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Agronomic and environmental performance of biochar amendment in alluvial soils under subtropical sugarcane production

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Abstract

This study investigated the amendment of sugarcane bagasse biochar (SCBB) on soil fertility, crop yield, and nutrient loss in two different-textured soils under sugarcane (*Saccharum* spp.) production. Eleven megagrams per hectare of freshly incorporated biochar increased yield of plant cane by 22% in light-texture soil (LS) and 12% in heavy-textured soil (HS). Although the overall yield of the ratoon crop was lower, the biochar treatment produced 20 and 14% higher yields than the control at the LS and HS sites, respectively. Biochar increased soil carbon (C_{soil}) across LS and HS sites by 15% and decreased the soil C/N ratio by 19%. Over the two growing seasons and sites, cumulative runoff volume, and loads of NO_3^-–N, PO_4^{-3}–P, biological oxygen demand (BOD_5), total organic C (TOC), and total suspended solids (TSS) were reduced by 33, 35, 39, 25, 24, and 54% with biochar. Calcium and K losses in runoff were also reduced by 43 and 24% with biochar. It reduced NH_4^+–N leaching in LS and HS soils over the two growing seasons by 33–167% and 66–81%, respectively, and reduced PO_4^{-3}–P leaching by 45–57% in HS over 2 yr. Although biochar is not considered a fertilizer, SCBB acted as a source of nutrients, increasing soil fertility and crop yield. It also reduced nutrient losses during heavy rain events typical of the subtropical climate of Louisiana.

1 | INTRODUCTION

Sugarcane(*Saccharum* spp.) is one of the major crops in Louisiana, the second largest producer of sugarcane in the United States (Viator et al., 2019). Harvest sugarcane generates an average of 4—8 Mg ha^{-1} (dry) green cane trash (residue) and milling, 10–12 Mg ha^{-1} (dry) bagasse (Johnson et al., 2007; Viator et al., 2007). Leaving harvest residue in the field, however, significantly reduces ratoon crop yield and soil fertility due to cooler soil temperature and restricted reemergence of the ratoon crop from sugarcane stubble (Viator & Wang, 2011; Viator, et al., 2008). Additionally, in the subtropical climate of Louisiana, waterlogging under the residue layer increases N loss, especially on poorly drained clay soils (R. Viator et al., 2009). Therefore, the harvest residue is often

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Abbreviations: BOD_5, biological oxygen demand; CEC, cation exchange capacity; DIW, deionized water; EC, electrical conductivity; HS, heavy-textured soil; ICP-OES, inductively coupled plasma-optical emission spectroscopy; LS, light-textured soil; SCBB, sugarcane bagasse biochar; TOC, total organic carbon; TSS, total suspended solids burned, which reduces the biomass by 70–90% (Mitchell et al., 2000). On the other hand, burning reduces the amount of surface organic matter incorporated into the soil (Newman, 2014), and the rapid release of nutrients into the soil during burning has only a short-lived positive effect on soil fertility (Glaser et al., 2002). Due to concerns over water and air quality, and loss of soil organic matter and N with burning, residue is elsewhere retained (Cheesman, 2004). Moreover, residue improves water retention, root development, and soil physical and microbial properties (Barzegar et al., 2000; Graham et al., 2002).

Research on residue management in Louisiana over the past several years has examined alternatives to burning intended to reduce the negative effect of residue on sugarcane yields. These include shredding the harvest residue to accelerate decomposition, or repositioning the residue into the furrow (sweeping), but were found ineffective (Kennedy & Arceneaux, 2006; Selim et al., 2017). In addition, soil conditioners, including mulches, composts, and manures, have reportedly improved soil fertility but had no significant effect on crop yield, sediment control, or surface runoff water quality parameters (Selim et al., 2019; H. P. Viator et al., 2009). To date, no management practice has been successful enough for adoption by the industry as a viable alternative to residue burning.

One soil conditioner not yet adequately examined with sugarcane in Louisiana is biochar, which elsewhere has been shown to improve soil fertility under different crop production and climatic conditions (Bohara et al., 2019; Domene et al., 2014; Glaser et al., 2002; Mao et al., 2012; Steiner et al., 2007). Whereas most organic amendments mineralize rapidly in highly weathered soils and under tropical conditions so that their contribution to increasing soil organic matter is temporary (Diels et al., 2004), biochar is significantly more stable against microbial degradation (Lehmann & Joseph, 2015). High C content, aromaticity, and functional properties similar to those of mineral matter, in part, explain its recalcitrance in subtropica and tropical soils (Xu et al., 2016).

Several studies have evaluated the effect of biochar on soil C content and soil fertility (Freibauer et al., 2004; Novak et al., 2009; Verheijen et al., 2010). A 4-yr study with wood biochar applied at 20 Mg ha^{-1} to a Colombian savanna Oxisol under maize (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation showed a gradual increase in maize yield to 140% compared with the control (Major et al., 2010). This was likely due to much higher content of plant-available Ca and Mg with biochar in the low cation exchange capacity (CEC), leached soil (Nangia et al., 2008). Biochar appears to increase nutrient retention and reduce nutrient leaching (Novak & Watts, 2004; Schneider et al., 2011). Biochar improves cation retention and adsorbs organic molecules due to its physical properties and chemical structure, including high surface charge density, surface area, internal porosity, and presence of both polar and nonpolar surface sites (Jeong et al., 2016; Laird et al., 2010).

Core Ideas

- Sugarcane bagasse-derived biochar offers both agronomic and water quality benefits.
- Biochar amendment increased cane yields by 22% in slit loam and 12% in clay soils.
- Biochar reduced total suspended solids, biological oxygen demand, and nutrient losses in runoff from both textured soils.
- Biochar increased soil organic C and decreased cation nutrient leaching.

The purpose of our study was to evaluate the effect of biochar made from sugarcane bagasse (a waste from milling) on agronomic and environmental parameters in sugarcane production with residue retention rather than burning. For that we analyzed and evaluated (a) nutrient content in the soil, (b) plant uptake, crop yield, and quality parameters, (c) nutrient loss through surface runoff and leaching, and (d) loads of sediment and pollutants exported in surface runoff water over two growing seasons in two texturally different alluvial soils under continuous sugarcane production. Although limited studies have investigated biochar amendment on nutrient uptake in potting studies (Hariyono et al., 2020; Liao et al., 2019; Lima & White, 2017), to the best of our knowledge, there has been no research to systemically evaluate the effects of biochar produced from bagasse on both the agronomic production and environmental quality of sugarcane cropping system in a subtropical region of the southern United States. Its use might improve soil and environmental quality, irrespective of whether residue is burned, and tend to offset yield reduction where residue is retained (Jeong et al., 2016).

2 | MATERIALS AND METHODS

2.1 | Site establishment and experimental design

Two research sites were established in April 2016 on different textured soils, Commerce silt loam (fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts; LS) and Sharkey clay (very-fine, smectitic, thermic Chromic Epiaquerts; HS) located at (30˚15′40.806′′ N, 91˚6′0.054′′ W) and (30˚16′9.696′′ N, 91˚5′58.344′′ W), respectively, at the Louisiana State University Sugar Research Station in St. Gabriel, LA. The Commerce soil is somewhat poorly drained and moderately slowly permeable, and the Sharkey soil is poorly to very poorly drained and very slowly permeable. The

TABLE 1 Dates of biochar application, sugarcane production stage, dates of harvest, and dates and rates of urea ammonium nitrate (UAN, 32% N) application in the 2-yr experiment at the light- (LS) and heavy-textured (HS) sites

Site	Year	Biochar applied	Stage	Harvested	UAN applied	Rate
						kg N ha^{-1}
LS	2016	2 May	Plant cane	14 Nov.	6 May	100
	2017		First stubble	30 Oct.	28 Apr.	122
HS	2016	3 May	Plant cane	14 Nov.	6 May	100
	2017		First stubble	30 Oct.	28 Apr.	122

sites had been in continuous sugarcane production prior to this study.

Either SCBB (American Biocarbon) applied at 11 Mg ha^{-1} in the furrow (0-to-30-cm depth and covered with soil) plus fertilizer (referred as SCBB) or no biochar plus fertilizer (control) was replicated four times in a completely randomized design at both sites. Although the development and use of the biochar spreader technology has made the incorporation of biochar more feasible on a commercial scale (Page-Dumroese et al., 2016), the rate used in this study was chosen based on literature. Plots at each site consisted of three 1.83-m × 15.24-m raised-bed rows, which were bordered by one row. Sugarcane was planted as billets at 12 Mg ha^{-1} with the locally common variety HoCP96-540 in September 2015. Biochar was applied in May 2016 manually to the side of the row followed by covering with soil. After biochar application, fertilizer (urea ammonium nitrate, 32% N) was knifed in at about 8 cm deep as in normal practice using a fertilizer applicator. The experiment ran for two growing seasons, 2016 and 2017. Plant and ratoon cane fertilizer applications were the same. Plant cane for 2016 was established on clean beds in fall 2015, and harvest residue was left in the field after the plant cane before the 2017 season. Further details on the field experiment are given in Table 1.

2.2 | Soil collection and analysis of plant-available nutrients

Composite soil samples (0–15 cm) were collected from each treatment plot before application of biochar, after each harvest and after the last water sample was collected (below). Samples were oven dried, ground to <2 mm, and analyzed for total C (C_{soil}) and total N (N_{soil}) using a CN analyzer (Elementar Americas, Vario EL Cube); they were extracted for Mehlich-3 P (P_{soil}), K (K_{soil}), Ca (Ca_{soil}), and Mg (Mg_{soil}) and analyzed using a Spectro CIROS^{CCD} inductively coupled plasma–optical emission spectrometry (ICP–OES); and pH (pH_{soil}) and electrical conductivity (EC_{soil}) were measured in deionized water (DIW) at a 1:1 soil/DIW ratio, using a VWR pH meter (sympHony) and Thermo Electron EC meter (Orion 145Aplus). Concentrations of NH_4^+–N and NO_3^-–N in the last set of samples were extracted with 1 M KCl and measured using an automated flow injection system (Lachat QuickChem 8500 Series 2).

2.3 | Biochar characterization and nutrient composition

Biochar pH and EC were measured in a slurry of 1 g powdered biochar and 20 ml DIW after agitation in a horizontal shaker for 1 h at 25 ˚C followed by 30 min of settling time (Singh et al., 2017). Biochar CEC was determined by the modified ammonium acetate compulsory displacement method that was adapted to biochars, and expressed as $cmol_c$ kg^{-1} (Domingues et al., 2017). The specific surface area was determined based on multipoint adsorption of N_2 at −196 ˚C, using a Micromeritics ASAP2020 gas adsorption and porosity system and the linearized BET (Brunauer–Emmett–Teller) isotherm (Sigmund et al., 2017). Ash content of biochar was determined by combustion of the oven-dried (105 ˚C) biochar at 750 ˚C in a muffle furnace for 6 h (Singh et al., 2017). Carbon, N, H, and S content in biochar were determined by dry combustion of 0.1 g powdered biochar, using a Perkin Elmer 2400 Series II CHNS analyzer. Biochar O concentration was calculated using Equation 1:

$$O\,(\%) = [100 - (C + H + N + S + \text{Ash})] \tag{1}$$

Biochar C, H, N, S, and O content were used to calculate molar C/N, O/C, and H/C ratios (Domingues et al., 2017). Contents of P, K, Ca, Mg, and Fe were determined according to the USEPA 3050b wet acid digestion method using 1:1 HNO_3, 30% H_2O_2, and HCl (USEPA, 1996). The digestate was then filtered and analyzed via Spectro CIROS^{CCD} ICP–OES. All measurements were performed in triplicate, and results are provided in Table 2.

2.4 | Plant nutrient uptake, crop yield, and quality assessment

Plant tissue samples were collected from the top visible dewlaps of sugarcane 12 wk after fertilizer application. Samples were oven dried at 45 ˚C and ground to <2 mm. Elemental

TABLE 2 Physiochemical properties of light- (LS) and heavy-textured (HS) soils and sugarcane bagasse biochar (SCBB)

Parameter	LS	HS	SCBB
pH	7.2	5.9	6.6
EC, dS m^{-1}	0.6	0.1	0.5
CEC, cmol kg^{-1}	12.8	20.1	5.6
BD, g cm^{-3}	1.6	1.3	–
SSA, m^2 g^{-1}	–	–	1.22
Volatile matter, %	–	–	29.50
Ash, %	–	–	16.46
Sand, %	17	12	–
Silt, %	58	37	–
Clay, %	25	51	–
C, %	0.92	0.85	71.2
N, %	0.10	0.11	0.34
S, %	10.75	12.02	0.11
O, %	–	–	9.16
H, %	–	–	2.73
C/N	10.85	8.87	244.44
O/C	–	–	0.27
H/C	–	–	0.46
P, mg kg^{-1}	33.16	41.05	1,200
K, mg kg^{-1}	127.34	253.98	5,300
Fe, mg kg^{-1}	410.97	381.29	810
Mg, mg kg^{-1}	593.72	1,101.08	890
Ca, mg kg^{-1}	2,456.78	4,177.79	10,940

Note. EC, electrical conductivity; CEC, cation exchange capacity; BD, bulk density; SSA, specific surface area.

composition of plant samples were determined by Spectro CIROS^{CCD} ICP–OES after HNO_3–H_2O_2 digestion (Huang et al., 2004).

An interim yield sample was taken (on the day of and prior to combine harvest) for sucrose quality parameters. Specifically, 10 stalks were harvested by hand from the middle row of each plot, leaves were stripped off, the tops were cut 10–12 cm below the apical meristem, and total fresh and average stalk weights were recorded. Plots were harvested thereafter with a chopper harvester to determine total plot weight. Cut stalks from each plot were weighed with a high dump wagon fitted with electronic load sensor cells. The total plot cane yield was determined by adding the weight of the 10 stalks and the plot harvest weight.

Stalks were shredded and analyzed using a SpectraCane automated near-infrared analyzer (Bruker Corporation) for quality components including sucrose, theoretical recoverable sugar, brix (total soluble solids), purity, and polarity. Shredded stalk was oven dried at 60 ˚C for ≥72 h, depending on moisture content, ground to <2 mm, and analyzed for total N (N_{leaf}) and total C (C_{leaf}), using the CN analyzer (Elementar Americas, Vario EL Cube) as above.

2.5 | Runoff water collection and analysis

Runoff subplots were installed in two control and SCBB plots at each site ($N = 8$). Each consisted of a 1-m^2 stainless steel frame with covered collection trough installed on the furrow where biochar was or was not applied. Runoff drained through polyvinyl chloride (PVC) pipe into 18.9-L plastic buckets inside covered, water-tight, 209-L PVC sumps. Plots were checked for runoff within 24 h of a rainfall event (defined as >1 cm precipitation with at least 24 h of no precipitation before or after, as measured by one gauge each in the LS and HS sites and corroborated with NOAA data from Baton Rouge, LA) and runoff volume measured by net mass. This protocol gave 13 runoff samples collected from May 2016 to November 2017 from plant cane and the first stubble crop. Runoff subplot apparatus was removed before harvest and reinstalled for the second growing season after the second N fertilization. Problems with the reinstalled apparatus resulted in loss of the first three runoff samples in 2017.

Samples of runoff were transported to the laboratory in Teflon bottles on ice, separated into subsamples, and either immediately analyzed or refrigerated at 4 ˚C pending

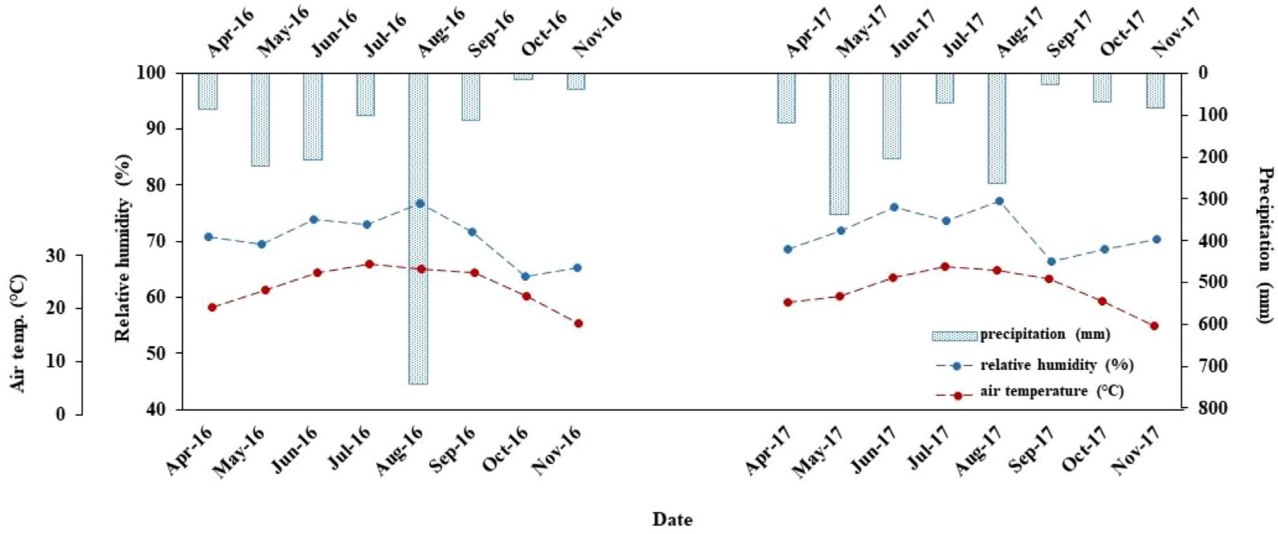

FIGURE 1 Average monthly temperature (˚C), relative humidity (%), and cumulative precipitation (mm) from April to November in 2016 and 2017 at the Louisiana State University Sugar Research Station in St. Gabriel, LA

TABLE 3 Analysis of variance for crop age, soil texture, and biochar amendment (sugarcane bagasse biochar [SCBB]) as fixed factors, and their interactions on top soil (0-15 cm) from Mississippi alluvial soils (light- [LS] and heavy-textured [HS]) under sugarcane production

Effect	C_{soil}	N_{soil}	C_{soil}/N_{soil}	P_{soil}	K_{soil}	Ca_{soil}	Mg_{soil}	NH_4^+–N	NO_3^-–N
	%			mg kg^{-1}					
Year/crop age									
2016/plant cane	1.27	0.15	8.08	39.25	194.81	3,313.77	871.24	1.63	22.44
2017/first stubble	1.61	0.13	12.12	30.24	276.09	3,620.67	918.28	0.90	3.76
p value	<.05	<.01	<.01	<.01	<.01	<.01	n.s.[†]	<.01	<.01
Site									
LS	1.34	0.15	8.62	28.95	157.02	2,588.46	621.31	1.29	14.58
HS	1.54	0.13	11.58	40.54	313.88	4,345.98	1,168.21	1.23	11.62
p value	n.s.	<.01	<.01	<.01	<.01	<.01	<.01	n.s.	<.05
Treatment									
Control	1.34	0.14	9.23	31.27	228.37	3,328.00	858.76	1.11	15.27
SCBB	1.54	0.14	10.97	38.22	242.53	3,606.44	930.76	1.42	10.93
p value	<.05	n.s.	<.05	<.05	<.01	<.01	<.05	<.05	<.01
Year × site	n.s.	<.01	<.01	n.s.	<.01	n.s.	n.s.	<.01	n.s.
Year × treatment	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	<.05
Site × treatment	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	<.05	n.s.
Year × site × treatment	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Note. Soil C_{soil} and N_{soil} were determined by dry combustion. Plant-available P_{soil}, K_{soil}, Ca_{soil}, and Mg_{soil} at harvest time were determined by inductively coupled plasma analysis of Mehlich-3 extracts. Soil NH_4^+–N and NO_3^-–N contents at the time of the last water collection were measured by 1 M KCl extraction of soil samples and using an automated flow injection system.

[†] n.s, not significant.

analysis within 48 h of collection. Samples were measured for pH, EC, total suspended solids (TSS), total organic C (TOC), biological oxygen demand (BOD_5), NO_3^-–N, PO_4^{-3}–P, SO_4^{-2}–S, and total dissolved nutrients (P, K, Ca, Fe, and Mg) after applicable USEPA holding time, preservation, storage, and analysis methods (9040C, 120.1, 160.2, 415.3, 405.1, 300, and 365.2 for water pH, EC, TSS, DOC, BOD_5, [NO_3^-/NO_2^-]–N, PO_4^{-3}–P, SO_4^{-2}–S, and dissolved nutrients, respectively). Blanks, control standards with differing concentrations, duplicate samples, and spiked samples

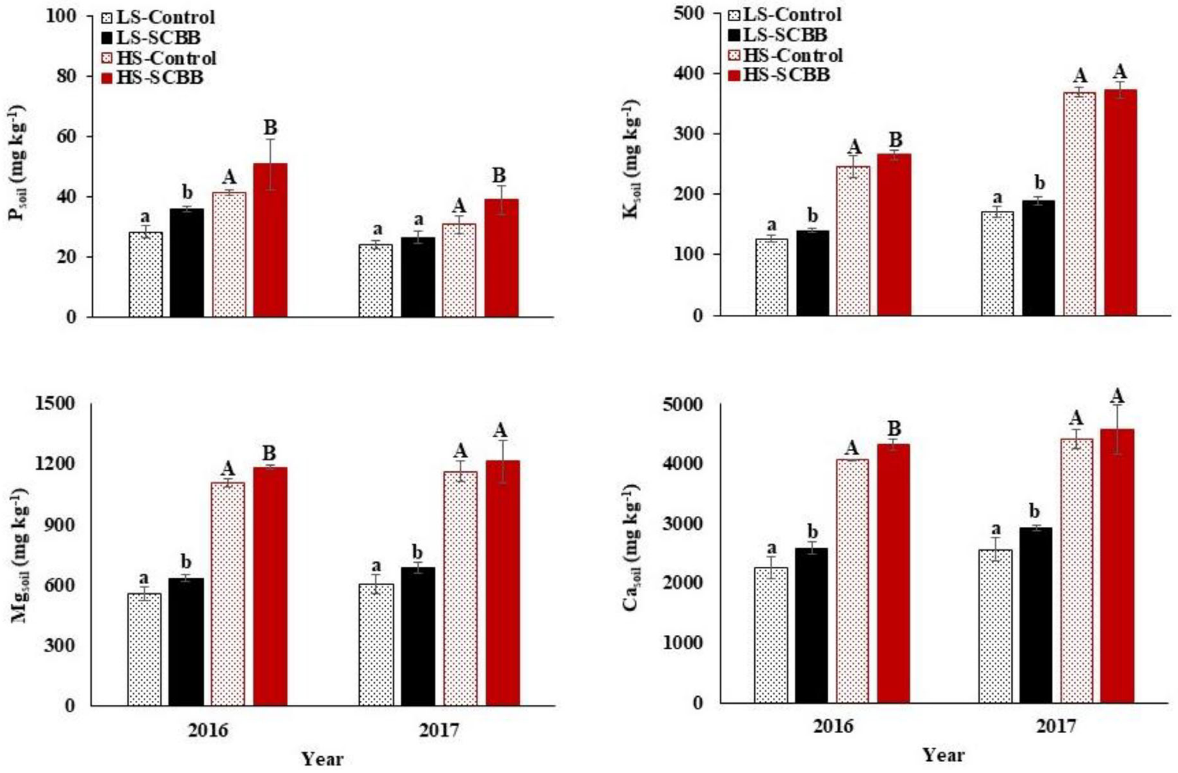

FIGURE 2 Biochar (sugarcane bagasse biochar [SCBB]) impact on plant-available nutrients in soils after the biochar application during the two growing seasons in two different-textured soils (light- [LS] and heavy-textured [HS]) under sugarcane production. For each element and within each year and soil, values with different letters are significantly different at $p < .05$

TABLE 4 Analysis of variance for crop age, soil texture, and biochar amendment (sugarcane bagasse biochar [SCBB]) as fixed factors, and their interactions on crop yield, quality parameters, and nutrient uptake during the two growing seasons for two Mississippi alluvial soils (light- [LS] and heavy-textured [HS]) under sugarcane production

Effect	Yield	Sugar	TRS[a]	Brix	Sucrose	N_{plant}	P_{plant}	K_{plant}	Ca_{plant}	Mg_{plant}
	——Mg ha^{-1}——		kg Mg^{-1}	——————%——————			——————g kg^{-1}——————			
Year/crop age										
2016/plant cane	88.69	9.54	111.59	16.97	17.41	1.08	2.75	33.03	9.69	3.45
2017/first stubble	72.00	8.20	108.11	15.60	17.27	1.11	3.09	27.58	9.88	3.39
p value	<.01	<.01	n.s.[†]	<.01	n.s.	n.s.	<.01	<.01	n.s.	n.s.
Soil texture										
LS	87.24	9.95	114.46	16.58	17.72	1.06	2.86	29.66	9.88	3.50
HS	73.45	7.79	105.23	16.00	16.96	1.13	2.97	30.95	9.69	3.33
p value	<.01	<.01	n.s.	<.01	n.s.	n.s.	n.s.	n.s.	n.s.	<.05
Treatment										
Control	74.13	8.29	107.50	16.10	17.04	1.03	2.81	29.06	9.25	3.29
SCBB	86.56	9.44	112.20	16.47	17.63	1.17	3.02	31.54	10.31	3.54
p value	<.01	<.01	n.s.	<.05	n.s.	<.01	<.05	<.01	<.01	<.01
Crop age × soil texture	<.01	<.01	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Crop age × treatment	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Soil texture × treatment	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Crop age × soil texture × treatment	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

[a] TRS, theoretical recoverable sugar.

[†] n.s., not significant.

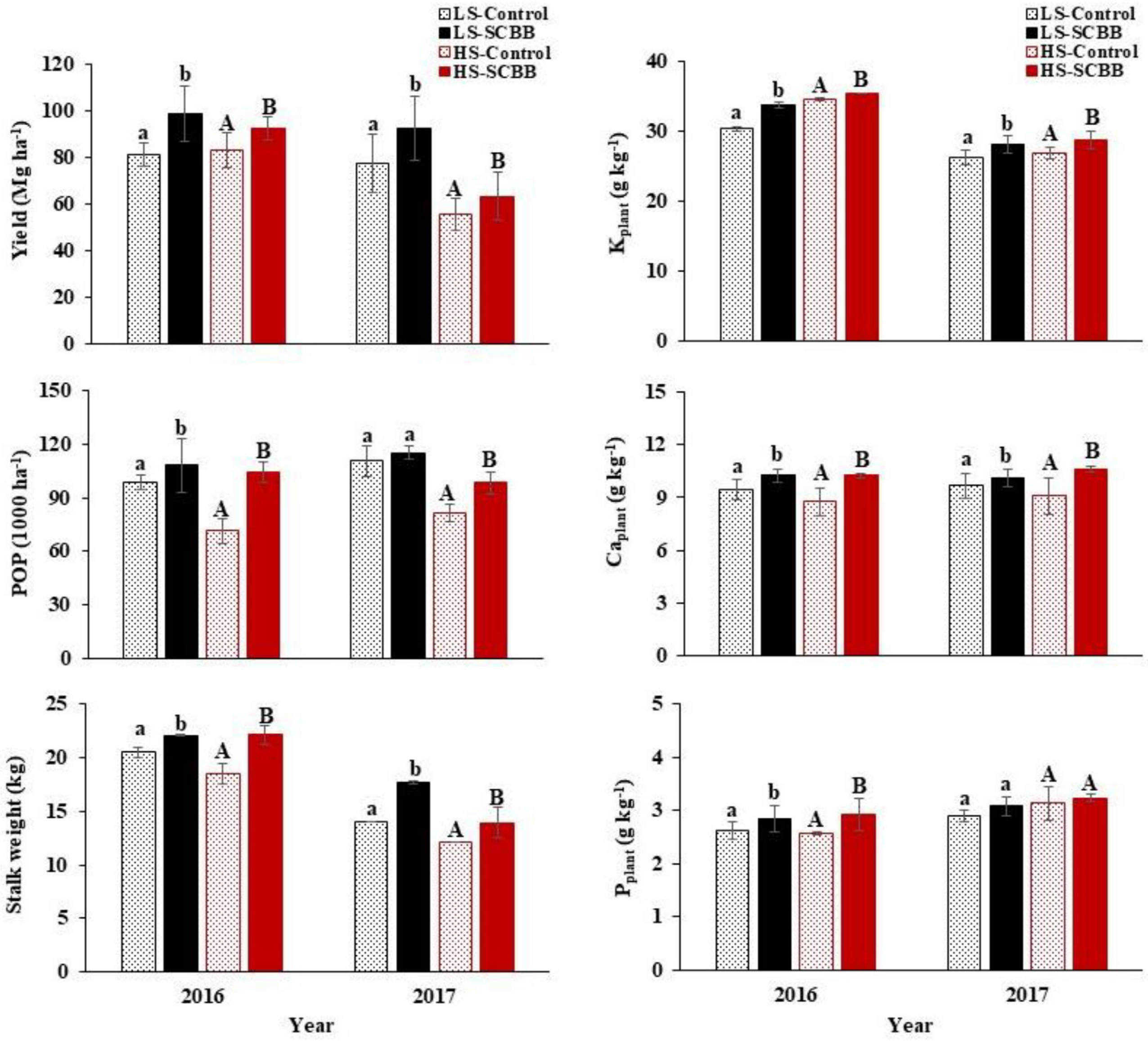

FIGURE 3 Biochar (sugarcane bagasse biochar [SCBB]) impact on crop yield, population (POP), stalk weight (10 plants), and plant nutrient uptake across two growing seasons in two different-textured soils (light- [LS] and heavy-textured [HS]) under sugarcane production. For each variable and within each year and soil, values with different letters are significantly different at $p < .05$

were included in each run. Water quality parameters (TSS, TOC, and BOD_5) and nutrient concentrations (NO_3^-/NO_2^-–N, PO_4^{-3}–P, SO_4^{-2}–S, P, K, Ca, Fe, and Mg) were calculated in milligrams per liter and also multiplied by runoff volume ($m^3\ ha^{-1}$) to estimate the total loads ($kg\ ha^{-1}$) for each runoff event.

2.6 | Leachate water collection and analysis

Two suction lysimeters (30- and 45-cm depths) were installed on one side of each runoff subplot. Approximately 80,000 Pa of suction was applied before an expected or at the beginning of a rain event. Leachate was siphoned with a plastic syringe 8–24 h after a rain event, and PO_4^{-3}–P and inorganic N (NO_3^-–N and NH_4^+–N) were measured using the automated flow injection system (Lachat QuickChem 8500 Series 2).

2.7 | Statistical analysis

All statistical analyses were performed using SigmaPlot software (version 13.0, Systat Software). One-way ANOVA was substituted with a nonparametric Kruskal–Wallis test (ANOVA on ranks) where the normality test failed. Three-way ANOVA was conducted with three fixed effects (year/crop age, site, and treatment).

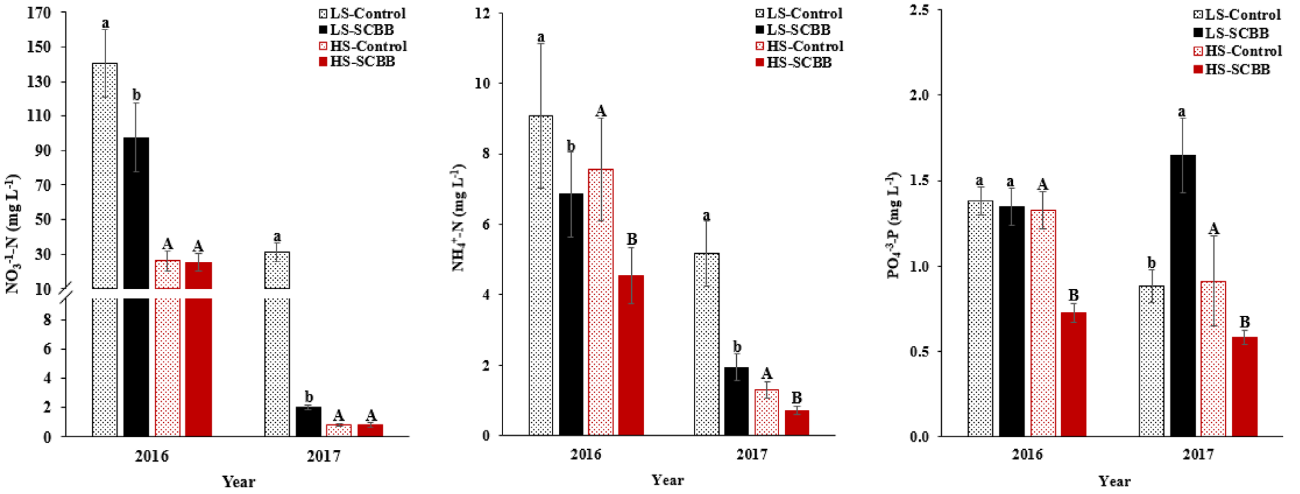

FIGURE 4 Effect of biochar (sugarcane bagasse biochar [SCBB]) amendment on average concentration of NO$_3^-$–N, NH$_4^+$–N, and PO$_4^{-3}$–P in leachate for two consecutive growing seasons at two sites (light- [LS] and heavy-textured [HS]). For each variable and within each year and site, values with different letters are significantly different at $p < .05$

3 | RESULTS AND DISCUSSION

3.1 | Climate conditions

Climatic conditions for the two growing seasons are given in Figure 1. There was more rainfall during the 2016 growing season (1,523 mm) than in 2017 (1,165 mm), with 742 mm occurring in August 2016. More than 190 and 290 mm of rain occurred soon after N fertilizer was applied in 2016 and 2017. Overall, rainfall was adequate for sugarcane growth. The average monthly temperature did not meet the optimum temperature for maximal growth (30–33 ˚C); however, it did not fall below 16 ˚C, at which sugarcane development is restricted (Cardozo & Sentelhas, 2013).

3.2 | Biochar characteristics and effects on soil properties

Table 2 presents major characteristics and nutrient contents of the LS and HS soils before fertilizer application in 2016. The pH of LS was neutral (7.2), whereas HS was acidic (5.9) and the EC was higher at LS (0.6 vs. 0.1 dS m^{-1}). Since inorganic C is undetectable in soil from this area (Selim et al., 2016), we interpreted soil C content as soil organic C (SOC). Both sites contained less SOC (0.92 and 0.85% at LS and HS sites, respectively) than found in other soils under sugarcane production in southern Louisiana (ranging from 1.0 to 2.4%; Johnson & Richard, 2005). Although the CEC was low in both soils, CEC and clay in the HS soil were, respectively, 57 and 100% higher, and Mehlich 3- extractable P, K, Mg, and Ca were 24–99% higher at HS, consistent with greater CEC and clay.

The physiochemical properties and elemental composition of biochar are also provided in Table 2. The pH was nearly neutral (6.6), the EC = 0.51 dS m^{-1}, and the CEC = 5.6 cmol$_c$ kg^{-1}. The specific surface area was small (1.22 m^2 g^{-1}), indicating the presence of organic substances, consistent with its small CEC (Ding et al., 2014). Elemental analysis indicated little N and H. The high C/N molar ratio of 244, along with small O/C and H/C ratios, suggested N loss during pyrolysis as well as high structural stability (Jeong et al., 2016; Oleszczuk et al., 2013). The pH and EC of the biochar (Table 2) used in this study were low compared with other biochars prepared from similar feedstock and at a similar temperature in the laboratory (Jeong et al., 2016; Tomczyk et al., 2020). Besides the nature of the plant biomass, biochar EC depends on conditions under which it is produced, which may differ in a commercial production from the laboratory setting (Ding et al., 2014; Lehmann, 2007).

Analysis of variance of treatments over 2 yr showed that biochar significantly increased C$_{soil}$ by 15% ($p < .05$) and C/N ratio by 19% ($p < .05$) across the two sites regardless of differences between sites and between plant cane and its ratoon crop (Table 3). Biochar also increased major plant-available nutrients at both sites. A closer examination of results showed that although biochar significantly increased plant-available P$_{soil}$, K$_{soil}$, Mg$_{soil}$, and Ca$_{soil}$ at the end of the 2016 season at both LS and HS, the effects tended to persist through the 2017 season at LS but not HS (Figure 2). In particular, major soil cationic nutrients at HS in 2017 were only numerically greater for SCBB than for the control (Figure 2), though P$_{soil}$ remained greater with SCBB. The opposite occurred at LS in 2017. Thus, the effect of biochar waned in <2 yr, despite that >80% of the feedstock P, K, Ca, and Mg is often retained in biochar (Wang et al., 2013). Jones et al. (2012) also showed

TABLE 5 Analysis of variance for crop age, soil texture, and biochar amendment (sugarcane bagasse biochar [SCBB]) as fixed factors, and their interactions on surface runoff quality parameters and total inorganic N (TIN) leaching for two Mississippi alluvial soils (light- [LS] and heavy-textured [HS]) under sugarcane production

	Surface runoff										**Leachate**
Effect	**Runoff volume**	**pH**	**BOD$_5$**	**TOC**	**TSS**	**NO$_3^-$–N**	**PO$_4^{-3}$–P**	**K**	**Ca**	**Mg**	**TIN**
	m^3 ha^{-1}		kg ha^{-1}								mg L^{-1}
Year/crop age											
2016/plant cane	676.3	5.9	16.3	7.7	4,064.4	9.2	10.9	2.2	7.6	0.7	55.7
2017/first stubble	2,834.6	6.7	20.9	30.4	8,573.7	8.3	5.8	17.0	28.5	11.2	4.97
p value	<.01	<.01	<.01	<.01	<.01	n.s.[†]	<.01	<.01	<.01	<.01	<.01
Site											
LS	2,448.1	6.2	22.6	21.1	7,865.2	6.5	11.8	10.3	16.5	8.5	51.33
HS	1,062.8	6.4	14.5	17.0	4,773.0	11.0	4.8	8.9	19.7	3.5	6.5
p value	<.01	<.01	<.01	<.01	<.01	<.01	<.01	n.s.	<.05	<.01	<.01
Treatment											
Control	2,096.4	6.2	21.3	21.7	8,687.4	10.6	10.4	10.9	23.0	6.6	39.24
SCBB	1,414.5	6.4	15.9	16.4	3,950.8	6.9	6.3	8.3	13.2	5.4	27.18
p value	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	n.s.	<.01
Year × site	<.01	n.s.	n.s.	<.01	<.01	<.01	n.s.	<.05	n.s.	<.01	<.01
Year × treatment	<.01	n.s.	<.01	<.01	<.01	n.s.	n.s.	<.05	<.01	n.s.	n.s.
Site × treatment	n.s.	<.01	<.01	n.s.	<.01	n.s.	n.s.	n.s.	n.s.	n.s.	<.01
Year × site × treatment	n.s.	n.s.	<.05	n.s.	<.01	n.s.	n.s.	n.s.	n.s.	n.s.	<.05

[†] n.s., not significant.

a decreasing residual effect of biochar on soil properties over time.

3.3 | Crop yield and nutrient uptake

A three-factor ANOVA (Table 4) showed effects of year, soil texture, biochar and their interactions on crop yield, quality parameters, and nutrient uptake. Texture had significant effects on crop yield ($p < .01$) and quality parameters including sugar ($p < .01$) and brix ($p < .01$). Yield at the HS site was lower than at LS ($p < .01$). However, biochar significantly increased yield by 15% on the two different-textured soils over two growing seasons ($p < .01$). Specifically, biochar increased plant cane yields in 2016 by 22% at LS ($p < .01$) and 12% at HS (Figure 3). Although the 2017 first stubble yields were expectedly lower than plant cane (5, 7, 33, and 32% in LS-Control, LS-SCBB, HS-Control, and HS-SCBB plots respectively), yield for LS-SCBB was 20% higher than for LS-Control ($p < .01$), and yield for HS-SCBB was 14% higher than HS-Control ($p < .01$; Figure 3). Thus, biochar tended to offset yield reduction when residue was retained. Moreover, whereas Alvarez-Campos et al. (2018) and Butphu et al. (2020) showed that various biochars significantly increased sugarcane yields in sand soils, our field study suggests that application of SCBB could increase yields in heavier as well as lighter texture soils.

The yield increase with SCBB was due to greater stalk weight and population (Figure 3). Nutrient levels in dewlap leaves also showed greater N, P, K, and Ca and Mg uptake in biochar-amended plots (Table 4, Figure 3), consistent with increasing concentration of most plant-available nutrients in soil (Table 3, Figure 2). According to Lehmann and Joseph (2015), plant uptake partly reflects the amount of nutrients in biochar, which are generally available. Thus, whereas Quirk et al. (2012) showed that most of the nutrients in cane feedstock are retained in biochar and can be returned to the field, Lima and White (2017) also reported that sugarcane exhibited high utilization of biochar Ca and K, leading to significant yield improvement. Although nutrient uptake is often increased with biochar amendment (Asai et al., 2009; Kloss et al., 2012; Lehmann et al., 2006; Zhang et al., 2016), its effect on crop yield has been mixed (Mukherjee & Lal, 2014). However, our field study demonstrated that biochar increased sugarcane yields as well as nutrient uptake.

3.4 | Leaching of NO_3^-–N, NH_4^+–N, and PO_4^{-3}–P

The effects of biochar on average concentration of leaching NO_3^-–N, NH_4^+–N, and PO_4^{-3}–P are shown in

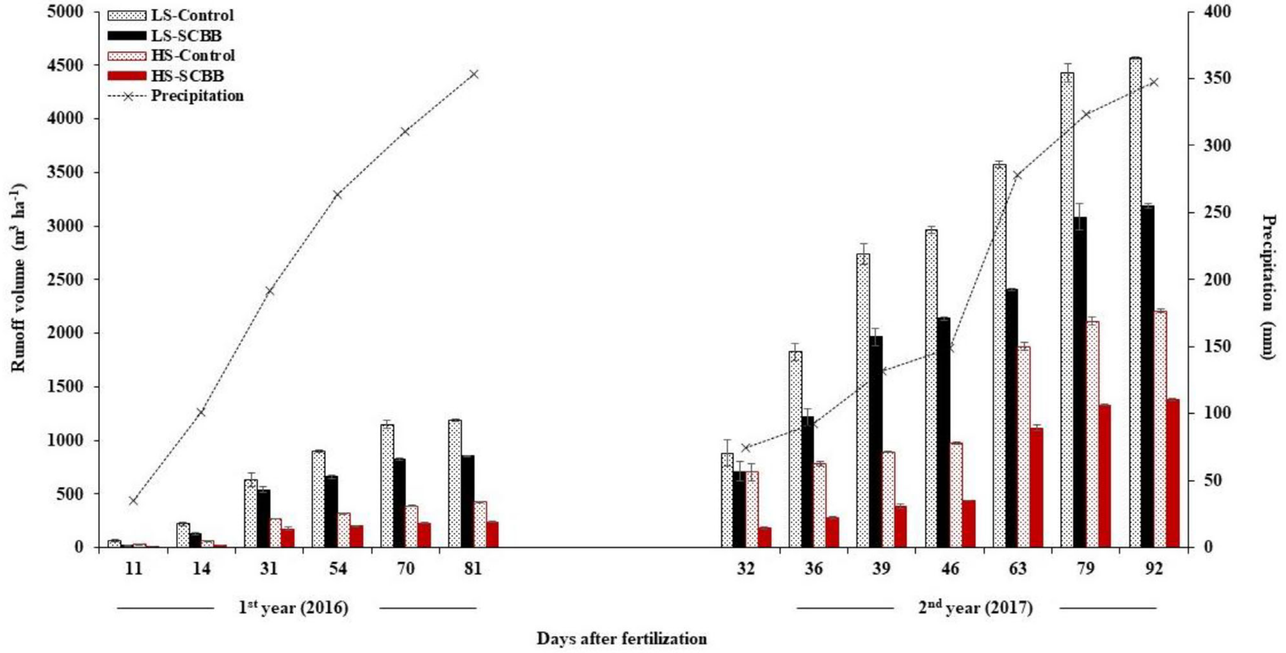

FIGURE 5 Effect of biochar (sugarcane bagasse biochar [SCBB]) amendment on cumulative runoff volume during two growing seasons from light- (LS) and heavy-textured (HS) soils. Fertilizer was applied on 6 May 2016 and 28 Apr. 2017

Figure 4. Although biochar reduced NO_3^-–N leaching at LS 31% ($p < .01$) during the first growing season and 93% during the second ($p < .01$), it did not significantly reduce leaching at HS, in part likely due to lower NO_3^-–N levels at HS (Table 3). Since the biochar surface is generally dominated by negative charge, reduction of NO_3^-–N leaching at LS may be attributable to retention of NO_3^-–N within biochar pores and the presence of some positive charge (Lawrinenko, 2016; Prendergast-Miller et al., 2014). On the other hand, biochar significantly reduced NH_4^+–N leaching at both LS and HS by 33–167% ($p < .01$) and 66–81% ($p < .01$), respectively, over 2 yr, consistent with added negatively charged biochar particles (Jeong et al., 2016). Overall, SCBB reduced total inorganic N (TIN; NO_3^--N + NH_4^+–N) by 44% ($p < .01$) across both sites and growing seasons (Table 5). While leachate TIN was significantly lower ($p < .01$) at HS, there was a significant soil texture × biochar treatment interaction, emphasizing the importance of soil properties on effects of biochar. Sika and Hardie (2014) also reported that pinewood biochar reduced ammonium nitrate leaching in a sandy soil. In addition, lower average concentration of NO_3^-–N and NH_4^+–N losses in the second growing season at both sites compared with the first season was similar to results for other crops (Lehmann & Schroth, 2003; Yadav et al., 2019).

In contrast with NO_3^-–N and NH_4^+–N, the effect of biochar on concentration of PO_4^{-3}–P leaching was mixed (Figure 4). Whereas biochar had no effect on PO_4^{-3}–P leaching at the LS site during the first growing season and significantly increased it during the second, biochar reduced leaching at HS during both growing seasons (Figure 4). Although biochar has been shown to potentially reduce long-term P leaching in coarser-textured soils with high P (Novak & Watts, 2004), the near neutral pH and relatively low soil test Ca and Mg at LS (7.2; Table 2) would limit the effect (Lindsay, 1979). Further, higher leachate PO_4^{-3}–P concentration with biochar than without in 2017 at LS may reflect slow movement of the P added with SCBB. In contrast, the acidic pH and higher soil test Ca and Mg at HS favored retention of phosphate (Lindsay, 1979).

3.5 | Runoff water quality parameters and nutrient loss

Thirteen rain events, ranging from 1.42 to 12.93 mm of rainfall during the 2016–2017 growing seasons (Figure 5), resulted in runoff collections and were used to measure runoff quality parameters and calculate nutrient loading loss. Across sites and years, biochar reduced total runoff by 33% ($p < .01$; Table 5). Specifically, it significantly reduced ($p < .05$) cumulative runoff by 28 and 30% at the LS site and by 43 and 38% at the HS site for 2016 and 2017, respectively (Figure 5). Less runoff with biochar may reflect increased surface storage and ponding time (Sadeghi et al., 2016) and/or reduced soil bulk density, greater water holding capacity, and increased aggregate size and stability with biochar amendment (Xiang-Hong et al., 2012). Comparing sites, however, there was surprisingly

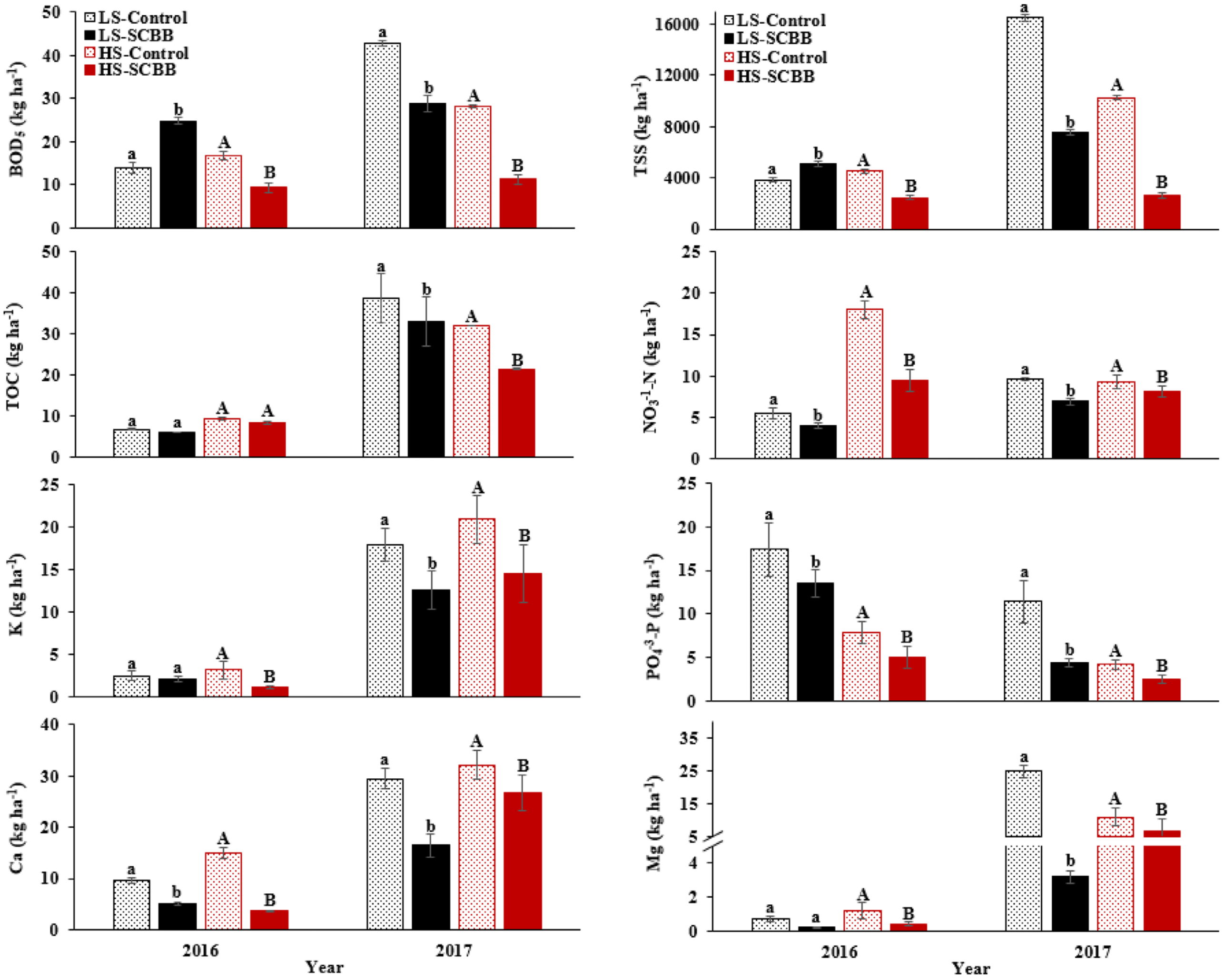

FIGURE 6 Biochar (sugarcane bagasse biochar [SCBB]) impact on surface water runoff quality parameters and nutrient losses across the two growing seasons in two different-textured soils (light- [LS] and heavy-textured [HS]) under sugarcane production. For each variable and within each year and soil, values with different letters are significantly different at $p < .05$. BOD_5, biological oxygen demand; TSS, total suspended solids; TOC, total organic C

57% less runoff ($p < .01$) from HS soil than from LS soil, possibly due to stable structure and high microporosity of the clayey soil (Ng Kee Kwong et al., 2002).

Across sites and years, biochar significantly reduced loads of all parameters except Mg and slightly increased pH (Table 5). However, loads of all parameters except NO_3^-–N and PO_4^{-3}–P were significantly greater in 2017, in large part reflecting about four times greater runoff than in 2016. Biochar generally reduced loads at both sites in both years (Figure 6), however, BOD_5 and TSS were greater with biochar at LS in 2016, leading to significant year × site × treatment effects (Table 5). It should be pointed that previous studies on runoff from Louisiana sugarcane fields found no effect of residue management practices on loads of nutrient runoff and suspended solids (Bengtson & Selim, 2006; Viator et al., 2009). In contrast, our study shows that biochar substantially reduced runoff, BOD_5, TOC, TSS, and major nutrients; however, the effect may not be immediate and its magnitude may vary with constituent and soil texture.

4 | CONCLUSIONS

Biochar is not a substitute for fertilizer, neither is its use yet considered a good farming practice. However, our results showed that biochar not only acted as reservoir of nutrients, but it also helped retain nutrients against loss in runoff and leaching and improved sugarcane yield. Reduced runoff and loads from sugarcane soil amended with SCBB are important findings that warrant further investigation including optimizing the rate of biochar application. Results indicate that much of the nutrient value of bagasse was returned to the soil, and its stability favors long-term C sequestration, and thus potential C credits. The latter should be considered by agricultural economists with respect to the profitability and sustainability of using biochar in southern Louisiana agriculture. Although this study was based on a common rate of biochar amendment, additional research is needed to evaluate potential beneficial results of other application rates in sugarcane production.

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AUTHOR CONTRIBUTIONS

Negar Tafti: Formal analysis; Investigation; Writing-original draft. Jim Wang: Conceptualization; Funding acquisition; Project administration; Resources; Supervision; Writing-review & editing. Lewis Gaston: Methodology; Writing-review & editing. Jong-Hwan Park: Investigation; Writing-review & editing. Meng Wang: Investigation. Scott Pensky: Investigation.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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