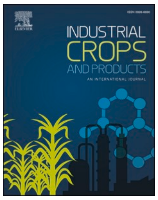
Industrial Crops & Products 161 (2021) 113224

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop



The effects of biochar on the biomass yield of elephant grass (*Pennisetum Purpureum* Schumach) and properties of acidic soils

Binh Thanh Nguyen [a], Long Ba Le [a], Long Phi Pham [a], Hiep Thai Nguyen [a], Tu Dinh Tran [b], Nam Van Thai [c,*]

[a] *Institute of Environmental Science, Engineering, and Management, Industrial University of Ho Chi Minh City, 12 Nguyen Van Bao, Go Vap District, Ho Chi Minh City, Viet Nam*

[b] *Faculty of History, University of Social Sciences and Humanities - Vietnam National University Ho Chi Minh City, 10 - 12 Dinh Tien Hoang, Ben Nghe Ward, District 1, Ho Chi Minh City, Viet Nam*

[c] *HUTECH Institute of Applied Sciences, Ho Chi Minh City University of Technology (HUTECH), 475A, Dien Bien Phu, Ward 25, Binh Thanh District, Ho Chi Minh City, Viet Nam*

ARTICLE INFO

Keywords:
Biochar
Elephant grass
Liming effect
Soil fertility
Soil quality index

ABSTRACT

Although biochar can be considered as a potential amendment to ameliorate degraded soils with many studies reported, little is known about its effects on acidic soils grown with elephant grass (*Pennisetum Purpureum* Schumach), a bioenergy crop. The current study aimed to (1) examine the effects of coffee husk-derived biochar on the grass's yield and properties of acidic soil and (2) identify potential mechanisms in determining the yield. A greenhouse pot experiment was conducted to test five treatments (no biochar – T1, 2% biochar-T2, 4% biochar-T3, 2% cow manure-T4, and a mixture of 1% biochar plus 1% cow manure –T5) in four replicates. The pots were grown with elephant grass for three successive harvests. Soil after each harvest was taken to analyze for 14 parameters, which were used for SQI estimation. Biochar significantly increased the biomass yield by 61 (T2) and 82 % (T3), compared to T1. pH, cation exchange capacity, and the concentration of Mehlich-1 P and exchangeable bases (K, Na, and Ca) were significantly enhanced, while exchangeable acidity and the concentration of exchangeable H^+, Al, and Fe were significantly decreased following biochar addition. The SQI was significantly better in the biochar-added soil than the non-biochar soil. The improved biomass yield could be involved in a few mechanisms, including liming effect, co-addition of nutrients with the added biochar, and nutrient use efficiency. In brief, biochar is a potential amendment in mitigating the constraints of acidic soils, leading to the enhanced biomass yield of elephant grass in the soils.

1. Introduction

Acidic soils, a marginal soil group popular all over the world, occupy as much as 50 % of the world's arable land and are likely to further increase due to ongoing soil acidification (Kunhikrishnan et al., 2016; von Uexküll and Mutert, 1995). Acidic soils are commonly low in fertility and productivity because of toxicities caused by a high concentration of aluminum (Al), manganese (Mn), and iron (Fe) and deficiency of phosphorous (P), and bases (calcium- Ca, magnesium – Mg, and potassium - K) (Dai et al., 2017; Kunhikrishnan et al., 2016). To maximize benefits, it is important to apply appropriate solutions to ameliorate the constraints of the soils. Two common directions of effectively using the soil can be related to the cultivated crops and agronomic practices. The former may be involved in the crop selection such as elephant grass (*Pennisetum Purpureum* Schumach), a bioenergy crop, well adaptable to the poor – quality soils and the latter may be related to soil amendments to reduce the toxicities while correct nutrient deficiency, thus improving the fertility of the soil.

Originated from Africa, elephant grass is a perennial tropical crop, commonly cultivated for high-quality and high-production forage for beef and dairy cattle. Given climate change reported recently due to the greenhouse effect partially caused by fossil fuel burning (Nasa, 2020), bio-energy derived from biomass can be a potential alternative in replacement of fossil fuel. Consequently, elephant grass can be used as a

---

* Corresponding author at: HUTECH Institute of Applied Sciences, Ho Chi Minh City University of Technology (HUTECH), 475A, Dien Bien Phu, Ward 25, Binh Thanh District, Ho Chi Minh City, Viet Nam.

E-mail address: tv.nam@hutech.edu.vn (N. Van Thai).

https://doi.org/10.1016/j.indcrop.2020.113224
Received 10 October 2020; Received in revised form 23 December 2020; Accepted 24 December 2020

new raw material for bioenergy production (Flores et al., 2012; Strezov et al., 2008). Nevertheless, the additional cultivation of the grass could result in competition between bioenergy production and food crop production, reducing available agricultural land, and possibly threatening food security.

Therefore, the marginal soils such as acidic soils could be an optimal solution for bioenergy-crop production with many studies conducted (Koide et al., 2018; Richards et al., 2014). The elephant grass can be adaptable to a wide range of environmental conditions with minimal nutrient demand and a wide range of soil pH (Strezov et al., 2008), making it suitable for acidic soils. Nevertheless, to get a better yield of elephant grass, the quality of the acidic soil should be improved.

One important and sustainable option to improve the quality of the acidic soils is to use biochar as an amendment because the material has high alkalinity (Fidel et al., 2017). Generally, biochar as a soil amendment can revert or prevent soil acidification and improve soil fertility and productivity, which were well documented by (Biederman and Harpole, 2013; Dai et al., 2017; Ding et al., 2016). In the acidic soil, biochar may remediate the toxic effects of Al, Mn, and Fe, while improving nutrient deficiency of P, and other base cations (Berek et al., 2018; Dai et al., 2017; Qian et al., 2013). These indicate that biochar could be a suitable amendment on acidic soil grown with elephant grass.

However, our up-to-date literature search revealed that insufficient studies were carried out to discuss the effects of biochar on the biomass yield of elephant grass planted in acidic soils. Therefore, the current study was conducted to (1) examine the effects of biochar on the yield of elephant grass and quality parameters as well as soil quality index (SQI) of acidic soil and (2) identify some potential mechanisms by biochar in determining the grass yield on the acidic soil in Vietnam. It could be hypothesized that biochar could increase the biomass yield of elephant grass and improve the quality parameters of the acidic soils and that the effect could be involved in some main mechanisms such as liming effect and nutrient improvement.

2. Materials and methods

2.1. The experimental materials

Soil samples used for the current study were taken from a *Rhodic Ferralsol* (FAO/UNESCO) historically planted with the coffee tree, located at 14.019489, 108.115231, in Dac Doa district, Gia Lai province, Vietnam. The coffee trees were cultivated 25 years ago and the soil was degraded due to inappropriate management practices (erosion, inorganic fertilizer application, product removal, and nutrient leaching). Due to decreased bean yield, the coffee trees are about to cut down to replant for the second cycle or possibly converted for other purposes such as forage production for dairy cow farming. The percent of clay, silt, and the sand component of the soil was 66.2, 23.7, and 10.1 %, respectively (more properties of the soil shown in Table 1). About 300 kg soil in 0-15 cm surface layer was taken from 10 points distributed over around 10-ha area. The taken soil was transferred to a greenhouse of Industrial University of Ho Chi Minh City for air-drying, grinding, and sieving through a 2-mm sieve for the pot experiment.

Biochar material used for the current study was produced from the coffee husk, using a method by Nguyen et al. (2018b) with some modification. The kiln reactor used to produce biochar was made from a steel sheet, which was rolled into a cylinder with a size of 0.8m × 1.5m (width x height). The coffee husk was collected from the same soil sampled-coffee tree plantation and air-dried before biochar production. Cow manure was bought from the local market surrounding the coffee plantation. Some properties of the biochar and cow manure were shown in Table 1.

2.2. Experimental setup

The current study was set up as a completely randomized design with four replicates in a greenhouse. Five experimental treatments included (T1) no amendment addition, (T2) 2% biochar addition, (T3) 4% biochar addition, (T4) 2% cow manure addition, and (T5) a mixture of 1% biochar plus 1% cow manure. The biochar and cow manure were mixed with around 7-kg soil at the mentioned rates and the mixtures were repacked into plastic pots (18cm × 35cm, diameter x height), each of which was pre-drilled to make 5 small holes (2 cm in diameter) at the bottom for over-water drainage. The stem-cutting method was used to plant elephant grass in individual pots (Ferreira et al., 2018). Individual cuttings included 3 nodes, two of which were buried under the pot soil and three cuttings were planted in one pot. The pots were watered bi-daily using tap water, and no fertilizers were applied during the 6-month experiment.

2.3. Measurements

Biomass harvest: The harvest was carried out in three cuts after 2, 4, and 6 months from planting. The harvests were implemented every 2 months because Arshadullah et al. (2010) found that the highest yield of elephant grass could be reached after 60 days from planting. For the harvests 1 and 2, the aboveground part at a 20-cm height from the stock was cut, washed with tap water, and oven-dried at 70 °C until constant weight. The dry weight was calculated in grams per harvest per pot and used for statistical analysis. For the last harvest, the aboveground part was collected in the same way as the two above harvests. The root mass and stubble mass were collected by pulling out the soil, root, and stubble from each pot onto a clear plastic sheet and a knife was used to cut the topsoil layer (0−15 cm). After hand separating the soil from the top layer, the biomass (root and stubble) was washed out with tap water, separated into root and stubble, oven-dried at 70 °C until constant weight, and weighed to determine dry mater per pot per harvest.

Chemical analyses: Before the experiment, the sieved soil, biochar, and cow manure were sampled in three replicates for chemical analyses. After each of three harvests, the soil from all pots was sampled separately for the 0−15 cm surface layer, air-dried, and ground to pass a 2-mm sieve before analyses.

Soil, biochar, and manure samples were analyzed for pH, exchangeable acidity, exchangeable H^+, plant-available nutrients

Table 1
Initial properties of experimental materials. (N.D. = Not Detected). Note: The soil had a particle size distribution of 66.2 for clay, 27.7 for silt, and 10.1 for sand. The biochar had 15 % of ash content.

Material	Statistics	pH	OC (%)	TKN (%)	CEC (cmol(+) kg^{-1})	Available concentration (mg kg^{-1})			Exchangeable concentration(mg kg^{-1})						
						NH_4^+	NO_3^-	Mehlich-1 P	Al	Fe	Mn	Ca	Mg	K	Na
Soil	Mean	5.9	2.9	0.18	12.8	27.7	8.2	15.4	82.2	4.9	6.8	182.0	27.4	231.8	481.0
	SE	0.0	0.2	0.02	0.2	0.8	0.2	0.5	1.5	0.5	0.2	7.0	1.1	6.3	1.7
Biochar	Mean	9.8	58.2	0.58	170.4	ND	ND	157.4	2.1	2.1	0.2	886.7	178.2	19025.8	1231.0
	SE	0.0	0.3	0.05	1.2	0.0	0.0	1.6	0.4	0.5	0.0	19.2	1.2	197.3	15.4
Manure	Mean	7.2	25.7	1.04	28.0	433.4	90.4	4309.0	0.2	2.3	3.4	1578.4	1626.7	10124.4	3637.9
	SE	0.1	0.7	0.05	0.4	8.2	1.3	14.8	0.0	0.1	0.1	90.8	99.8	300.2	14.4

(Mehlich-1 P, NH_4^+, and NO_3^-), exchangeable cations (Al, Fe, Mn, Na, K, Mg, and Ca), and cation exchange capacity (CEC). Besides, the before - experiment soil was analyzed for particle size distribution (Carter and Gregorich, 2008), total Kjeldahl nitrogen (TKN) (Phares et al., 2020), and organic carbon (OC), and the biochar and cow manure were analyzed for OC and ash content (for biochar). The materials were added with distilled water at a 1:2 (w/w) ratio and the extract was measured for pH. OC was measured using the Walkley – Black method. Exchangeable acidity and H^+ were measured using the titration method (Carter and Gregorich, 2008). The concentrations of NH_4^+ and NO_3^- were measured using 2 M KCl (Carter and Gregorich, 2008). Available P was determined based on the Mehlich-1 method (HCl + H_2SO_4 extraction) (Novak et al., 2018) and the extract was measured using the Murphy-Riley colorimetric method (Murphy and Riley, 1962). The concentrations of exchangeable Al, Fe, Mn, Na, K, Mg, and Ca were measured using the barium chloride method (Carter and Gregorich, 2008) and the extract was measured using Inductively coupled plasma - optical emission spectrometry (ICP-OES). CEC was measured using the ammonium acetate method as used in Nguyen and Lehmann (2009).

2.4. Statistical analyses

All original data were subjected to statistical analysis using one-way Analysis of Variance (ANOVA) for a completely randomized design. The simple linear regression analysis was performed to examine the dependency of biomass yield on individual soil parameters. Additionally, the soil quality index (SQI) was computed based on the principal component analysis/factor analysis method (Mukherjee and Lal, 2014) using Eq. (1)

$$SQI = \sum_{i=1}^{n} w_i \ s_i \tag{1}$$

Where n is the number of soil parameter; w_i is the weightage of the ith parameter, and s_i is the score of the ith parameter. The w_i (the weightage) was determined using the principal component analysis/factor analysis and s_i is determined through Eqs. (2) and (3). The fourteen soil parameters analyzed were divided into three groups, including “more is better”, “less is better” and “neutral”. The more-is-better parameters included all soil parameters having positive correlations with biomass yield; the less-is-better parameters included those having negative correlations with biomass yield and the neutral including those having no relationship with biomass yield. For the more-is-better and neutral parameters, s_i is determined following Eq. (2).

$$\frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{2}$$

For the less-is-better parameters, s_i is determined following Eq. (3)

$$\frac{x_{max} - x_i}{x_{max} - x_{min}} \tag{3}$$

Where x_i, x_{min}, and x_{max} are the analyzed value, minimum value, and maximum values of the parameter i, respectively.

The principal component analysis/factor analysis (PCA/FA) was used to determine the weightage (w_i) of individual soil parameters. The PCA/FA was applied to the whole data following the procedure described by Mukherjee and Lal (2014). Factors having either eigenvalue greater than 1 or a percentage greater than 5% were retained for weightage estimation of the soil parameters having a high loading value (>0.5) with the corresponding factor. The weightage was computed as that $\frac{e_i}{Sum}$, where e_i is the eigenvalue of factor i, and Sum is the sum of the eigenvalue of all factors remained after PCA/FA. The computed SQI was also subjected to statistical analyses, including one-way ANOVA and simple linear regression analysis as mentioned above.

3. Results

3.1. The biomass yield of elephant grass

In general, the aboveground biomass of elephant grass of treatment 3 (T3, soil added with 4% of biochar) was the highest, and that of T1 (soil added without any amendment) and T4 (soil added with cow manure) was the lowest in three successive harvests over 6 experimental months (Fig. 1a). For the first harvest, T3 had the aboveground biomass yield of 44.7 (g pot^{-1}), significantly higher than the other treatments and T1 had the lowest aboveground yield (13.1, g pot^{-1}). For the second and the third harvests, the highest aboveground biomass was also found in T3, while the lowest biomass was found in T1. Along the three harvests, the aboveground yield of T3, T2 (soil added with 2% biochar), and T5 (soil added with 1% biochar plus 1% cow manure) decreased to a greater extent than the other treatments. The root weight and stubble weight were also significantly higher in treatment 3 than in treatments 1 and 5 (Fig. 1b and c). Finally, the total biomass of T3 was the highest, followed by T2, T5, T4, and T1 (Fig. 1d).

3.2. Soil properties

The pH value, organic carbon (OC), and cation exchange capacity (CEC) of the original soil samples were 5.9, 2.9 (%), and 12.8 (cmole(+) kg^{-1}), much lower than those of the tested biochar (9.8, 58.2, and 170.4), and cow manure (7.2, 25.7, and 28.0), respectively (Table 1). The concentrations of NH_4^+ (433, mg kg^{-1}), NO_3- (90.4, mg kg^{-1}), and Mehlich-1 P (4309, mg kg^{-1}) of the cow manure were much higher than the other experimental materials. The tested soil also had the concentration of exchangeable Al, Fe, and Mn much higher than the other materials, while biochar had an exchangeable K concentration higher than the other materials, and cow manure had the concentration of exchangeable Ca, Mg, and Na better than the others.

After the first harvest, soil CEC (17.7, cmole(+) kg^{-1}) and pH (7.8) of T3 were significantly higher than the other treatments, and lowest in the T1 (13.6, and 6.0, respectively) (Fig. 2a and b). After the second harvest, these two soil parameters of T3 also were still highest, but after the third harvest, these parameters were statistically similar in all five treatments. In contrast, the soil of T1 was significantly higher in exchangeable acidity and exchangeable H^+ than the other treatments, especially T3 and T2 after the first harvest (Fig. 2c and d). After the third harvest, exchangeable acidity was still significantly highest in T1 and lowest in T3, while exchangeable H^+ was not clearly different in all five treatments.

For the first and second harvest, the concentrations of NH_4^+ (21.1 and 20.3, mg kg^{-1}) and NO_3- (15.2 and 23.6, mg kg^{-1}) of T4 were the highest and those of T3 (14.5 and 14.8; 11.2 and 16.0, respectively) were the lowest (Fig. 3a and b). For the last harvest, the concentration of these two forms of nitrogen was not different among the five treatments. Along the harvest times, the concentration of NH_4^+ was decreased while that of NO_3- was increased in all five treatments. The soil of treatments 2, 3, 4, and 5 was improved with available P concentration, compared to treatment 1 after all three harvests (Fig. 4a). For the first and the third harvest, the concentration of Mehlich-1 P of T5 was the highest (21.0 and 17.4, mg kg^{-1}), and its concentration of T1 (14.8 and 9.8) was the lowest of the five treatments, while for the second harvest, its concentration of T4 was the highest (18.2) and that of T1 was the lowest (13.0, mg kg^{-1}). The concentration of Mehlich-1 P was decreased along the harvest times in all five treatments. The concentration of exchangeable Al was the highest in treatment 1, 68.0 (after the first harvest), 72.1 (after the second harvest), and 78.5 (mg kg^{-1}, after the third harvest) and the lowest in T3 (13.8, 36.7, and 42.9, mg kg^{-1}), respectively (Fig. 4b). Along the harvest times, the exchangeable Al concentration was increased but its difference among the three harvests of T3 was greater than that of T1. For the exchangeable Fe concentration, T3 had the concentration significantly lower, and T1 and T5 had the

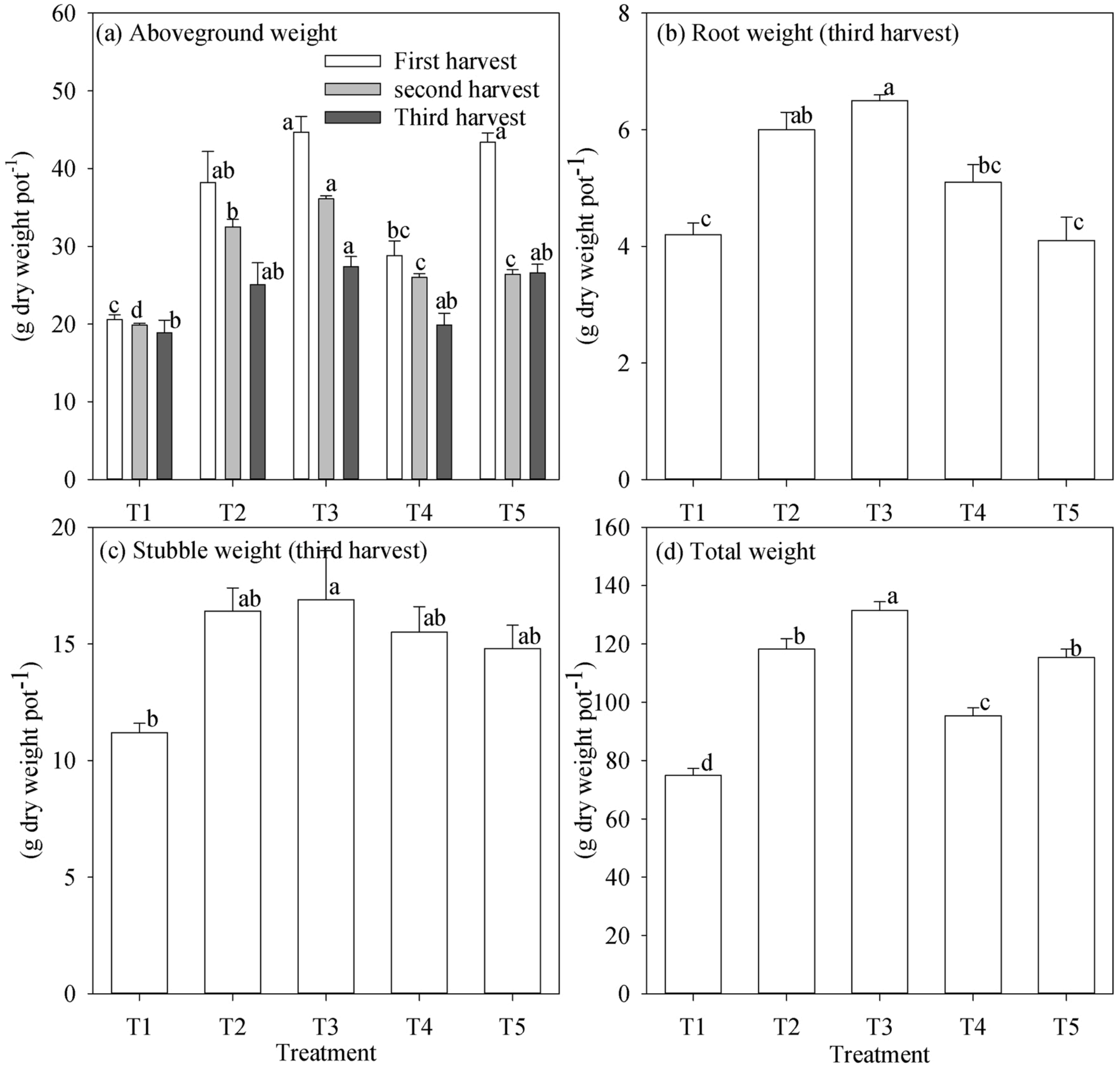


Fig. 1. Biomass yield of elephant grass in three successive harvests of five treatments. For each harvest in panel a and within each panel (panels b, c, and d), columns attached with the same letter were not significantly different from the others. The error bars indicated standard errors (SE) computed from 4 replicates.

concentration significantly higher than other treatments only after the first harvest (Fig. 4c). The concentration of exchangeable Mn was not different among five treatments in three harvests, varying from 3.9 to 7.3 (mg kg^{-1}) (Fig. 4d).

Of the four base cations, soil K of T3 had the exchangeable concentration (1076, 937, and 558, mg kg^{-1}, after the first, second, and third harvest, respectively) significantly higher than that of the other treatments in all three harvests (Fig. 5a). Along with the harvest times, the concentration of exchangeable K was decreased in all five treatments, and the greatest decrease was found with T3 and the smallest decrease was with T1. The concentration of exchangeable Na and Mg was highest in T4 and lowest in T1 after only the first harvest. For Ca, its exchangeable concentration was still highest in T4 after the first and the second harvest, and lowest in T1 (Fig. 5c). After the third harvest, its concentration was not significantly different among the five treatments. The similarity of the four base cations was a decrease in their exchangeable concentration along the harvest times.

3.3. *Relationships of the biomass yield and soil properties*

After the first harvest, the aboveground biomass of elephant grass was significantly correlated with soil properties, including CEC, pH, exchangeable acidity, the concentration of exchangeable H^+, NH_4^+, NO_3^-, Mehlich-1 P, exchangeable Al, Fe, Ca, and K (Table 2). The positive correlations were found with CEC, pH, the concentration of Mehlich-1 P, and the concentration of exchangeable Ca, and K, while negative correlations were found with the other soil parameters. After the second harvest, the aboveground biomass was significantly and positively correlated with CEC, pH, Mehlich-1 P, and exchangeable K, and negatively correlated with exchangeable acidity, exchangeable H^+, and exchangeable Al (Table 2). After the third harvest, the aboveground yield of the grass was well correlated with pH, exchangeable acidity, and the exchangeable concentration of Al and K (Table 2).

PCA/FA showed that of the five factors having the highest eigenvalue, factor 1 had high loading value with pH, exchangeable acidity, CEC, exchangeable Al, and exchangeable K; factor 2 had a high loading value with NH_4^+, Mehlich-1 P, exchangeable Fe, exchangeable Mg, and exchangeable Na; factor 3 had with exchangeable H^+ and NO_3^-; factor 4 had with exchangeable Ca, and the last one had with exchangeable Mn (Supplemental Table 1). Fig. 6a showed that T3 had the highest SQI and T1 had the lowest SQI of the five treatments after each of three harvests. The SQI was also decreased along the harvest times and the difference in SQI among the three harvests of T3 was the greatest and that of T1 was the smallest. The SQI was significantly correlated with the biomass yield after each of the three harvests (Fig. 6a, b, and c). This relationship explained as much as 79, 81, and 33 % of the total variance of the

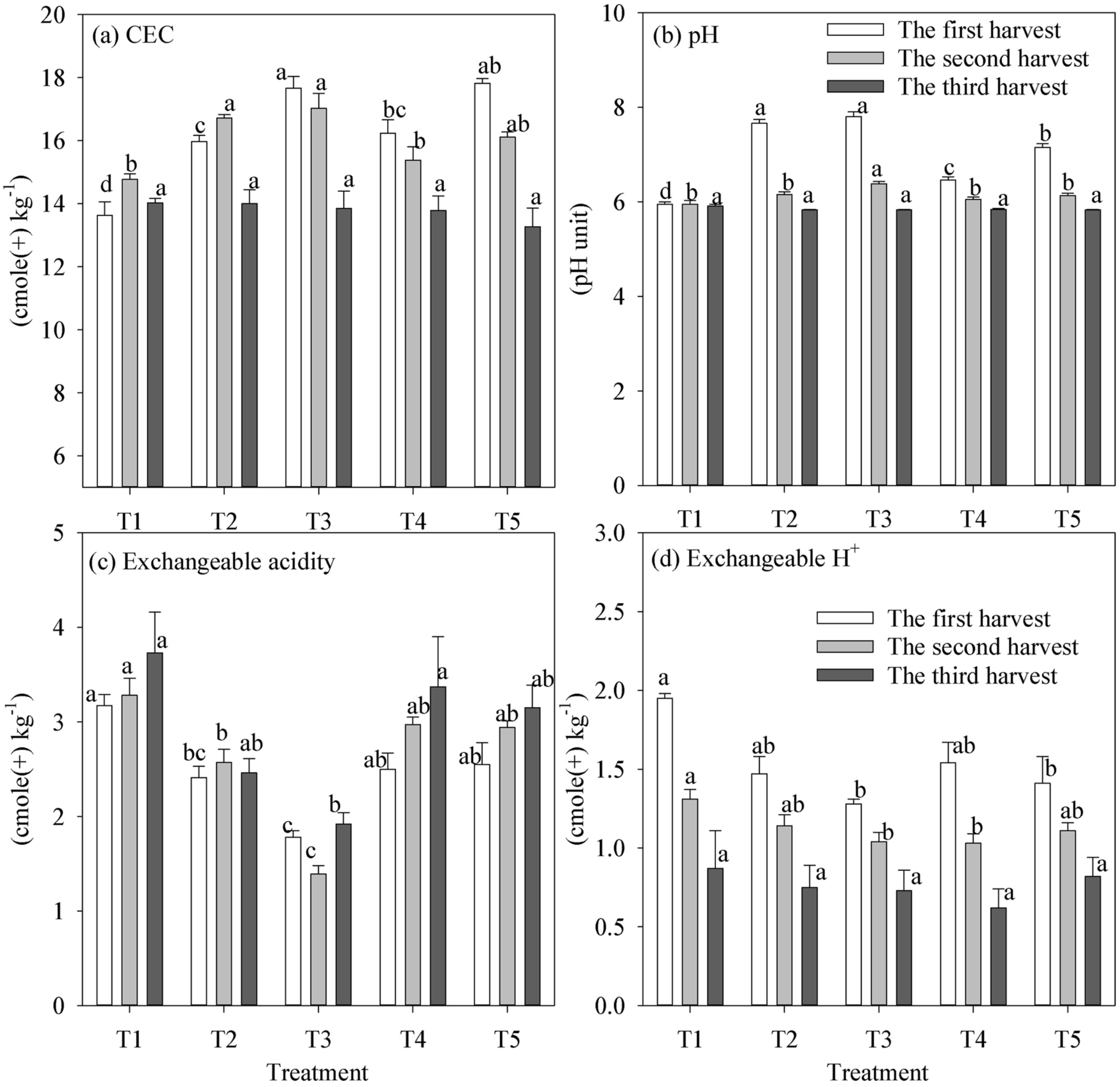


Fig. 2. CEC (a), pH (b), exchangeable acidity (c), and exchangeable H^+ (d) of soil after each of three harvests. For each harvest within individual panels, columns attached with the same letter were not significantly different from the others. The error bars indicated standard errors (SE) computed from 4 replicates.

biomass yield after the first, second, and third harvest, respectively.

4. Discussion

4.1. *The effects of biochar on the biomass yield*

There are many studies conducted to address the effects of biochar on the growth and biomass yield of various crops (Jeffery et al., 2011; Ye et al., 2019). The increment of biomass yield by biochar addition higher on the acidic soils than the other soils (Jeffery et al., 2011) may indicate that biochar could be a potential amendment for acidic soils in improving crop productivity. Nevertheless, biochar addition on soils planted with elephant grass was limitedly reported and discussed, while its addition on the other bio-energy crops was reported more frequently. For example, the grain yield of sorghum was increased by 100 % as a result of biochar addition in combination with NPK fertilizer application, compared to non-biochar and NPK fertilizer application (Steiner et al., 2007). The biomass yield of switchgrass was increased by 8.3 % through biochar addition on various marginal soils in the US (Koide et al., 2018). The current study found that biochar addition at 2 and 4% increased the biomass yield of elephant grass by 61 and 82 %, averaged over 3 harvests, compared to the non-biochar treatment. In addition, the effects of biochar on biomass yield and soil properties were weakened along the three harvests, being stronger in the first harvest and weaker in the last harvest. Similarly, Cornelissen et al. (2018) found that the effect of rice-husk biochar on corn yield faded from season 2 onwards and Steiner et al. (2007) reported that biomass yield of biochar treatments was reduced rapidly after the first harvest. These findings could be useful for reference in planting other crops, especially bio-energy crops in acidic soils. Some mechanisms possibly related to these effects would be discussed in the following sections.

It is also important to notice that the elephant grass is a perennial crop, which may need a large air space for stem and great soil volume for root to develop. The former may not be a limiting factor for the current study because the experimental space was larger enough for the crop to grow while the latter could be the case, which may restrict the root and the whole crop to develop. Nevertheless, some other studies used pot experiments to test the effects of various experimental factors on elephant grass (Alwi et al., 2018; Ansa, 2019; Liang et al., 2018). Although the grass root may grow to the subsoil layers, the greatest root portion was found within the 0–20 cm surface layer (Saraiva et al., 2014; Zhiping et al., 2004). The current experiment was set up to have around 30-cm soil depth within the experimental pots to capture most of the root mass. In addition, biochar addition significantly increasing the root weight of elephant grass after 6 months (Fig. 1b) compared to the other treatments may indicate that the soil volume needed for the root

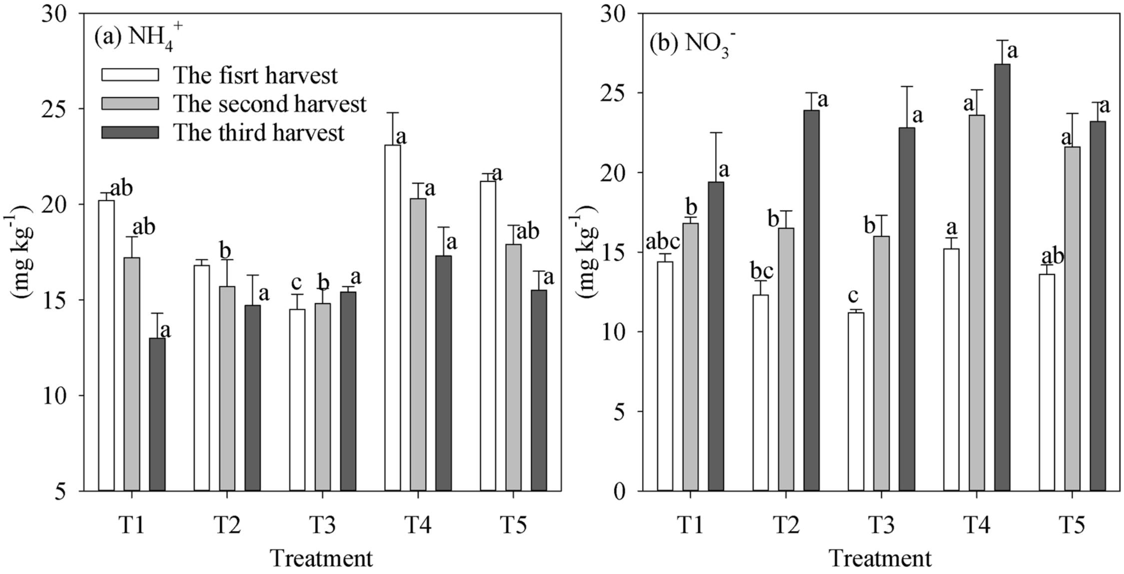


Fig. 3. The concentration of NH_4^+ (a) and NO_3^- (b) of soil after each of three harvests. For each harvest within individual panels, columns attached with the same letter were not significantly different from the others. The error bars indicated standard errors (SE) computed from 4 replicates.

system, especially in treatments 1, 4, and 5 to develop was still available within the experimental time frame.

4.2. *The effects of the amendments on soil properties*

The tested soil was relatively low in pH (5.9), while biochar had high pH (9.8) (Table 1), leading to enhanced pH of the biochar-added soil as shown in Fig. 2b. Similarly, Dai et al. (2014) reported that depending on soil and biochar properties, acidic-soil pH was increased significantly due to biochar addition but the increment was decreased with time after the experiment. Having higher CEC value and the concentration of exchangeable K, Na, Ca, and Mg (Table 1), biochar addition could account for the increased concentrations of these parameters of the biochar-added soil, in line with other studies (Wang et al., 2014). The change magnitude of these parameters could be determined by their relative difference between the tested soil and added biochar. With a similar explanation, Hailegnaw et al. (2019) found that the increased CEC and exchangeable Ca concentration of the biochar-added soil were found in the soils having initial CEC and the concentration of exchangeable Ca lower than the added biochar and vice versa. The highest increase caused by biochar addition was found with exchangeable K concentration (Fig. 5a), mostly due to the material containing high K concentration, which was reported by many studies (Bista et al., 2019; Poormansour et al., 2019).

In contrast, the same soil added with biochar had significantly lower exchangeable acidity and exchangeable concentration of H^+ and Fe after the first harvest (Figs. 2c, d, and 4 c) as well as exchangeable Al concentration after all three harvests (Fig. 4b). The changes in these parameters are much related to soil chemistry, which is commonly reflected through pH value. An increase in soil pH would lead to a reduction of these parameters, typically exchangeable acidity and exchangeable Al concentration (Hamilton et al., 2003; Jha et al., 2016; Sanchez, 2019). The exchangeable acidity is comprised of exchangeable Al^{3+} and H^+, of which the Al portion was decreased with biochar application rates, but increased with harvest times, varying from 28 to 44 % (after the first harvest) to 61–76% (after the third harvest) in the current study (data not shown). These indicated that biochar addition may have a relatively stronger effect on removing the exchangeable H^+ ion, while had a relatively weaker effect on exchangeable Al^{3+} reduction.

The concentration of NH_4^+ was found to decrease while that of NO_3^- was to increase with harvest times in the current study (Fig. 3). This is in line with finding from a study by Dai et al. (2014) and the authors found that the decreased concentration of NH_4^+ and increased concentration of NO_3^- was negatively correlated with each other. The authors also pointed out that nitrification was the process mainly responsible for the decrease of NH_4^+ concentration and the increase of NO_3^- concentration over the experimental duration. In general, the concentration of NH_4^+ and NO_3^- can be determined by the balance of ammonification and nitrification. Stronger nitrification due to aerobic soil conditions than ammonification may result in a decrease in NH_4^+ concentration and an increase in NO_3^- concentration after three harvests in the current study. A slight increase in NH_4^+ concentration over three harvests in treatment 3 could be considered as a random effect because an additional statistical analysis was conducted and showed that the NH_4^+ concentration after three harvests of treatment 3 was not significantly different. The amendments also played an important role in influencing the concentration of these two nutrients. With a negative priming effect (Rittl et al., 2015), the suppression effect of biochar on native soil C mineralization could lead to reduced soil N mineralization because the two processes are commonly accompanied by each other (Jensen et al., 1997). This could be the main reason to explain the lower concentration of NH_4^+ and NO_3^- of treatments 2 and 3, compared to other treatments. Moreover, cow manure containing a greater concentration of NH_4^+ and NO_3^- (Table 1) could lead to a higher concentration of these two N forms of the treatments 4 and 5. Both processes of negative priming effect from biochar addition and co-addition of NH_4^+ and NO_3^- from cow manure possibly happening in the treatment 5 may explain its concentration of NH_4^+ and NO_3^- lower than the treatment 4 but higher than the other treatments after the first harvest (Fig. 3). In addition, the adsorption of NH_4^+ and NO_3^- on biochar (Fidel et al., 2018) could be an additional reason in explaining the lowest concentration of the two nutritional forms of nitrogen in the biochar treatments 2 and 3. The better growth of elephant grass in treatment 3 could be another reason to reduce these two forms of nitrogen due to the grass uptake and biomass removal after the first harvest.

The concentration of Mehlich-1 P of all four amendment treatments was significantly higher than that of treatment 1 that could be explained for several reasons. The first and most important reason could be involved in the liming effect, referring to as an increment of soil pH caused biochar. Following biochar addition, soil pH was significantly increased (from 5.95 in treatment 1–6.46 in treatment 4 and over 7.0 in

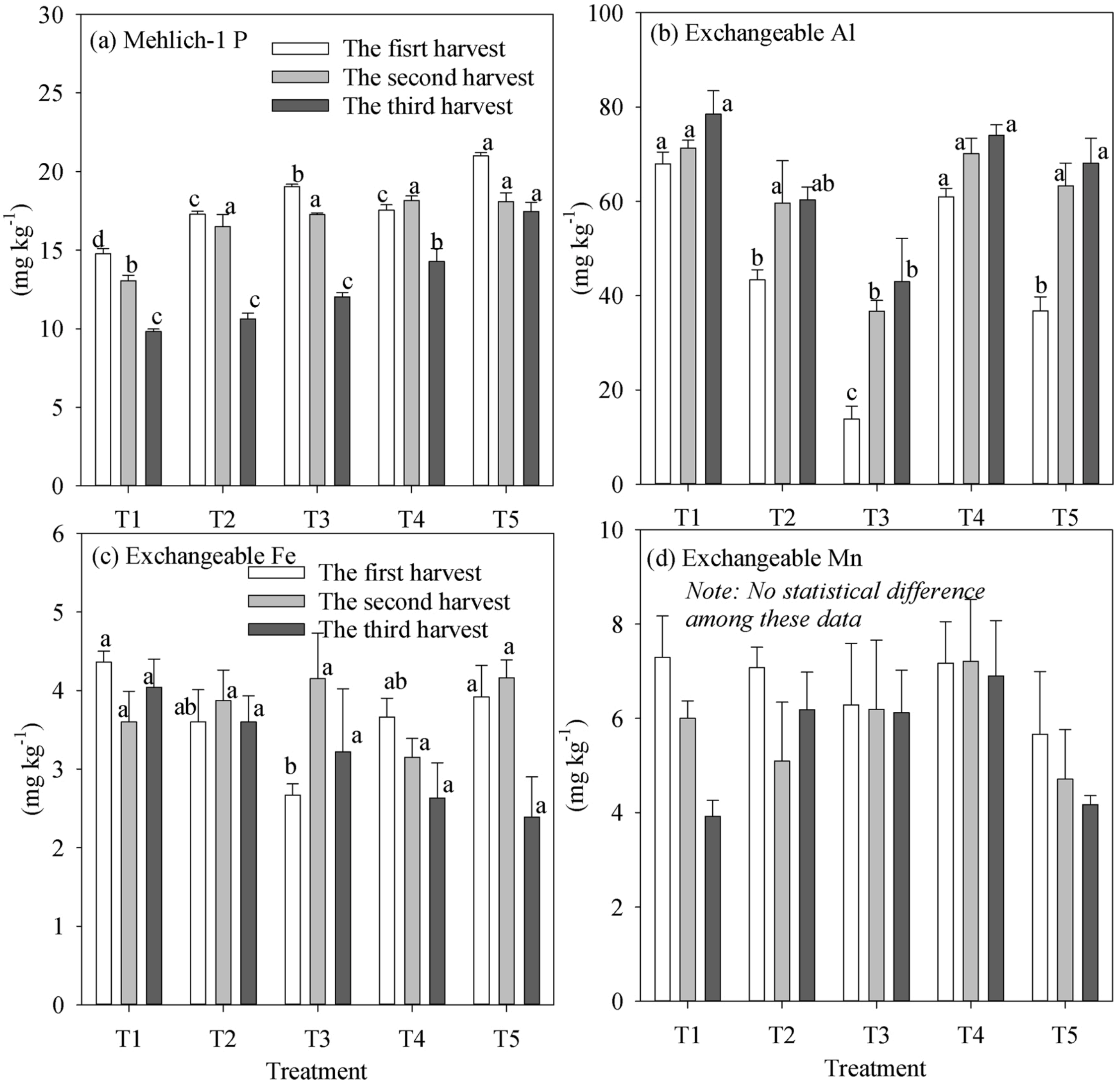


Fig. 4. The concentrations of Mehlich-1 P (a), Al (b), Fe (c), and Mn (d) of soil after each of three biomass harvests. For each harvest within individual panels, columns attached with the same letter were not significantly different from the others. The error bars indicated standard errors (SE) computed from 4 replicates.

other treatments, Fig. 2b) and the exchangeable concentration of Al and Fe was decreased (Fig. 4b and c), leading to an increase in P availability due to a reduction of its fixation by iron and aluminum oxides in low pH (Ding et al., 2016; Hale et al., 2020). A similar reason was also well documented by Atkinson et al. (2010) and the change magnitude of soil pH as a result of biochar addition could affect P sorption and desorption and then its availability in soil (Xu et al., 2014). The second one could be explained with co-addition of P with the amendments, which were attributed to explaining similar findings by Nguyen et al. (2018a). Compared to the tested soil, biochar and cow manure had a much high concentration of Mehlich-1 P (Table 1), which could be mechanically added to the soil, enhancing the P availability of the treatments 2, 3, 4, and 5 as shown in Fig. 4a.

Nevertheless, most soil parameters in the current study showed a significant difference among the five treatments after the first harvest, but insignificant difference or lesser significant difference in the case of SQI after the last harvest. This may indicate that some properties of the biochar-added soil could revert to their origin after a certain time. Ouyang et al. (2014) showed that soil C mineralization happened rapidly within the first 80–100 days from the amendment day and afterward the rate of this process was quite similar among the biochar and non-biochar added soils. From a 4-season experiment, Griffin et al. (2017) concluded that the effect of biochar on the concentration of K^+, PO_4-P, and Ca^{2+} was found clearly in the second season and faded in the following years. The weakening effect of biochar on soil fertility in the current study could be explained with a few mechanisms, discussed in the following section.

4.3. Key mechanisms of biochar in improving soil quality and the biomass yield of elephant grass

In general, biochar addition directly improved soil quality and subsequently enhanced biomass yield of the tested grass that could be explained with a few important mechanisms, including liming effect, co-addition of nutrients with the added biochar, and nutrient use efficiency. The liming effect of biochar, indicated through the improvement of soil pH or reduction of soil acidity as a result of an application of alkaline material, could be seen in Fig. 2. The effect was identified as the main mechanism to improve crop productivities through a meta-analysis study (Dai et al., 2020). Liming effects led to improved SQI due to reduced Al toxicity (reduced exchangeable Al concentration) and improved nutrient availability (improved Mehlich-1 P and exchangeable bases) of acidic soil in the current study, which was pointed out as the main consequent mechanisms of biochar addition (Dai et al., 2017). Likewise, Qi et al. (2017) found that the acidic biochar induced an unclear impact on nutrient concentrations, CEC, and pH, while neutral-pH

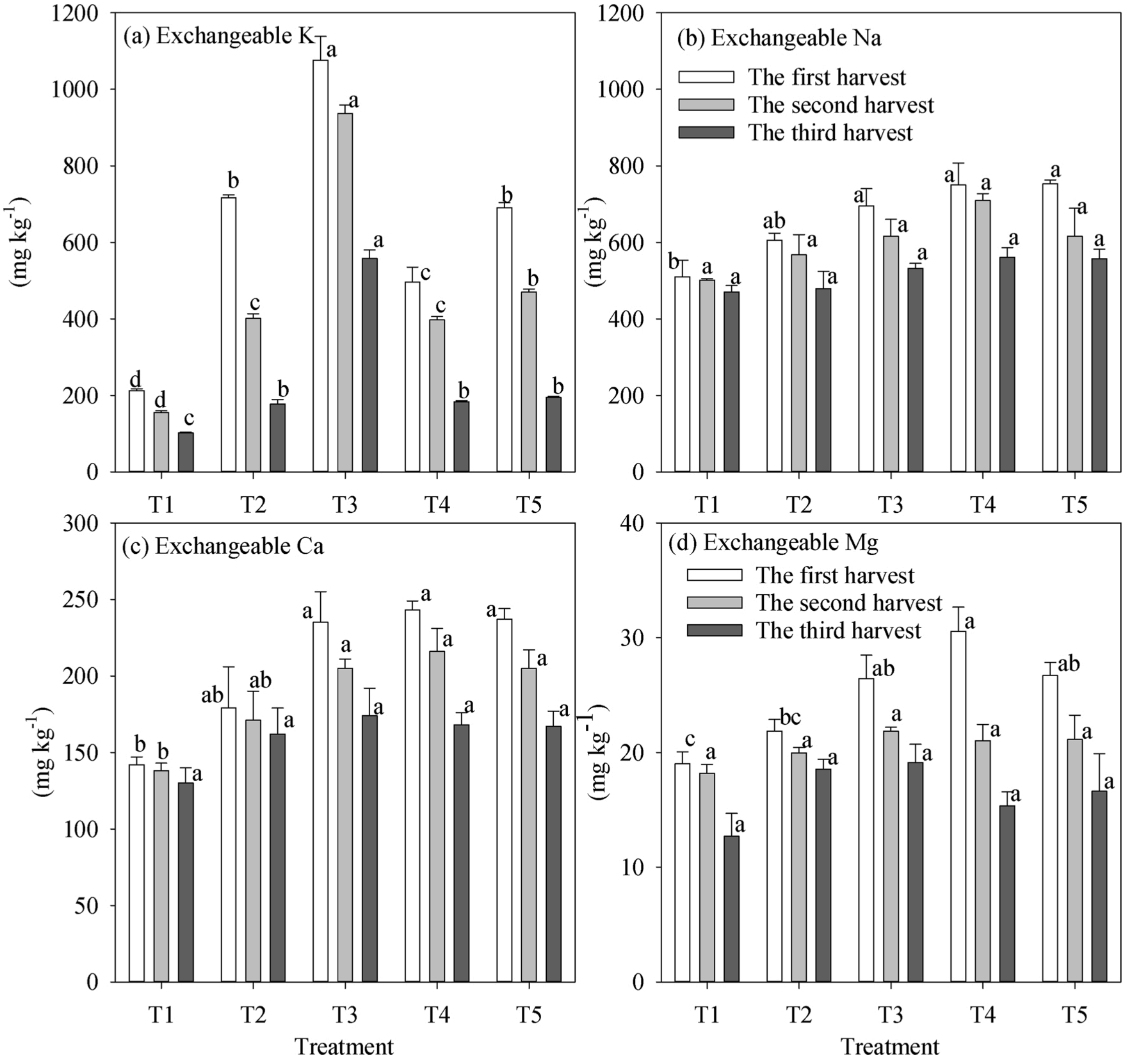


Fig. 5. The exchangeable concentration of the base cations of soil after each of the three biomass harvests. For each harvest within individual panels, columns attached with the same letter were not significantly different from the others. The error bars indicated standard errors (SE) computed from 4 replicates.

Table 2
The correlation coefficient of biomass yield with soil parameters after each of the three harvests. The bold numbers indicated that the relationship was significant at $P < 0.05$.

Soil parameters	Biomass yield after each of the three harvests		
	Harvest 1	Harvest 2	Harvest 3
pH	**0.86**	**0.73**	**−0.53**
Exchangeable acidity	**−0.71**	**−0.88**	**−0.47**
Exchangeable H	**−0.77**	**−0.49**	−0.09
CEC	**0.78**	**0.78**	−0.21
NH_4^+	**−0.44**	−0.43	−0.12
NO_3^-	**−0.47**	−0.30	−0.13
Mehlich-1 P	**0.79**	**0.44**	0.33
Exchangeable Al	**−0.83**	**−0.71**	**−0.49**
Exchangeable Fe	**−0.49**	0.30	−0.07
Exchangeable Mn	−0.15	−0.03	0.15
Exchangeable Ca	**0.50**	0.34	0.37
Exchangeable Mg	0.31	0.41	0.36
Exchangeable K	**0.82**	**0.84**	**0.50**
Exchangeable Na	0.43	0.18	0.19

biochar significantly enhanced soluble nutrient concentrations and pH of acidic soil. The second important mechanism in enhancing soil quality and the biomass yield of elephant grass could be involved in nutrient addition to the tested soil through the added biochar (co-addition mechanism). Biochar, considered as a nutrient source (Ding et al., 2016), had nutrient concentrations of Mehlich-1 P and exchangeable bases, especially K, as well as CEC and OC much higher than the tested soil (Table 1), leading to mechanically enriching these soil parameters through biochar addition. These nutrients enclosed within the added biochar resulted in better soil quality and grass yield as seen in Fig. 6. The last mechanism related to the efficiency of nutrient usage could be seen with NH_4^+ and NO_3^-, which could be involved in the adsorptive capacity of biochar (Kaur and Sharma, 2020). Nutrient adsorption played an important role in keeping the nutrients, reducing their losses through leaching as mentioned above, or gasification (Nguyen et al., 2019; Weldon et al., 2019). These could be seen in Fig. 3a, which showed that the concentration of NH_4^+ of treatment 1 was decreased while that of treatment 3 tended to increase with three harvest times. Similarly, the NO_3^- concentration was higher in treatment 1 after the first harvest, whereas it was higher in treatment 3 after the third harvest.

The relationships between the aboveground biomass yield of the elephant grass with soil parameters and SQI were stronger after the first harvest ($r^2 = 0.79$) but weaker after the third harvest ($r^2 = 0.33$) (Fig. 6b, c, and d). The weakening effect of biochar could be related to a few mechanisms. The first could be involved in soil buffering capacity, which is the ability of soil to resist changes. From a three-year open-field experiment, Jones et al. (2011) found that the pH of soil added with 50 ton ha^{-1} biochar was reverted to be similar to that of the non-biochar

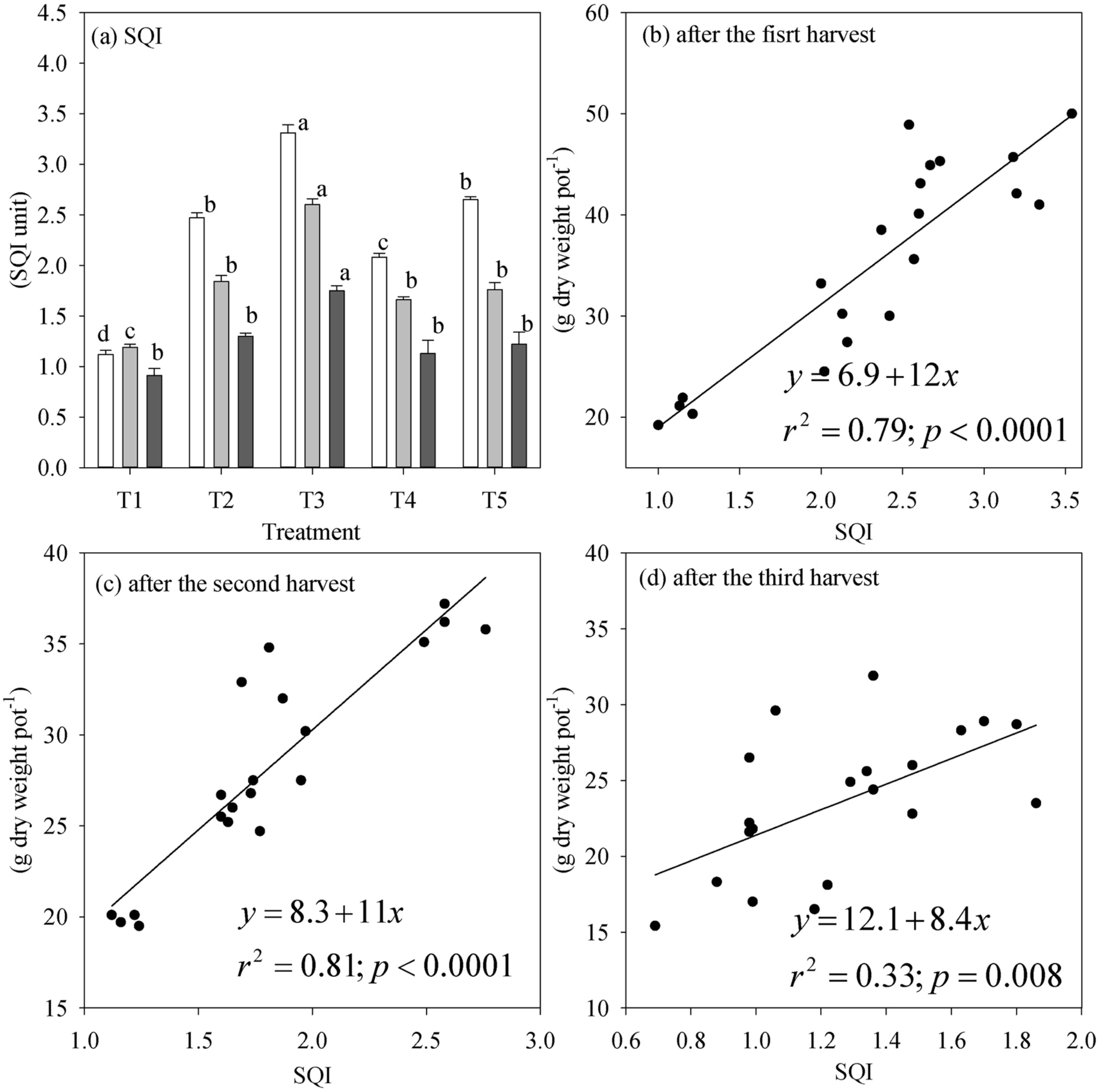


Fig. 6. Soil quality index (SQI) as affected by soil amendment (a) and simple relationship between the biomass yield of elephant grass and SQI after each of three harvests (b, c, and d). Note: significant relationships were shown with the coefficient of determination (r^2), probability (p), and linear regression equation.

added soil. The change magnitude could be determined by the difference in the buffering capacity of the soil and of the added biochar. The second could be related to nutrient depletion through grass uptake and biomass removal, mitigating the change of soil properties caused by biochar addition. Nutrient uptake could be one mechanism in reducing soil nutrient availability of the biochar-added soil (Wang et al., 2018). The last one could be involved in nutrient losses through leaching from this pot experiment and gasification of nitrogen. Although the current study was conducted in a greenhouse using pots as containers for grass growth, the bottom of the pots was drilled to create 5 small holes (2 cm in diameter) for water drainage in case of overwatering. These holes created an opportunity for nutrient leaching in cases of overwatering bi-daily during the experiment. Leaching of nutrients was attributed to being the main reason of fading the effect of biochar on corn yield (Cornelissen et al., 2018).

The weakening effects of biochar on biomass yield and soil properties along three harvests in the current greenhouse experiment could likely exist in large-scale fields. This may suggest that replenishment of biochar after a few harvests should be implemented for better biomass yield. A combination of biochar with inorganic fertilizers may be an option to increase the biomass yield of the grass. Therefore, more studies on biochar applied in acidic soils planted with elephant grass in both greenhouse and open large-scale fields are in need to clarify the effects. Various biochar types and application rates in combination with inorganic fertilizers would be necessarily tested.

5. Conclusions

Cultivation of a bio-energy crop, such as elephant grass in acidic soils could be a potential option in optimizing soil production. To maximize its productivity, the application of biochar is an option because it increased the biomass yield of elephant grass, compared to the non-biochar and cow manure addition. Some soil properties such as pH, CEC, available P, and exchangeable bases (K, Na, and Ca) were significantly enhanced, while some others such as exchangeable acidity, H^+, Al, and Fe were significantly decreased following biochar addition. Consequently, SQI was significantly better in the biochar-added soil than the non-biochar treatment. The improved biomass yield by biochar addition could be involved in a few mechanisms, including liming effect, co-addition of the nutrient with the added biochar, and nutrient use efficiency. Nevertheless, the effect of biochar was weakened within three harvests that could be involved in a few other mechanisms, including soil buffering capacity, nutrient depletion through grass uptake and biomass removal, and nutrient losses through leaching and gasification. Biochar addition increased the quality of the acidic soils and the elephant grass's yield but the effects got weaker after a few harvests in the greenhouse conditions.

CRediT authorship contribution statement

Binh Thanh Nguyen: Conceptualization, Validation, Writing - original draft, Writing - review & editing. **Long Ba Le:** Resources, Software, Supervision. **Long Phi Pham:** Methodology, Investigation. **Hiep Thai Nguyen:** Methodology, Investigation. **Tu Dinh Tran:** Formal analysis, Writing - original draft. **Nam Van Thai:** Data curation, Writing - original draft, Writing - review & editing.

Declaration of Competing 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.

Acknowledgments

The authors are grateful to the Industrial University of Ho Chi Minh City (IUH) and the Institute of Environmental Science, Engineering, and Management (IESEM) of IUH, Vietnam. Many thanks are given to the staff and students at IESEM for their help with field trips.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.indcrop.2020.113224.

References

Alwi, Y., Jamarun, N., Sy, A., Zain, M., 2018. Effect of NPK fertilizer and water stress on growth and proline content of wild elephant grass (Pennisetum polystachion). Sch. J. Agric. Vet. Sci. 5, 124–129.

Ansa, J., 2019. Effect of cutting frequency on forage growth and yield in elephant grass in the southern rainforest of Nigeria. Int. J. Environ. Agric. Res. 5, 1–5.

Arshadullah, M., Anwar, M., Rana, A., 2010. Effect of nitrogen fertilization and harvesting intervals on the yield and forage quality of elephant grass (pennisetum purpureum) under mesic climate of pothowar plateau. Pak. J. Agric. Sci. 47, 231–234.

Atkinson, C., Fitzgerald, J.D., Hipps, N.A., 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant Soil 337, 1–18.

Berek, A., Hue, N., Radovich, T., Ahmad, A., 2018. Biochars improve nutrient phyto-availability of Hawai'i's highly weathered soils. Agronomy 8.

Biederman, L.A., Harpole, W.S., 2013. Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. GCB Bioenergy 5, 202–214.

Bista, P., Ghimire, R., Machado, S., Pritchett, L., 2019. Biochar effects on soil properties and wheat biomass vary with fertility Management. Agronomy 9.

Carter, M.R., Gregorich, E.G., 2008. Soil Sampling and Methods of Analysis, 2nd edition. CRC Press, Taylor & Francis Group, Boca Raton.

Cornelissen, G., Jubaedah, Nurida, N.L., Hale, S.E., Martinsen, V., Silvani, L., Mulder, J., 2018. Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol. Sci. Total Environ. 634, 561–568.

Dai, Z., Wang, Y., Muhammad, N., Xiongsheng, Y., Xiao, K., Meng, J., Liu, X., xu, J., Brookes, P., 2014. The effects and mechanisms of soil acidity changes, following incorporation of biochars in three soils differing in initial pH. Soil Sci. Soc. Am. J. 78, 1606.

Dai, Z., Zhang, X., Tang, C., Muhammad, N., Wu, J., Brookes, P., xu, J., 2017. Potential role of biochars in decreasing soil acidification - A critical review. Sci. Total Environ. 581.

Dai, Y., Zhixiang, J., Xing, B., 2020. Combined effects of biochar properties and soil conditions on plant growth: A meta-analysis. Sci. Total Environ. 713, 136635.

Ding, Y., Liu, Y., Liu, S., Li, Z., Tan, X., Huang, X., Zeng, G., Zhou, L., Zheng, B., 2016. Biochar to improve soil fertility. A review. Agron. Sustain. Dev. 36, 36.

Ferreira, E., Abreu, J., Martinez, J., Braz, T., Ferreira, D., 2018. Cutting ages of elephant grass for chopped hay production. Pesquisa Agropecuaria Tropical 48.

Fidel, R., Laird, D., Thompson, M., Lawrinenko, M., 2017. Characterization and quantification of biochar alkalinity. Chemosphere 167, 367–373.

Fidel, R.B., Laird, D.A., Spokas, K.A., 2018. Sorption of ammonium and nitrate to biochars is electrostatic and pH-dependent. Sci. Rep. 8, 17627.

Flores, R.A., Urquiaga, S., Alves, B.J.R., Collier, L.S., Boddey, R.M., 2012. Yield and quality of elephant grass biomass produced in the cerrados region for bioenergy. Engenharia Agrícola 32, 831–839.

Griffin, D., Wang, D., Parikh, S., Scow, K., 2017. Short-lived effects of walnut shell biochar on soils and crop yields in a long-term field experiment. Agric. Ecosyst. Environ. 236, 21–29.

Hailegnaw, N., Mercl, F., Pračke, K., Száková, J., Tlustoš, P., 2019. Mutual relationships of biochar and soil pH, CEC, and exchangeable base cations in a model laboratory experiment. J. Soils Sediments.

Hale, S.E., Nurida, N.L., Jubaedah, Mulder J., Sørmo, E., Silvani, L., Abiven, S., Joseph, S., Taherymoosavi, S., Cornelissen, G., 2020. The effect of biochar, lime and ash on maize yield in a long-term field trial in a Ultisol in the humid tropics. Sci. Total Environ. 719, 137455.

Hamilton, A.C., Takashi, M., Fernando, L.A., 2003. Relationship between acidity and chemical properties of brazilian soils. Sci. Agric. 60, 337–343.

Jeffery, S., Verheijen, F.G.A., van der Velde, M., Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric. Ecosyst. Environ. 144, 175–187.

Jensen, L., Müller, T., Magid, J., Nielsen, N., 1997. Temporal variation of C and N mineralization, microbial biomass and extractable organic pools in soil after oilseed rape straw incorporation in the field. Soil Biol. Biochem. 29, 1043–1055.

Jha, P., Sathyaseelan, N., Rashmi, I., Meena, B., Jatav, R.C., Biswas, A., Singh, M., Patra, A., 2016. Ameliorating effects of leucaena biochar on soil acidity and exchangeable ions. Commun. Soil Sci. Plant Anal. 47.

Jones, D., Rousk, J., Edwards-Jones, G., Deluca, T., Murphy, D., 2011. Biochar-mediated changes in soil quality and plant growth in a three year field trial. Soil Biol. Biochem. 45.

Kaur, V., Sharma, P., 2020. Application of biochar as an adsorbent and its significance on berseem (Trifolium alexandrinum) growth parameters in farm soil contaminated with PAH. J. Soil Sci. Plant Nutr.

Koide, R.T., Nguyen, B.T., Skinner, R.H., Dell, C.J., Adler, P.R., Drohan, P.J., Licht, M., Matthews, M.B., Nettles, R., Ricks, K., Watkins, J., 2018. Comparing biochar application methods for switchgrass yield and C sequestration on contrasting marginal lands in Pennsylvania, USA. BioEnergy Res. 1–19.

Kunhikrishnan, A., Thangarajan, R., Bolan, N., Xu, Y., Mandal, S., Gleeson, D., Seshadri, B., Zaman, M., Barton, L., Tang, C., Luo, J., Dalal, R., Ding, W., Kirkham, M.B., Naidu, R., 2016. Functional Relationships of Soil Acidification, Liming, and Greenhouse Gas Flux, Advances in Agronomy. Academic Press Inc, pp. 1–71.

Liang, X., Erickson, J., Sollenberger, L., Rowland, D., Silveira, M., Vermerris, W., 2018. Growth and transpiration responses of elephantgrass and energycane to soil drying. Crop Sci. 58.

Mukherjee, A., Lal, R., 2014. Comparison of soil quality index using three methods. PLoS One.

Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27, 31–36.

Nasa, 2020. The Causes of Climate Change, the Greenhouse Effect. Assessed February 2020 at. https://climate.nasa.gov/causes/.

Nguyen, B.T., Lehmann, J., 2009. Black carbon decomposition under varying water regimes. Org. Geochem. 40, 846–853.

Nguyen, B.T., Trinh, N.N., Le, C.M.T., Nguyen, B.T., Tran, T.V., Thai, B.V., Le, T.V., 2018a. The interactive effects of biochar and cow manure on rice growth and selected properties of salt-affected soil. Arch. Agron. Soil Sci. 64, 1744–1758.

Nguyen, T.Q.H., Le, K.T., Nguyen, M.K., Le, T.N.H., 2018b. Potential of biochar production from agriculture residues at household scale: a case study in Go Cong Tay District, Tien Giang Province, Vietnam. Environ. Nat. Resour. J. 16.

Nguyen, B.T., Phan, B.T., Nguyen, T.X., Nguyen, V.N., Van Tran, T., Bach, Q.-V., 2019. Contrastive nutrient leaching from two differently textured paddy soils as influenced by biochar addition. J. Soils Sediments.

Novak, J., Johnson, M., Spokas, K., 2018. Concentration and release of phosphorus and potassium from lignocellulosic- and manure-based biochars for fertilizer reuse. Front. Sustain. Food Syst. 2.

Ouyang, L., Tang, Q., Yu, L., Zhang, R., 2014. Effects of amendment of different biochars on soil enzyme activities related to carbon mineralisation. Soil Res. 52.

Phares, C.A., Atiah, K., Frimpong, K.A., Danquah, A., Asare, A.T., Aggor-Woananu, S., 2020. Application of biochar and inorganic phosphorus fertilizer influenced rhizosphere soil characteristics, nodule formation and phytoconstituents of cowpea grown on tropical soil. Heliyon 6 e05255-e05255.

Poormansour, S., Razzaghi, F., Sepaskhah, A., 2019. Wheat straw biochar increases potassium concentration, root density, and yield of faba bean in a sandy loam soil. Commun. Soil Sci. Plant Anal. 50, 1–12.

Qi, F., Dong, Z., Naidu, R., Bolan, N., Lamb, D., Ok, Y.S., Liu, C., Khan, N., Johir, M.A.H., Semple, K., 2017. Effects of acidic and neutral biochars on properties and cadmium retention of soils. Chemosphere 180.

Qian, L., Chen, B., Hu, D., 2013. Effective alleviation of aluminum phytotoxicity by manure-derived biochar. Environ. Sci. Technol. 47, 2737–2745.

Richards, B., Stoof, C., Cary, I., Woodbury, P., 2014. Reporting on marginal lands for bioenergy feedstock production: a modest proposal. Bioenergy Res. 7.

Rittl, T., Novotny, E., Balieiro, F., Hoffland, E., Alves, B., Kuyper, T., 2015. Negative priming of native soil organic carbon mineralization by oilseed biochars of contrasting quality: priming effects of oilseed biochars. Eur. J. Soil Sci. 66.

Sanchez, P., 2019. Soil acidity. Properties and Management of Soils in the Tropics. Cambridge University Press, Cambridge, pp. 210–235. https://doi.org/10.1017/9781316809785.01.

Saraiva, F., Dubeux Jr, J., Lira, M., Mello, A., Santos, M., Cabral, F., Teixeira, V., 2014. Root development and soil carbon stocks of tropical pastures managed under different grazing intensities. Tropical Grasslands - Forrajes Tropicales 2, 254–261.

Steiner, C., Teixeira, W., Lehmann, J., Nehls, T., Macêdo, J., Blum, W., Zech, W., 2007. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant Soil 291, 275–290.

Strezov, V., Evans, T., Hayman, C., 2008. Thermal conversion of elephant grass (Pennisetum purpureum Schum) to bio-gas, bio-oil and charcoal. Bioresour. Technol. 99, 8394–8399.

von Uexküll, H.R., Mutert, E., 1995. Global extent, development and economic impact of acid soils. Plant Soil 171, 1–15.

Wang, Y., Yin, R., Liu, R., 2014. Characterization of biochar from fast pyrolysis and its effect on chemical properties of the tea garden soil. J. Anal. Appl. Pyrolysis 110.

Wang, L., Xue, C., Nie, X., Liu, Y., Chen, F., 2018. Effects of biochar application on soil potassium dynamics and crop uptake. J. Plant Nutr. Soil Sci.

Weldon, S., Rasse, D., Budai, A., Tomic, O., Dörsch, P., 2019. Biochar and denitrification: examining the effect of a biochar temperature series on the kinetics of gaseous N turnover. Which properties matter? Soil Biol. Biochem. 135.

Xu, G., Sun, J., Shao, H., Chang, S.X., 2014. Biochar had effects on phosphorus sorption and desorption in three soils with differing acidity. Ecol. Eng. 62, 54–60.

Ye, L., Camps Arbestain, M., Shen, Q., Lehmann, J., Singh, B., Sabir, M., 2019. Biochar effects on crop yields with and without fertilizer: a meta-analysis of field studies using separate controls. Soil Use Manag. 36.

Zhiping, Q., Rao, I., Ricaurte Oyola, J., Amézquita, E., Sanz, J., Kerridge, P., 2004. Root distribution and nutrient uptake in crop-forage systems on Andean Hillsides. J. Sustain. Agric. 23, 39–50.