.org/10.1016/s0378-3774(01)00101-9

[33] Horney, R.D., Taylor, B., Munk, D.S., Roberts, B.A., Lesch, S.M. and Plant, R.E. (2005) Development of Practical Site-Specific Management Methods for Reclaiming Salt-Affected Soil. *Computers and Electronics in Agriculture*, **46**, 379-397. https://doi.org/10.1016/j.compag.2004.11.008

[34] Bouka, E., Ganyo, K.K., Ablédé, K.A., Mathé, E.E. and Sogbédji, M.J. (2019) Caractérisation de l'état de Salinité des Sols et des Eaux Du Site Maraîcher de Atti-Apédokoe dans la Préfecture de l'Avé au Togo. *Bulletin de la Recherche Agronomique du Bénin*, 162-174. https://www.researchgate.net/publication/341792938_Caracterisation_de_l'etat_de_salinite_des_sols_et_des_eaux_du_site_maraicher_de_Atti-Apedokoe_dans_la_prefecture_de_l'Ave_au_Togo#fullTextFileContent

[35] Nelson, D.W. and Sommers, L.E. (1996) Total Carbon, Organic Carbon and Organic Matter. In: Sparks, D.L., Ed., *Methods of Soil Analysis*, *Part* 3. *Chemical Methods*, American Society of Agronomy and Soil Science Society of America, 961-1010.

[36] Olsen, S.R. and Sommers, L.E. (1982) Phosphorus. In: *Methods of Soil Analysis*, *Part* 2, American Society of Agronomy and Soil Science Society of America, 403-430.

[37] Helmke, P.A. and Sparks, D.L. (1996) Lithium, Sodium, Potassium, Rubidium and Cesium. In: Sparks, D.L., Ed., *Methods of Soil Analysis*, *Part* 3, *Chemical Methods*,

American Society of Agronomy and Soil Science Society of America, 551-574.

[38] Jackson, M.L. (1959) Soil Chemical Analysis. *Journal of Agricultural and Food Chemistry*, **7**, Article 138.

[39] Rhoades, J.D., Kandiah, A. and Mashali, A.M. (1992) The Use of Saline Waters for Crop Production. FAO Irrigation and Drainage Paper 48.

[40] Shainberg, I. and Letey, J. (1984) Response of Soils to Sodic and Saline Conditions. *Hilgardia*, **52**, 1-57. https://doi.org/10.3733/hilg.v52n02p057

[41] Bradford, M.M. (1976) A Rapid and Sensitive Method for the Quantitation of Microgram Quantities of Protein Utilizing the Principle of Protein-Dye Binding. *Analytical Biochemistry*, **72**, 248-254. https://doi.org/10.1006/abio.1976.9999

[42] Bogdanov, S., Lüllmann, C., Martin, P., Der Ohe, W, V., Russmann, H., Vorwohl, G. Oddo, P., *et al.* (1999) Honey Quality and International Regulatory Standards: Review of the International Honey Commission. *Bee World*, **80**, 61-69. https://doi.org/10.1080/0005772X.1999.11099428

[43] Heath, R.L. and Packer, L. (1968) Photoperoxidation in Isolated Chloroplasts. *Archives of Biochemistry and Biophysics*, **125**, 189-198. https://doi.org/10.1016/0003-9861(68)90654-1

[44] Qaoud, H.A., Ali, I.A., Al-Fares, H., Qubbaj, T. and Shtaya, M.J.Y. (2023) Effect of Salinity on the Growth and Some Morphological Traits of Pearl Millet. *Pakistan Journal of Botany*, **55**, 807–811. https://doi.org/10.30848/pjb2023-3(20)

[45] Benmahioul, B., Khelil, B., Kaïd-Harche, M. and Daguin, F. (2010) Étude de la germination et de l'effet du substrat sur la croissance de jeunes semis de I L. Germination Study and Substrate Effect on the Growth of Young Seedlings of *Pistacia vera* L. *Acta Botanica Malacitana*, **35**, 107-114. https://doi.org/10.24310/abm.v35i0.2865

[46] Punia, H., Tokas, J., Malik, A., Singh, S., Phogat, D.S., Bhuker, A., *et al.* (2021) Discerning Morpho-Physiological and Quality Traits Contributing to Salinity Tolerance Acquisition in Sorghum [*Sorghum bicolor* (L.) Moench]. *South African Journal of Botany*, **140**, 409-418. https://doi.org/10.1016/j.sajb.2020.09.036

[47] Benmahioul, B., Daguin, F. and Kaid-Harche, M. (2009) Effects of Salt Stress on Germination and *in Vitro* Growth of Pistachio (*Pistacia vera* L.). *Comptes Rendus. Biologies*, **332**, 752-758. https://doi.org/10.1016/j.crvi.2009.03.008

[48] Nasri, S. and Benmahioul, B. (2015) Effet de la contrainte saline sur la germination et la croissance de quelques provenances algeriennes d'arganier (*Argania spinosa* L.). *Algerian Journal of Arid Environment*, **5**, 98-112.

[49] Paranychianakis, N.V. and Chartzoulakis, K.S. (2005) Irrigation of Mediterranean Crops with Saline Water: From Physiology to Management Practices. *Agriculture, Ecosystems & Environment*, **106**, 171-187. https://doi.org/10.1016/j.agee.2004.10.006

[50] Amira, M.S. and Qados, A. (2011) Effect of Salt Stress on Plant Growth and Metabolism of Bean Plant *Vicia faba* (L.). *Journal of the Saudi Society of Agricultural Sciences*, **10**, 7-15.

[51] Magistad, O.C., Ayers, A.D., Wadleigh, C.H. and Gauch, H.G. (1943) Effect of Salt Concentration, Kind of Salt, and Climate on Plant Growth in Sand Cultures. *Plant Physiology*, **18**, 151-166. https://doi.org/10.1104/pp.18.2.151

[52] Mayak, S., Tirosh, T. and Glick, B.R. (2004) Plant Growth-Promoting Bacteria Confer Resistance in Tomato Plants to Salt Stress. *Plant Physiology and Biochemistry*, **42**, 565-572. https://doi.org/10.1016/j.plaphy.2004.05.009

[53] Kaiwen, G., Zisong, X., Yuze, H., Qi, S., Yue, W., Yanhui, C., *et al.* (2020) Effects of Salt Concentration, Ph, and Their Interaction on Plant Growth, Nutrient Uptake, and Photochemistry of Alfalfa (*Medicago sativa*) Leaves. *Plant Signaling & Behavior*, **15**, Article 1832373. https://doi.org/10.1080/15592324.2020.1832373

[54] Zahra, N., Mahmood, S. and Raza, Z.A. (2018) Salinity Stress on Various Physiological and Biochemical Attributes of Two Distinct Maize (*Zea mays* L.) Genotypes. *Journal of Plant Nutrition*, **41**, 1368-1380. https://doi.org/10.1080/01904167.2018.1452939

[55] Tort, N. and Turkyilmaz, B.A. (2004) Physiological Investigation on the Mechanisms of Salinity Tolerance in Some Barley Culture Forms. *Journal of Forensic Sciences*, **27**, 1-16.

[56] Szabados, L. and Savouré, A. (2010) Proline: A Multifunctional Amino Acid. *Trends in Plant Science*, **15**, 89-97. https://doi.org/10.1016/j.tplants.2009.11.009

[57] Savouré, A., Jaoua, S., Hua, X., Ardiles, W., Van Montagu, M. and Verbruggen, N. (1995) Isolation, Characterization, and Chromosomal Location of a Gene Encoding the δ1-Pyrroline-5-Carboxylate Synthetase in *Arabidopsis thaliana*. *FEBS Letters*, **372**, 13-19. https://doi.org/10.1016/0014-5793(95)00935-3

[58] Toumi, M., Barris, S. and AId, F. (2014) Effet des Stress Hydrique et Osmotique Sur l'accumulation de Proline et de Malondialdehyde (MDA) Chez Deux Variétés de Colza (*Brassica napus* L.). *Bulletin de l'Institut Scientifique de Rabat*, *Section Sciences de la Vie*, **36**, 17-24.

[59] Singh, I.N., Paleg, I.G. and Aspinall, D. (1973) Stress Metabolism I. Nitrogen Metabolism and Growth in the Barley Plant during Water Stress. *Australian Journal of Biological Sciences*, **26**, 45-56. https://doi.org/10.1071/bi9730045

[60] Katsuhara, M., Otsuka, T. and Ezaki, B. (2005) Salt Stress-Induced Lipid Peroxidation Is Reduced by Glutathione S-Transferase, but This Reduction of Lipid Peroxides Is Not Enough for a Recovery of Root Growth in Arabidopsis. *Plant Science*, **169**, 369-373. https://doi.org/10.1016/j.plantsci.2005.03.030

[61] Mahi, Z., Dedaldechamp, F., Maurousse, L., Lemoine, R. and Belkhodja, M. (2015) Etude de La Peroxydation Lipidique (MDA) et l'Activité Antioxydative (POD) chez Deux Halophytes: *Atriplex halimus* L. et *Atriplex canescens* (Pursh) Nutt Sous L'effet Du Sel Study of Lipid Peroxidation (MDA) and Antioxidative Activity (POD) in Two Halophy. *International Journal of Innovation and Applied Studies*, **10**, 450-458.

[62] Hussain, B., War, A.R. and Sharma, H.C. (2014) Jasmonic and Salicylic Acid-Induced Resistance in Sorghum against the Stem Borer Chilo Partellus. *Phytoparasitica*, **42**, 99-108. https://doi.org/10.1007/s12600-013-0343-8

[63] Toderich, K., Shuyskaya, E., Rakhmankulova, Z., Bukarev, R., Khujanazarov, T., Zhapaev, R., *et al.* (2018) Threshold Tolerance of New Genotypes of *Pennisetum glaucum* (L.) R. Br. to Salinity and Drought. *Agronomy*, **8**, Article 230. https://doi.org/10.3390/agronomy8100230

[64] Rekaby, S.A., Awad, M.Y.M., Hegab, S.A. and Eissa, M.A. (2020) Effect of Some Organic Amendments on Barley Plants under Saline Condition. *Journal of Plant Nutrition*, **43**, 1840-1851. https://doi.org/10.1080/01904167.2020.1750645

[65] Walker, D.J. and Bernal, M.P. (2004) Plant Mineral Nutrition and Growth in a Saline Mediterranean Soil Amended with Organic Wastes. *Communications in Soil Science and Plant Analysis*, **35**, 2495-2514. https://doi.org/10.1081/lcss-200030347

[66] Litardo, R.C.M., Bendezú, S.J.G., Zenteno, M.D.C., Pérez-Almeida, I.B., Parismoreno, L.L. and García, E.D.L. (2022) Effect of Mineral and Organic Amendments

on Rice Growth and Yield in Saline Soils. *Journal of the Saudi Society of Agricultural Sciences*, **21**, 29-37.

[67] Choudhary, O.P., Josan, A.S., Bajwa, M.S. and Kapur, M.L. (2004) Effect of Sustained Sodic and Saline-Sodic Irrigation and Application of Gypsum and Farmyard Manure on Yield and Quality of Sugarcane under Semi-Arid Conditions. *Field Crops Research*, **87**, 103-116. https://doi.org/10.1016/j.fcr.2003.10.001

[68] Ali, S., Rizwan, M., Qayyum, M.F., Ok, Y.S., Ibrahim, M., Riaz, M., *et al.* (2017) Biochar Soil Amendment on Alleviation of Drought and Salt Stress in Plants: A Critical Review. *Environmental Science and Pollution Research*, **24**, 12700-12712. https://doi.org/10.1007/s11356-017-8904-x

[69] Ibrahim, M.E.H., Ali, A.Y.A., Elsiddig, A.M.I., Zhou, G., Nimir, N.E.A, Agbna, G.H.D. and Zhu, G. (2021) Mitigation Effect of Biochar on Sorghum Seedling Growth under Salinity Stress. *Pakistan Journal of Botany*, **53**, 387-392. https://doi.org/10.30848/pjb2021-2(21)

[70] Kul, R., Arjumend, T., Ekinci, M., Yildirim, E., Turan, M. and Argin, S. (2021) Biochar as an Organic Soil Conditioner for Mitigating Salinity Stress in Tomato. *Soil Science and Plant Nutrition*, **67**, 693-706. https://doi.org/10.1080/00380768.2021.1998924

[71] Goel, V.L. and Behl, H.M. (2002) Selection of leucaena Species for Afforestation and Amelioration of Sodic Soils. *Land Degradation & Development*, **13**, 387-393. https://doi.org/10.1002/ldr.518