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Research Article

Compost and Biochar to Promote Soil Biological Activities under Sweet Potatoes Cultivation in a Subtropical Semiarid Region

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South Texas is located in a subtropical semiarid climate, and due to high temperature and irregular precipitation, farmers opt to leave their fields fallow during the summer months jeopardizing overall soil health. We evaluated whether sweet potato (*Ipomoea batatas*) cultivation coupled with drip irrigation could restore soil biological activities compared with bare fallow. Additionally, because sweet potatoes have high demand of soil nutrients, especially potassium (K), we evaluated the nutrient supply of locally sourced soil amendments. Sweet potato was cultivated during summer 2018 in McAllen, Texas, under control (no fertilizer), NPK (synthetic fertilizer), RC (yard-waste compost), and AC (compost produced under an enhanced composting process), and biochar (gasified walnut shell at 900°C), each with three replicates. Soil amendments were applied at different amounts to result in a rate of 80 kg K ha^{-1}. Soil biological indicators were microbial biomass phosphorous, phosphatase activity, and the rate of fluorescein diacetate hydrolysis (FDA). Available nitrogen, phosphorus, potassium, and sodium were also quantified. Aboveground biomass and storage root yield estimated sweet potato's agronomic performance. Cultivation and irrigation stimulated soil enzyme activities and microbial biomass-phosphorous. Sweet potato yields were the highest in NPK treatment but still 2.8 times lower than variety's potential yield. Storage root yield was inversely related to aboveground biomass, suggesting that growing conditions benefited the production of shoot versus roots. Both biochar and AC treatments stimulated FDA rates and K availability. Soil pH and sodium concentration increased in all treatments over the growing season, possibly due to river-sourced irrigation water. Together, these findings show that crop cultivation promoted soil biological activities and the maintenance of nutrient cycling, compared to bare-fallow conditions. For a better agronomic performance of sweet potato, it would be necessary to identify management practices that minimize increase in soil pH and salinity.

1. Introduction

In the South Texas region of the Lower Rio Grande Valley on the border with Mexico is a well-established and diverse agricultural expanse, boasting citrus, cotton, sugar cane, onions, and leafy vegetables. Under a subtropical semiarid climate, the average temperature in South Texas throughout the summer is 35°C, presenting extreme drought and flooding periods with increasing intensity and frequency [1]. The average annual rainfall is 430 to 685 mm with irregular distribution throughout the year, making the agricultural industry highly dependent on irrigation water [2]. Soils were formed in sediments deposited by the Rio Grande River, as mostly clay and sand, and are generally alkaline [3]. In the fluvial plains, which host the majority of vegetable cultivation, organic matter levels are low and physical structure of the soil is weak. The soils also suffer from salinity issues deposited by irrigation water from the Rio Grande that contains between 600 ppm and 1,200 ppm of dissolved sodium and chloride salts, depending upon the seasons and rainfall [3]. Furthermore, the typically high temperatures promote water loss via evaporation increasing the accumulation of salts in the soil [4]. Given the high temperatures and water challenges, vegetable farmers leave the land bare fallow throughout the summer, as crops are often damaged by extreme heat, and high irrigation costs make production impracticable.

Detrimental effects to soil health have been reported in bare-fallow field in the summer, jeopardizing the use and long-term productivity of soils. For instance, in a long-term field experiment in Victoria, Australia, whose climate conditions mirror South Texas, researchers found that cereal crop rotations including bare-fallow seasons reduced soil organic carbon by 8 to 12% compared to continuous cropping [5]. Also, in the semiarid Australia, Sallaway et al. [6] observed soil loss through erosion of up to 13.3 tons per hectare with bare fallow, whereas with covered soil (sorghum stubble), losses were not observed following precipitation events. Uncovered bare soils exposed to high temperatures were also often prone to losses in soil biological activities such as nutrient cycling, degradation of toxic compounds, and maintenance of soil biodiversity [7]. These responses are driven mainly by a reduction in organic matter input from roots and litter, reduced soil water content, and temperature increases, resulting in desiccation of extracellular enzymes and overall microbial activity [8]. A reduction of microbial activities decreases the mineralization of nitrogen (N) and phosphorous (P), requiring application of more mineral fertilizer for optimal crop yield [9]. Compost and biochar are known to alleviate deficiencies in biological activities and nutrient supply [10, 11]. Due to their high organic matter content, compost materials can stimulate microbial activity and nutrient mineralization [12]. Biochar, a charcoal-like soil amendment produced from biomass residues, may work as a source of nutrients through its ash; however, its effects on biological activities and plant growth vary with the nature of the biochar and soil types [13, 14]. The supply of nutrients is a special concern in organic agriculture as productivity is challenged by the availability and timing of nutrient delivery in the soil, especially for high-nutrient demanding crops. Depending on their physicochemical properties, compost and biochar can also increase soil moisture retention, which would be beneficial for cropping systems in sandy soils of arid and semiarid climates [15–17].

We selected sweet potato (*Ipomoea batatas*) as a crop model for this study given its strong resistance to heat [18], rapid soil cover, and moreover its applicability as an additional revenue stream that supports food and nutritional security. The high nutritional value of sweet potato and its potential to thrive under a South Texas' summer present opportunities to augment grower earnings and diversify specialty crop offerings. Before committing acreage, farmers would benefit from tailoring crop and soil fertility management towards maximum efficiency and sustainability. Similar extreme weather and soil conditions can develop in other regions due to global climatic changes [19], and developing tailored sweet potato management in South Texas could generate tools to maintain soil health while yielding nutritional crops for impacted areas.

In comparison to grain crops, root crops such as sweet potatoes have even higher nutritional requirements and high yield potential, so they perform more poorly in nutrient-depleted soils [20, 21]. Sweet potatoes require on average 75 kg N ha^{-1}, 25–50 kg P ha^{-1}, and 75–100 kg K ha^{-1} [22, 23]. With a high demand for organic production, there is limited information on the provision of nutrients from organic fertilizers for sweet potato. In particular, there is a need to clarify whether sufficient potassium (K) can be sourced from organic materials and whether it is timely synchronized with plant demands. In this study, two composts and one biochar material as organic source of nutrients were investigated. Biochar materials have inherently high K content, as over 85% of the K is not lost during the gasification or pyrolysis processes [24].

We aim to evaluate whether sweet potato cultivation during the summer improves soil biological activities compared to bare-fallow soil. We also aim to identify which locally sourced soil amendment is best suitable for sweet potato performance, especially with regard to K supply. Our hypotheses were that soil biological activities will increase by (i) cultivating sweet potato coupled with drip irrigation and (ii) substituting organic amendments relative to synthetic fertilizer, resulting in nutrient release for the plants.

2. Materials and Methods

2.1. Site Description, Experimental Setup, and Sampling. The field trial was conducted during the Summer in 2018 in McAllen, TX in the Rio Grande Valley (26.2034° N, 98.2300° W). The field site was located in an isolated area inside the McAllen Composting Facility previously used as a vegetable garden. Prior to the present study, the site had been under fallow for the past 3 years. In McAllen during the summer of 2018, the mean high temperature during the summer months is 40.25°C with irregular rain patterns. Figure 1 shows average temperature and precipitation levels for summer 2018. The soil is classified as Brennan fine sandy loam (fine-loamy, mixed, superactive, hyperthermic aridic Haplustalfs, USDA Soil Classification, NRCS Web Soil Survey) with 74% sand, 14% silt, and 12% clay.

Total carbon and nitrogen contents were 5 g kg^{-1} and 1 g kg^{-1}, respectively. Sweet potato, variety Beauregard, was planted on June 8th, 2018, and harvested on September 7th, 2018. The field trial used a randomized block design with three blocks containing five amendments, resulting in a total of 15 plots (each plot in 2.5 m × 2.5 m). The amendment treatments were control (no fertilizer), synthetic fertilizer (NPK; type 14-14-14), regular compost (*RC*; 0.55% N, 0.27% P, and 0.74% K), accelerated compost (*AC*; 0.35% N, 0.18% P, and 0.66% K), and walnut shell biochar (biochar; 0.47% N, 0.72% P, and 9.32% K). Compost materials were produced from mixed yard brush feedstock by the McAllen Composting Facility using a static aerated pile system. AC was produced under similar conditions as RC and received a commercial inoculant that aims at hastening the composting

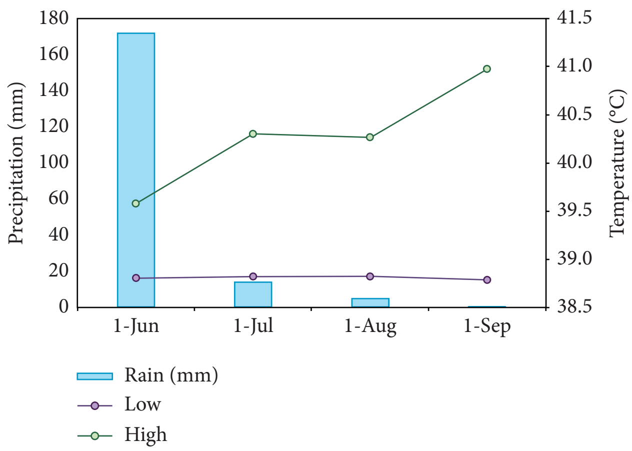

Figure 1: Temperature and precipitation data from June to September 2018 in McAllen, TX, USA. Data were obtained from [25].

process (Harvest Quest International, Inc., Rocky River, OH). Biochar was obtained as a by-product from the gasification of walnut shells using a Biomax 50 downdraft gasifier (50 kW Biomax 50, Community Power Corporation, Littleton, CO, USA) at approximately 900°C. Detailed description of biochar production and characterization can be found in the literature [26]. A day before planting, soil amendments were applied at a normalized rate of 80 kg of K ha^{-1}. As a root crop, sweet potato yields are limited by the availability of K that assists with the carbohydrates' synthesis and transport to the roots. Field studies recommend rates between 75 and 100 kg K ha^{-1} to achieve sweet potato potential production [27–29]). Within the period of investigation, water was applied twice a day (8 a.m. and 8 p.m.) for 30 minutes through an automated drip irrigation system, maintaining soil water at 22%. The irrigation water had a pH of 7.8, total dissolved solids at 706 ppm, total alkalinity as $CaCO_3$ at 98 ppm, and total hardness as $CaCO_3$ at 275 ppm, being classified as very hard according to the U.S. Geological Survey [30].

Manual weed control was done weekly throughout the trial period (14 weeks). Soil samples were taken before planting, when soil was bare fallow, as well as 39, 48, and 92 days after planting (DAP). Three samples from the middle row of each plot were taken using a tubular soil sampler (2.2 cm diameter) at a consistent depth of 15 cm. In the laboratory, all samples were homogenized with a 2 mm sieve, and the weight of wet and dry samples (60°C) was recorded for assessment of gravimetric water content. Samples temporarily stored at 4°C underwent nutrient and microbial assessments within the same week. Harvest of shoot biomass and storage roots occurred at 92 days after planting, and yield assessments were recorded from the middle row of each plot. Shoot biomass and storage root samples were oven-dried at 60°C to determine dry weights.

2.2. Soil pH and Nutrient Availability. Soil pH measurements were performed using a 1 : 1 (w/w) ratio of soil and deionized water following an equilibration time of 1 h [31]. Quantification of nitrate (NO_3^-) and ammonium (NH_4^+) was determined using 10 g of soil with 50 mL of KCl (2 M) under agitation for one hour before filtration through Whatman No. 42 filter paper [32]. For NH_4^+ quantification, in a buffered alkaline condition, NH_4^+ reacts with salicylate producing a blue-green solution allowing measurement at 650 nm [33]. NO_3^- determination was performed by reaction with vanadium(III) chloride in an acidic condition producing a blue-pink solution, measured at 540 nm [34]. A plate reader was used to colorimetrically determine concentrations of NO_3^- and NH_4^+ using standard curves to calculate the concentration of both ions (Synergy™ HTX multimode microplate reader; BioTek Instruments, Winooski, VT, USA). A membrane anion exchange resin (AER) was used to extract plant-available phosphorus (P) from the soils [35]. In brief, moist soil, equivalent to 2 g of dry soil, was mixed with 30 mL of nanopure distilled water, and the AER was placed in a 50 mL centrifuge tube and shaken for 16 hours. Once removed from the soil solution, the AER was rinsed with water and equilibrated under agitation with 30 mL of 0.1 M NaCl + HCl for 2 hours for the extraction of P from the membranes. The extract was reacted with Malachite solution, and the P content was determined colorimetrically at 610 nm. Available cation K^+ and Na^+ were extracted by shaking 5 g of soil with 25 mL of ammonium acetate (1 M $NH_4(C_2H_3O_2)$ at pH 7) for 5 minutes. The soil solution was filtered (Whatman No. 42) into a 50 mL centrifuge tube. Subsequent to filtration, the solutions were diluted to 1 : 10 with ultrapure distilled water (ELGA LabWater LLC, High Wycombe, UK) and analyzed using PerkinElmer 8300 inductively coupled plasma optical emission spectrometer (ICP-OES) (PerkinElmer, Shelton, CT). The operation parameter for the analysis is shown in Table 1. For all analyses, standard calibration curves were used with correlation coefficients (R^2) of 0.99 or higher.

3. Soil Microbial Biomass and Enzyme Activities

3.1. Microbial Biomass Phosphorus. Phosphorous associated with soil microbial biomass can improve P availability in soil-plant systems by preventing P adsorption and fixation processes in the soil. Additionally, during microbial turnover, microbial biomass P (MBP) may be released slowly and taken up by the crop plants more efficiently [36]. MBP was extracted through a hexanol-fumigation method [37]. Strips of AER were shaken for 16 hours with suspensions of soil (2 g) in 29 ml of distilled H_2O and 1 ml of liquid hexanol, following the same extraction procedure described for plant-available P. Subsequent to equilibration, the samples were rinsed with distilled water to remove soil particles from the AER strips. Phosphorus adsorbed by the AER strips was eluted using a 0.1 M NaCl + HCl and measured colorimetrically (BioTek Instruments, Winooski, VT, USA). The amount of hexanol-released P was calculated from the difference between the amount of inorganic P adsorbed by AER in nonfumigated (plant-available P) and fumigated soils.

3.2. Enzyme Activities. The activities of alkaline phosphatase (AlkP) and acid phosphatase (AcdP), i.e., the enzymes that hydrolyze organic P into orthophosphate, the bioavailable P

Table 1: ICP-OES parameters for the analysis of K^+ and Na^+ for the various soil treatments.

Parameter	Instrumental settings
λ_{na}	588.983 nm
λ_k	766.455 nm
RF power	1500 W
Nebulizer	GemCone (low flow)
Plasma flow	15 L/min
Auxiliary flow	0.2 L/min
Nebulizer flow	0.55 L/min
Sample flow	1.50 mL/min
Injector	2.0 mm alumina
Spray chamber	Cyclonic
Integration time	20 seconds
Replicates	3

form in soil, were measured following the method of Marx et al. [38] as modified by Poll et al. [39]. In brief, 1 g of fresh soil was dispersed in 100 ml of autoclaved H_2O using an ultrasonic water bath (Branson 3800 Ultrasonic Cleaner, Branson, Germany) operating at 40 kHz for 5 minutes. The assay was performed using 25 μl aliquots of the soil suspension on a microplate (Black 384 well, Greiner Bio-One GmbH, Frickenhausen, Germany) with six analytical replicates, 4-methylumbelliferyl phosphate as substrate, and 0.1 M 4-morpholineethanesulfonic acid buffer (pH 6.1) or modified universal buffer (pH 11) as buffer for AcdP and AlkP, respectively. Fluorescence was measured after 30, 60, 120, and 180 minutes by a microplate reader Synergy™ HTX multimode microplate reader (BioTek Instruments, Winooski, VT, USA) at 360/460 nm and converted into nmol substrate g soil^{-1} h^{-1} using a standard curve with 4-methylumbelliferone added to the soil suspension of each sample. Enzyme activity was linearly related to the intensity of fluorescence and was calculated according to the standards.

The fluorescein diacetate (FDA) hydrolysis assay provides an estimate of overall microbial activity in the soil sample by measuring the hydrolysis of FDA by a wide variety of enzymes, including esterases, proteases, and lipases [40]. In a 125 mL autoclaved Erlenmeyer flask, 1.0 g of air-dried soil and 20 ml of 60 mM sodium phosphate buffer (pH 7.6) were added and mixed for 15 minutes at 100 rpm in a reciprocating shaker while capped with a rubber stopper. Subsequently, 100 μL of 4.9 mM FDA lipase substrate solution (20 mg FDA lipase substrate in 10 ml acetone) was added and mixed for 1 h and 45 minutes at 100 rpm and at a temperature of 37°C. The mixing was followed by the addition of 20 mL of acetone to the suspension under agitation to mix the contents. A 30 mL aliquot of the soil suspension was transferred to a 50 ml tube and centrifuged for 5 minutes at 6000 rpm (Eppendorf model 5810R). The supernatant was filtered through a Whatman No. 4 filter paper. A standard curve containing 0.03, 0.1, 0.3, and 0.5 mg of fluorescein was prepared. The absorbance of samples and standards was measured using a microplate reader (BioTek Instruments, Winooski, VT, USA) at a wavelength of 490 nm.

3.3. Data Analyses. Analysis of variance (ANOVA) determined whether there are any differences in plant and soil responses across the amendments with subsequent post hoc analyses (Tukey's honest significant differences test). Significance was accepted at $\alpha < 0.05$. Before the analysis of the data through ANOVA, the homogeneity of variances and normality of the residuals were tested. If the data did not meet the requirements for ANOVA, then the data were log transformed. Pearson correlation analysis was used to examine the relationships among nutrient availability and soil microbial variables. All statistical analyses were performed using *R* language program [41].

4. Results

4.1. Plant Performance. Regular weekly maintenance kept the field free of weeds, and no incidence of insect damage or diseases appeared throughout the growing season. Phillips et al. [42] indicate Beauregard variety's potential yield can reach approximately 24.5 tons per hectare. However, in the present study, none of the trial experimental yielded this benchmark productivity. Storage root yield in NPK treatment was significantly higher than other treatments at 8.72 tons per hectare (Figure 2(a)). All other treatments averaged 3.5 tons per hectare. Average aboveground biomass production across all treatments was 30.15 tons per hectare (Figure 2(b)). In addition, the storage root yield was inversely related to aboveground biomass (Table 2; $r^2 = -0.54$, $p < 0.001$).

4.2. Soil Nutrient Availability. Treatment effects on NH_4^+-N concentrations were only observed at 48 DAP with NPK treatment having the highest concentration (4.48 μg N g soil) (Table 3), whereas NO_3-N concentration during the bare-fallow period (prefertilization) was observed to be significantly higher throughout the growing season. The average NO_3^--N concentrations observed at 92 DAP ($p < 0.0001$) were the second highest (Table 3). The lowest observed NO_3^- concentrations were found at 48 DAP, with average across all treatments of 0.96 μg N g^{-1} soil. There were no differences in NO_3^- concentrations between treatments at 39 and 48 DAP. However, at 92 DAP, NPK and AC treatments had the highest NO_3^--N concentrations in all treatments ($p < 0.0001$) with 11.01 and 11.46 μg N g^{-1} soil, respectively.

The exchangeable P concentration at the beginning of the growing season was 0.15 μg P g^{-1} soil and was observed to significantly increase to 5.26 μg P g^{-1} soil. However, no observable differences in the P concentrations between treatments and sampling timepoints (i.e., 39, 48, and 92 DAP) were determined.

Initial K^+ concentrations were found to be 36.53 μg K g^{-1} soil and were observed to significantly increase in the NPK, AC, and biochar treatments. However, with the control and RC treatments, no observed changes in the concentrations of soil available K^+ occurred from initial treatment to the end of the study. Treatment effects were only observed at 48 DAP, with biochar having the highest K^+ concentration (85.9 μg K^+ g^{-1} soil). Soil pH was observed to significantly increase towards the end of the growing season (92 DAP) (Table 4). None of the treatments were observed to alter soil pH. The

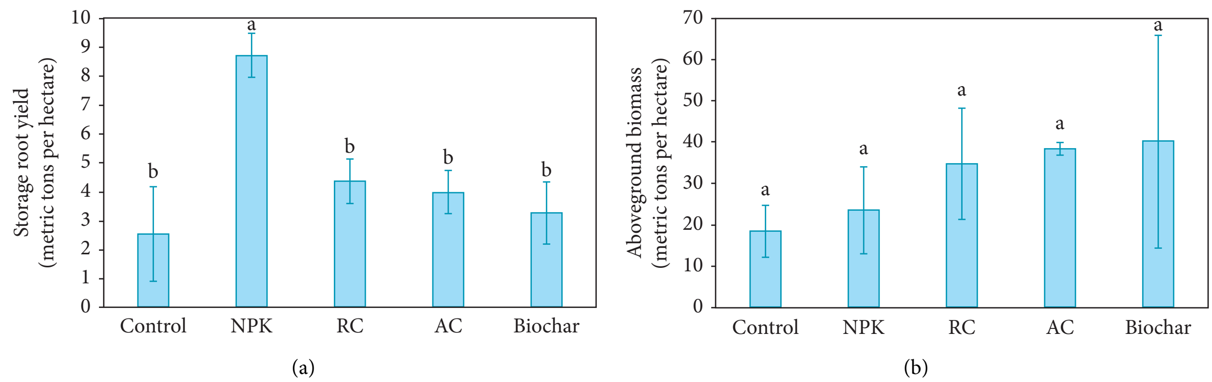

Figure 2: Storage root yield (a) and aboveground biomass (b) of sweet potato variety Beauregard grown for 92 days. Error bars represent ± one standard error ($n = 3$). Means followed by the same letter are not significantly different ($p > 0.05$). Control: no amendment; NPK: synthetic fertilizer; RC: regular compost; AC: accelerated compost; and biochar: biochar produced from walnut shell feedstock.

Table 2: Correlation matrix between sweet potato performance and soil attributes.

	Root yield	Biomass	pH	Na	NH_4^+	NO_3^-	*p*	K	AlkP	AcdP	FDA	MBP
Root yield		-0.54^{***}	-0.52^{***}	0.08^{NS}	0.36^{*}	0.27^{NS}	0.00^{NS}	-0.12^{NS}	-0.03^{NS}	-0.05^{NS}	-0.20^{NS}	0.05^{NS}
Biomass			0.07^{NS}	0.01^{NS}	-0.17^{NS}	-0.13^{NS}	-0.09^{NS}	0.06^{NS}	0.11^{NS}	0.03^{NS}	-0.01^{NS}	0.01^{NS}
pH				-0.18^{NS}	-0.33^{*}	-0.34^{*}	-0.21^{NS}	0.22^{NS}	-0.12^{NS}	0.02^{NS}	0.00^{NS}	-0.31^{*}
Na					0.06^{NS}	0.48^{***}	-0.03^{NS}	-0.04^{NS}	0.61^{***}	0.56^{***}	0.08^{NS}	0.29^{*}
NH_4^+						0.69^{***}	0.51^{***}	0.02^{NS}	0.14^{NS}	0.00^{NS}	0.03^{NS}	0.4^{**}
NO_3^-							0.46^{**}	0.02^{NS}	0.42^{**}	0.25^{NS}	0.1^{NS}	0.38^{**}
P								0.27^{NS}	0.16^{NS}	-0.01^{NS}	0.61^{***}	0.17^{NS}
K									-0.03^{NS}	-0.26^{NS}	0.24^{NS}	-0.01^{NS}
AlkP										0.81^{***}	0.17^{NS}	0.37^{*}
AcdP											0.12^{NS}	0.27^{NS}
FDA												0.20^{NS}
MBP												

Significance of correlations indicated by *, **, and *** is equivalent to $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively. NS, nonsignificant.

storage root yield was found to be inversely related to soil pH (Table 2; $r^2 = -0.52$, $p < 0.001$). In general, the concentration of Na^+ was observed to increase over the growing season, but only significantly in NPK and AC treatments (Table 4).

4.3. Soil Biological Activities. Overall, MBP increased from an analytically undetectable level to an average of 1.33 μg P g^{-1} soil across all treatments and sampling points (Figure 3(a)). Given the large data variation observed, treatment effects on MBP were not statistically significant. The FDA assay, which indicates overall microbial activity, increased in all treatments after planting, but only significantly in the RC and biochar treatments at 39 DAP (Figure 3(b)). Comparing across treatments at 39 DAP, FDA in the biochar treatment was significantly larger than in NPK and AC. In addition, no treatment effects were observed at other sampling points in the study. FDA was observed to correlate significantly with soil exchangeable P ($r^2 = 0.61$, $p < 0.001$). Overall, AlkP activity was approximately 5 times larger than AcdP activity. AlkP concentration in the preplanting was generally similar to those observed at 39 and 48 DAP. However, compared to the 92 DAP, AlkP at the preplanting was significantly lower than AlkP observed in AC (Figure 3(c)). Over the growing season, AlkP activity significantly increased in the control and AC treatments. AlkP correlated significantly with MBP ($r^2 = 0.37$, $p < 0.05$). AcdP increased over the course of the growing season, with the exception of the biochar treatment (Figure 3(d)). No further treatment effects were observed.

5. Discussion

5.1. Climate and Edaphic Conditions Control Sweet Potato Yield. The field trial confirmed sweet potato could produce storage roots and aboveground biomass under the high heat of South Texas (Figure 4). However, none of the fertilizer treatments supported the yields of 20 tons per hectare obtained in research trials with the same variety (i.e., Beauregard) in Louisiana and Virginia [42, 43]. Climatic conditions and soil quality in South Texas may have played a significant role on nutrient availability and ultimately storage root development. In South Texas, particularly in the Lower Rio Grande Valley, soils are characterized as nutrient poor soils, as shown by its low percentage of nitrogen and carbon (trial site avg. 0.1% and 0.5%, respectively) and high alkalinity, limiting the availability of micronutrients such as iron, manganese, copper, cobalt, and zinc. Additionally,

Table 3: Soil concentrations of available N, P, and K during the growing season of sweet potatoes at preplanting and 39, 48, and 92 days after planting.

	Treatments	Bare fallow (preplanting)	39	48	92
				Days after planting	
NH_4^+-N (μg N g^{-1} soil)	Control	2.34 ± 1.45	3.18 ± 2.7 aA	1.32 ± 0.37 bA	4.17 ± 3.68 aA
	NPK		3.11 ± 2.81 aB	4.48 ± 1.74 aA*	4.66 ± 0.8 aB
	RC		0.99 ± 0.38 aA	0.95 ± 0.91 bA	2.11 ± 0.76 aA
	AC		1.33 ± 0.13 aA	0.56 ± 0.27 bA	1.63 ± 0.59 aA
	Biochar		1.37 ± 1.06 aA	1.11 ± 0.31 bA	1.84 ± 0.97 aA
NO_3^-N (μg N g^{-1} soil)	Control	25.97 ± 0.4	1.59 ± 0.32 aB*	0.16 ± 0.19 aB*	4.21 ± 2.27 bA*
	NPK		2.21 ± 0.81 aAB*	1.92 ± 0.05 aB*	11.01 ± 0.34 aA*
	RC		2.05 ± 1.73 aAB*	0.26 ± 0.76 aB*	4.31 ± 0.39 bA*
	AC		3.55 ± 3.39 aB*	0.83 ± 1.22 aB*	11.46 ± 2.12 aA*
	Biochar		2.29 ± 1.46 aA*	1.64 ± 1.21 aA*	4.16 ± 0.76 bA*
P (μg P g^{-1} soil)	Control	0.15 ± 0.02	8.22 ± 4.86 aA*	5.04 ± 0.9 aA*	2.81 ± 1.44 aA*
	NPK		4.71 ± 0.55 aA*	8.79 ± 6.48 aA*	5.15 ± 1.82 aA*
	RC		6.43 ± 3.31 aA*	3.86 ± 0.82 aA*	4.45 ± 3.31 aA*
	AC		5.7 ± 3.35 aA*	3.53 ± 1.94 aA*	5.5 ± 3.34 aA*
	Biochar		6.67 ± 5.16 aA*	4.71 ± 3.71 aA*	3.38 ± 2.2 aA*
K (μg K g^{-1} soil)	Control	36.53 ± 2.81	60.89 ± 17.17 aA	61.1 ± 14.9 abA	53.39 ± 9.43 aA
	NPK		78.04 ± 11 aA*	61.5 ± 21.2 abB*	59.56 ± 29.37 aB*
	RC		65.78 ± 9.57 aA	51.9 ± 3.36 abA	49.86 ± 9.27 aA
	AC		71.2 ± 13.5 aA*	47.1 ± 7.64 bA*	55.4 ± 4.72 aA*
	Biochar		69.65 ± 25.5 aA*	85.9 ± 11.3 aA*	67.01 ± 20.1 aA*

Values are means ± standard errors ($n = 3$). Values within a column and nutrient followed by the same lowercase letter or within a row followed by the same uppercase letter are not significantly different ($p > 0.05$). Values followed by asterisk (*) are significantly different than preplanting values ($p < 0.05$). Control: no amendment; NPK: synthetic fertilizer; RC: regular compost; AC: accelerated compost; biochar: biochar produced from walnut shell feedstock.

Table 4: Soil pH and sodium concentration during the growing season of sweet potatoes at preplanting and 39, 48, and 92 days after planting.

	Treatments	Preplanting	39	48	92
				Days after planting	
pH	Control	7.7 ± 0.02	7.82 ± 0.1 aB	7.84 ± 0.09 aB	9.23 ± 0.19 aA*
	NPK		7.95 ± 0.11 aB	7.89 ± 0.02 aB	8.96 ± 0.26 aA*
	RC		7.88 ± 0.14 aB	7.91 ± 0.1 aB	9.21 ± 0.24 aA*
	AC		7.99 ± 0.14 aB	7.93 ± 0.1 aB	9.05 ± 0.06 aA*
	Biochar		7.98 ± 0.21 aB	7.94 ± 0.11 aB	9.18 ± 0.2 aA*
Na^+ (cmol kg^{-1})	Control	0.09 ± 0.01	0.07 ± 0.02 aA	0.07 ± 0.01 aA	0.12 ± 0.05 aA
	NPK		0.08 ± 0.03 aB	0.08 ± 0.03 aB	0.15 ± 0.05 aA*
	RC		0.07 ± 0.02 aA	0.08 ± 0.01 aA	0.11 ± 0.03 aA
	AC		0.07 ± 0.01 aB	0.08 ± 0.02 aB	0.15 ± 0.02 aA*
	Biochar		0.07 ± 0.02 aA	0.07 ± 0.01 aA	0.12 ± 0.05 aA

Values are means ± standard errors ($n = 3$). Values within a column and variable followed by the same lowercase letter or within a row followed by the same uppercase letter are not significantly different ($p > 0.05$). Values followed by asterisk (*) are significantly different than preplanting values ($p < 0.05$). Control: no amendment; NPK: synthetic fertilizer; RC: regular compost; AC: accelerated compost; biochar: biochar produced from walnut shell feedstock.

farmers irrigate their crops using the Rio Grande River as a water source, which compounds the problems associated with high temperature and evaporation rates and results in an increase in the overall salinity of soils. Increased soil salinity can further reduce the availability of important nutrients for crops as it indirectly affects the pH of local soils. An increase in pH and Na^+ over the growing season was indeed observed (Figure 4). Additionally, soil pH and storage root yield had a significant negative correlation (Table 2). Increase in alkalinity and salt content can occur when irrigation water contains high amounts of sodium, bicarbonate, calcium, and magnesium, which is of common occurrence in the Rio Grande basin where rainfall is light and most of its waters are quite concentrated [44]. The analysis of the irrigation water of this study indicated high levels of dissolved calcium and magnesium, expressed by the total hardness of 275 ppm as $CaCO_3$. The agricultural challenges faced in South Texas are not unique to the region; several areas, e.g., East Asia [45, 46], are susceptible to similar challenges as global temperatures increase, and changing precipitation patterns are compromising soil health [47]. While significant efforts are focused on the breeding of salt-tolerant crops that can maintain crop productivity and withstand high temperatures, alkalinity,

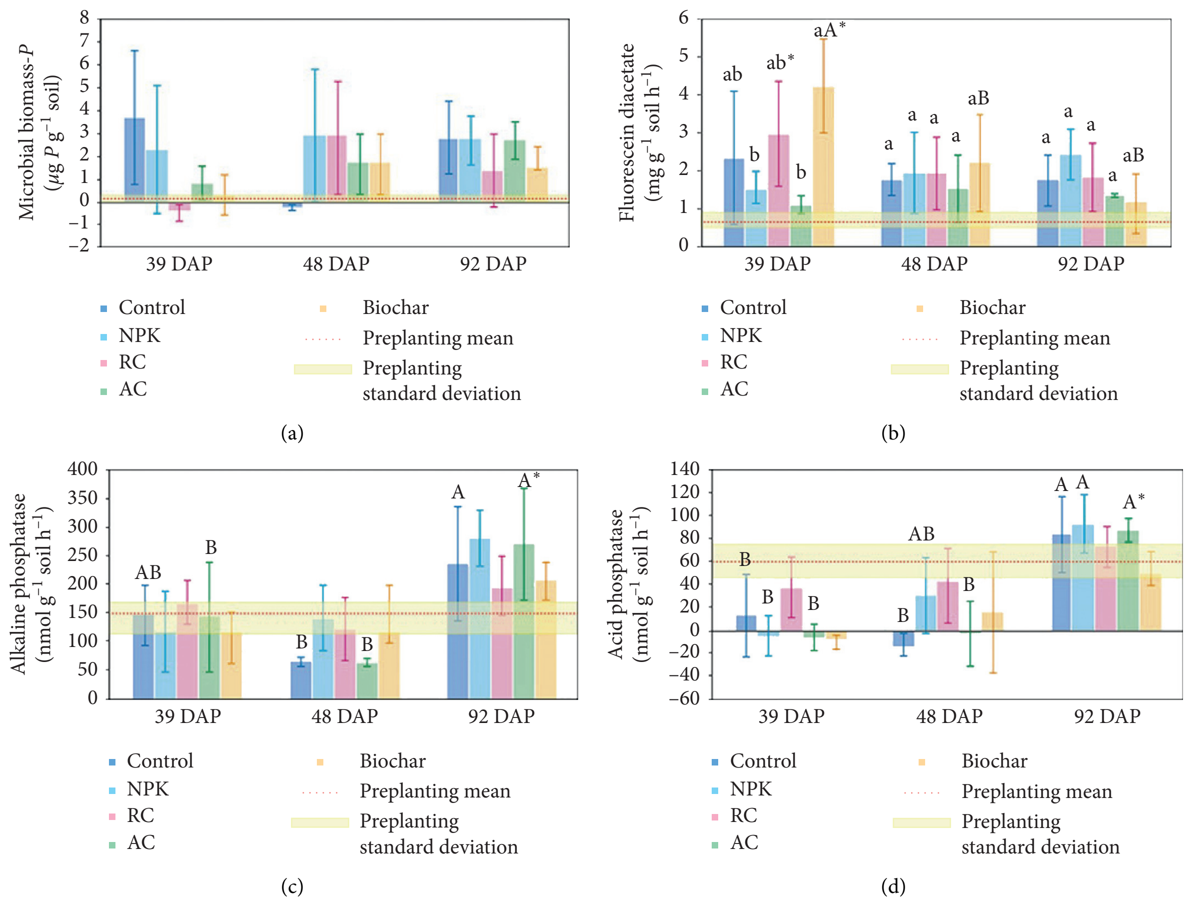

FIGURE 3: Soil enzyme activity and microbial biomass P during the growing season of sweet potatoes at preplanting and 39, 48, and 92 days after planting. Error bars represent ± one standard error ($n = 3$). Values followed by the same lowercase letter are not significantly different within the same sampling date, and means followed by the same uppercase letter are not significantly different across sampling dates within the same treatment. Means followed by asterisk (*) are significantly different than prefertilization mean ($p < 0.05$). There were no significant differences between the treatments within each sampling date for MBP, alkaline phosphatase, and acid phosphatase. DAP = days after planting.

and salinity conditions [48], future soil research focusing on amendments that promote soil pH decreases and maintenance of nutrient cycling is much needed in semiarid climate. It should be noted also that, due to low organic matter contents, the soil has a low buffer capacity for pH changes; hence, rapidly pH increases over the growing season. Hence, a pH decrease can perhaps be expected once an intensive rain event washes off the calcium and magnesium that have accumulated in the soil surface.

In this trial, we normalized the fertilizer application rate by 80 kg of K ha^{-1}. While the synthetic fertilizers offered a balanced supply of N, P, and K, the organic amendments supplied lower amounts of N and P, which possibly explain the lower yields in these treatments.

A complementary mechanism explaining the low yields in this study can be related to root to shoot partitioning. Aboveground biomass production was similar to those obtained by other studies [49, 50] but inversely related to storage root yield ($r^2 = -0.54$, $p = 0.034$). Some growing factors, such as soil water content and nitrogen availability, may have favored the production of aboveground biomass in lieu of storage roots [21]. Excess N applications have been shown to frequently depress tuber yield owing to the preferential partitioning of resources to foliage instead of tuber production [51]. Furthermore, excess soil water content may also have been detrimental to storage root development. During the first month of the growing season, the site received 170 mm of precipitation (Figure 1). However, in the remaining growing season, the site received daily drip irrigation. Future research should explore reduced irrigation frequency and nitrogen rates, which will also benefit the maintenance of soil pH and salinity.

5.2. Cropping Stimulates Soil Biological Activities More than Organic Amendments. We hypothesized that plant growth, irrigation, and fertilizer inputs would stimulate soil biological activities by promoting microbial biomass growth and enzyme activities and increasing the release of nutrients compared to the conditions under bare fallow. With exception of RC-amended soils, the results showed MBP increased substantially from the preplanting period, when the

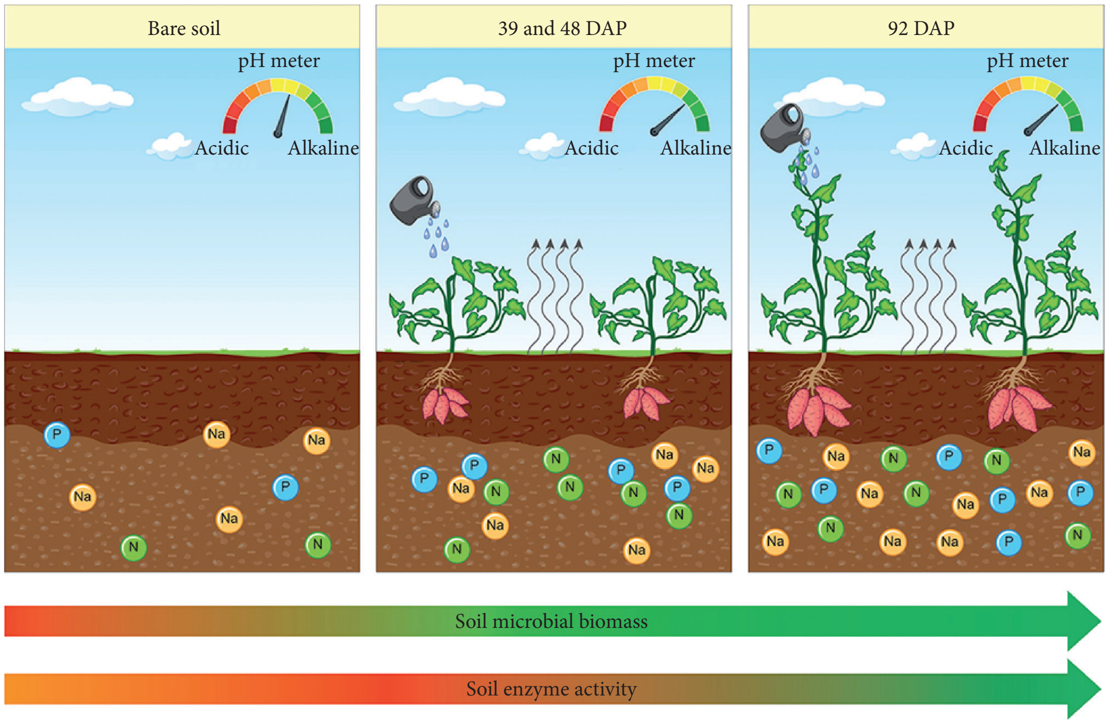

FIGURE 4: Chemical and biological changes in soils upon cultivation with sweet potatoes and drip irrigation during the summer in semiarid South Texas. DAP = days after planting.

soil was bare, to 39 DAP (Figure 4). By 92 DAP, all treatments had increased MBP compared to bare-fallow conditions. This suggests that bare-fallow as practiced by many farmers in the subtropical semiarid South Texas leads to a suppression of soil microorganisms' activities and growth. Phosphatase activities at 39 and 48 DAP were similar to those measured during the preplanting period (preplanting data, Figure 3), only surpassing those initial levels at 92 DAP, indicating a lag phase in microorganism activity after introduction of cultivation. Compared to soils with vegetative cover, bare-fallow soils do not have carbon inputs and also have higher surface temperatures. These factors contribute to an exhaustion of organic substrates/resources and possibly a gradual denaturation of the enzyme proteins essential for nutrient cycling, decomposition of toxic compounds, and formation of soil aggregates for carbon storage [52]. The high amount of vegetative canopy generated by sweet potato may have posed as a soil cover for the maintenance of soil biological activities.

It was also expected that the organic amendments (RC, AC, and biochar) would further enhance the biological activities compared to bare-fallow or unamended control, especially those associated with nutrient release such as phosphatase activity. The FDA measurements represent the total microbial activity based on the hydrolysis of fluorescein diacetate by a wide variety of enzymes, including esterases, proteases, and lipases [53]. FDA technique can be a reliable estimate of the amount of active microbial biomass decomposing organic materials, as has been observed in straw litter and soil [54]. Biochar treatment promoted the highest FDA activity at 39 DAP, being 6 times larger than in bare-fallow conditions and 1.8 times larger than control (about 70% larger than control). Biochar effect was transient with FDA activity levels returning to the same levels as the other treatments at 48 and 92 DAP. These transient increase in FDA had no effect on yield, but they did correlate positively with exchangeable P ($r^2 = 0.61$, $p < 0.0001$), suggesting that amendment-induced FDA activities may have promoted the release of P. When investigating enzymatic activities involved on organic matter decomposition, Foster et al. [55] observed that pine-wood biochar stimulated the activity of some enzymes (i.e., *a*-1,4-glucosidase and *ß*-D-cellobiohydrolase) but suppressed the activity of others (i.e., *ß*-1,4-glucosidase and phosphatase activities). Similar FDA responses to biochar were observed in a 30-day incubation study with peanut shell biochar at different rates (0%, 2.5%, 5.0%, and 10% w/w) under saline soil conditions. Bhaduri et al. [56] observed that biochar at 5 and 10% (w/w) application rates significantly increased FDA activity by 28% compared to control. The peanut shell and the walnut shell biochars had similar C and N contents; however, the applied rates of peanut shell biochar were 100 and 200 times larger than the rates we applied to reach a rate of 80 kg K per hectare.

5.3. Multiple Benefits: Waste Management and Nutrient Cycling. With an increasing demand for organic products [57], South Texas, a prominent agricultural region may consider expanding infrastructure to capitalize on current cropping residues (e.g., sugar cane bagasse, avocado stones, and citrus peels) and transform them into soil amendment. Among the amendments originated from waste management, both AC and biochar treatments increased available K, while AC also increased NO_3^--N in the soil. The biochar and AC amendments were beneficial in increasing these macronutrients while not increasing Na^+ and pH relative to other amendments. The compost amendments were sourced locally at the McAllen Composting Facility managed by the City of McAllen. They produce compost with raw materials obtained from yard waste delivered by the city and residents as well as food waste from school districts. The biochar tested in the current study was obtained as a by-product from a walnut processing facility that uses gasified walnut shells for electricity generation providing a large environmental benefit through the waste-to-bioenergy treatment, addressing farm level challenges such as waste management, renewable energy generation, and C sequestration (Pereira et al., 2016). In both cases, compost and biochar serve as sound alternatives of waste management with positive outcomes as soil amendments.

6. Conclusions

Crop cultivation during the hot summers of South Texas can promote soil biological activities as indicated by the enhanced MBP and FDA activities compared to precultivation conditions when the soil was bare-fallow. Continuous irrigation under high temperatures and evaporation increased soil salinity and alkalinity in all treatments, including control. Sweet potato yields were lower than those normally obtained from the Beauregard variety, possibly due to a reduced micronutrient availability under the alkaline soil conditions. Also, high N in the amended soils and drip irrigation condition favored aboveground biomass growth due to high N and moisture availability. Our study suggests that biochar and accelerated compost promoted the availability of K, and the development of soil amendments from waste materials should be expanded in the region to accommodate the demand for organic fertilizers. To assess the long-term influence of the amendments and production conditions on sweet potato yield and soil quality, future field trials should be carried across multiple growing seasons.

Data Availability

The data used for this study can be obtained upon request made to the corresponding author.

Disclosure

Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the USDA.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Josabeth Navarro and Jahdiel Salazarhese equally contributed to this work.

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