DOI: https://doi.org/10.29298/rmcf.v12i65.780

Article

Biocarbón de bambú como mejorador de la fertilidad del suelo en caña de azúcar

Bamboo biocharcoal as soil fertility enhancer in sugar cane

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Resumen

El deterioro de los suelos se debe, en gran medida, a la escasez y mala calidad del agua, y en particular a la disminución de la fertilidad de los mismos. El biocarbón es un subproducto de la pirolisis de biomasa residual que ayuda a recuperar la fertilidad edáfica. El presente trabajo tiene como objetivo evaluar enmiendas orgánicas de biocarbón de *Bambusa vulgaris* en *Saccharum* spp. var. CP 72-2086. Para ello, se utilizó un diseño factorial 2^2, T0= testigo sin biocarbón (S-AB); T1=10 t ha^{-1} (BBV) y T2= 20 t ha^{-1} (BBV) de biocarbón de *Bambusa vulgaris;* T3= 10 t ha^{-1} (BBVV) y T4= 20 t ha^{-1} (BBVV) de biocarbón de *Bambusa vulgaris vittata*, distribuidos en bloques al azar*.* En el modelo estadístico las variables evaluadas fueron: biomasa de raíz, altura, diámetro y número de brotes. Las variables respuesta se analizaron por medio de un análisis de varianza (ANOVA) con base en un modelo lineal generalizado, y la comparación de medias de *Tukey* con un nivel de significancia de 5 %. La aplicación de biocarbón de bambú en el cultivo de caña de azúcar mejoró las propiedades físicas y químicas del suelo, ya que aumentó la capacidad de campo, el punto de marchitez permanente, la humedad, el pH y la capacidad de intercambio catiónico. El biocarbón de bambú en una concentración de 20 t ha^{-1} es una buena enmienda orgánica al suelo, puesto que incrementa la disponibilidad de nutrimentos lo que beneficia el crecimiento del cultivo.

Palabras clave: Biodisponibilidad de nutrimentos, crecimiento, enmienda, mejorador, pirolisis, suelo.

Abstract

The deterioration exhibited by the soils is largely due to the scarcity and poor quality of water, and to the decrease in their fertility, in particular. Biocharcoal or biochar is a byproduct of the pyrolysis of residual biomass, which helps to recover soil fertility. The present work aims to evaluate organic bamboo biochar amendments in *Saccharum* spp. var. CP 72-2086. For this purpose, a factorial design 2^2, T0 = control without biochar (S-AB); T1 = 10 t ha^{-1} (BBV) and T2 = 20 t ha^{-1} (BBV) of *Bambusa vulgaris* biochar; T3 = 10 t ha^{-1} (BBVV) and T4 = 20 t ha^{-1} (BBVV) of *Bambusa vulgaris vittata* biochar, distributed in random blocks. In the statistical model, the assessed variables were root biomass, height, diameter and number of shoots. The response variables were analyzed by means of an analysis of variance (ANOVA) based on a general linear model and the comparison of Tukey means with a significance level of 5 %. The application of bamboo biochar in the cultivation of sugarcane improved the physical and chemical properties of the soil by increasing the field capacity, the permanent wilting point, the moisture content, pH and the cation exchange capacity. Bamboo biochar in a concentration of 20 t ha^{-1} is a good organic amendment to the soil since it increases the availability of nutrients benefiting the growth of this species.

Key words: Nutrient bioavailability, growth, amendment, enhancer, pyrolysis, soil.

Fecha de recepción/Reception date: 27 de mayo de 2020
Fecha de aceptación/Acceptance date: 23 de julio de 2020

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Introduction

The deterioration of soils is largely due to the scarcity and poor quality of water and, in particular, to the decrease in soil fertility. The latter occurs due to a serious condition of erosion, degradation, contamination and loss of organic matter that directly affect food production (Semarnat-Colpos, 2003). Consequently, crop nutrition is affected by severe nutrient deficiencies; therefore, in some cases, over-fertilization occurs. This directly affects food quality and environmental health, in addition to increasing production costs.

There is concern about the indiscriminate use of chemical fertilizers, since in general, the doses used are not those required for the crops and occasionally the natural contribution of nutrients that the soil can make is not taken into account. If the nutrient supply does not meet the demand of a crop, the maximum yields allowed by the peculiarity of each agroecosystem are not reached, and as a collateral effect, soil degradation is generated (Escalante, 2013).

Given the worrying situation of soil deterioration, it is imperative to implement strategies to improve soil quality. In addition, climate change tends to aggravate the situation, due to its effect on water availability (deficiency or excess), extreme drought or torrential rains, high or low temperatures that affect food production and the conservation of soil quality. Therefore, the call is to carry out a soil management that ensures both its conservation and production (Funes-Monzote and Monzote, 2001; Sánchez *et al*., 2011).

Mexico's soils exhibit strong physical, chemical and biological degradation. There are technologies to counteract them, which help to recover their fertility and sequester carbon, such as the application of biochar, a product obtained through the thermal treatment of biomass pyrolysis, under a limited environment or without oxygen (Lehmann *et al*., 2006). Pyrolysis is the thermochemical process that takes place at temperatures ranging from 300 to 600 °C.

Biochar consists mainly of carbon (70-80 %). This material is considered an important component in proposals to mitigate emissions of greenhouse gases such as CO_2 and

NO_2, because it retains and captures those (Lehmann *et al*., 2006). It is also relevant as an enhancer of the physical, chemical and biological characteristics and properties of the soil (Lehmann and Joseph, 2009). It has been documented that biochar in soil can increase cation exchange capacity and favor the development of microorganisms (Liang *et al*., 2006); it also enhances nutrient retention and soil structure (Liu *et al*., 2012).

Biochar is made from different raw materials; the most commonly used being wood from trees, agro-industrial waste, agricultural waste, livestock and poultry manure, and pruning waste (Pérez, 2015). Although its production and application to the soil is a technology used in several parts of the world (Lehman and Joseph, 2009; Steiner, 2010; Waters *et al.*, 2011), little information is available on this subject in Mexico. In general, it is recommended that biochar be produced only where sufficient biomass is available, such as in the case of by-products from agroforestry activities or urban organic waste, which can be used as feedstock.

Bamboo of the species *Bambusa vulgaris* Schrad. ex J.C. Wendl. is widely distributed in the national territory; however, it is one of the most underutilized bamboos because, compared to other species, it is not structural. *B vulgaris* is used in other countries in the paper industry (Banik, 2015; Banik, 2016). In addition, bamboo is a sustainable alternative to replace wood, since it requires only 5 years for harvesting, as opposed to the 20 to 40 years needed for timber forest resources. During the process of harvesting bamboo culms (stalks) in a commercial forestry plantation, solid residues are generated, which can be used to produce biochar.

This paper presents the studies carried out on the performance of two biochars produced from overripe bamboo canes (*Bambusa vulgaris* Schrad. ex J.C. Wendl. var. *vulgaris* and *Bambusa vulgaris* Schrad. ex J.C. Wendl. var. *vittata*), and their evaluation on soil fertility in the sugarcane crop variety CP 72-2086.

Materials and Methods

A trial was implemented in a nursery belonging to the *Tecomán* Experimental Field of the National Institute for Research on Forestry, Agriculture and Livestock (INIFAP), located on the Pacific coast of Mexico, in the municipality of *Tecomán* in the state of *Colima*, between 18°57'58.9" to 18°57'58.8" N and 103°50'33" to 103°50'32.6" W, at an altitude of 59 m, where a very warm semi-dry climate prevails [BS_1(h')]. The average annual temperature is 30 °C, with an average annual precipitation of 810.6 mm and rainfalls mainly in summer (INEGI, 2017).

For the trial, sugarcane plants from in vitro culture, of the commercial variety CP 72-2086, were utilized, having been established in greenhouses for a period of 2 months (in the tillering stage), in 190 cm^3 polyethylene tubes. Plants were transplanted bare-root in 12 × 23 cm (3 L) high-density black polyethylene bags supplemented with 2 kg of agricultural soil, which was previously subjected to a chemical analysis.

Soil sampling and chemical analysis

Agricultural soil from *Ingenio Quesería S.A. de C.V.* (sugarcane area) was used to transplant the plants in polyethylene bags. Completely random sampling was carried out by taking six of the bags of soil in order to obtain three homogeneous samples of 1 kg each. This procedure was followed at the beginning (unamended soil) and at the end of the trial (soil amended with biochar after 70 days).

The physical and chemical properties were determined according to the norm NOM.021-RECNAT-2002 (Semarnat, 2002) with the corresponding methodologies: pH (AS-02); moisture content (AS-05); organic matter content (AS-07); total nitrogen (AS-08); texture (AS-09); phosphorus (AS-11); cation exchange capacity and exchangeable bases (AS-12); micronutrients (AS-14); electrical conductivity (AS-18); Ca Mg, Na and P (AS-19); total carbonates (AS-20).

Bamboo biochar and performed analyses

We used 25-year-old overripe (dead) bamboo culms of *Bambusa vulgaris* var. *vulgaris* Schrad. ex Wendl. and *Bambusa vulgaris* var. *vittata* Schrad. ex Wendl. from the "*La máquina*" plot of *Ingenio Quesería S.A. de C.V.,* selected through random sampling, with a field moisture range of 20-25 %. The extracted culms were sawn into 20 cm logs and pyrolized in a NOVATECH® vertical kiln for 4.5 h at an average temperature of 550 ºC. Once carbonized, the particle size was reduced using a KRETOR® extractor mill, and the percentage of particles retained on the 6.3, 4.0, 2.0, 0.84, 0.5, 0.4, 0.074, 0.044 mm sieves was determined using a MOMBOLDY® vibratory sieve shaker.

The physical and chemical analyses of the biochar were performed according to the following standards: pH ASTM D 1293-18 (ASTM,1999), organic matter UNE-EN-14774 (UNE-EN, 2010); nitrogen, phosphorus and potassium, according to NOM-021-RECNAT-2000 established in methodologies AS-08; AS-10 and AS-13, respectively (Semarnat, 2002).

Experimental design

A 2^2 factorial arrangement was applied, whose factors were BBV (*Bambusa vulgaris*), BBVVV (*Bambusa vulgaris vittata*) and the levels of 10 and 20 t ha^{-1}, plus a control. The evaluated treatments were: T0 (S-AB) without biochar application; T1= 10 t ha^{-1} of BBV; T2= 20 t ha^{-1} of BBV; T3= 10 t ha^{-1} of BBVVV and T4= 20 t ha^{-1} of BBVVV; T3= 10 t ha^{-1} of BBVV and T4= 20 t ha^{-1} of BBVV. The experimental unit was each sugarcane plant. A randomized block experimental design with six replications was used, with a total of 30 experimental units of *Saccharum* spp. var. CP 72-2086. The blocking factor was the particle size.

Application of biochar

Hernández-Hernández (2015) used charcoal residue doses corresponding to 0, 10, 15, 15, 20, 25, 30, 35 and 40 t ha^{-1} with favorable results in the application of 10 and 20 t ha^{-1}, which is why these were used in the experiment documented herein. Prior to application, both biochars were weighed individually for each experimental unit in order to obtain doses equivalent to 10 and 20 t ha^{-1}, which were added to the top of each bag; subsequently, they were watered with a watering system. The duration of the experiment was 70 days after the application of biochar.

Response variables evaluated in the crop

The variables studied were root volume, height, diameter of each of the primary and secondary shoots of the sugarcane plants, as well as the number of total shoots. Evaluations were performed every 15 days for 70 days after transplanting; at each measurement, six individuals per treatment were randomly selected for evaluation.

Statistical analysis

The response variables were analyzed by analysis of variance (ANOVA) based on a generalized linear model and Tukey's comparison of means, with a 5 % significance level, using the Minitab statistical package, version 17. The statistical model used was the one proposed by Sitún (2005):

$$Y_{ij} = \mu + T_i + B_j + \varepsilon_{ij}$$

Where:

μ = Overall mean of the response variable to be evaluated

T_i = The effect of the i^{th} level of the different treatments to be used

B_j = The effect of the j^{th} block or repetition

ε_{ij} = Experimental error associated with the i-j^{th} experimental unit

Results and Discussion

Bamboo biochar characterization

Table 1 shows the results of the analyses. The biochars of both species exhibited a moderately acid pH, in contrast to other studies in which they have been characterized as alkaline materials and have been used to improve the pH balance of the soil (Amonette and Joseph, 2009). The alkaline pH of biochar is due to the relationship of the production temperature and the type of feedstock; i.e., wood-based biochar tends to have a higher pH than biochar made from crop residues and manure (Gul *et al*., 2015; Abujabhah *et al*., 2016).

Table 1. Soil macro- and micronutrient analysis and biochar analysis of *Bambusa vulgaris* Schrad. ex J.C. Wendl. and *Bambusa vulgaris* Schrad. ex J.C. Wendl. var. *vittata.* parameters.

Parameters	Unit	Soil (day 0)	Soil (day 70)	BBV	BBVV
EC	dS m^{-1}	0.76	1.56	2.35	1.290
CEC	meq $100g^{-1}$	12.85	24.69	-	-
OM	%	6.09	5.91	86.94	92.28
P	ppm	20	64.08	8532.8	6836.1
K	ppm	259.99	377.83	312.6	458.4
Ca	ppm	2005.54	4283.14	2122.5	631.5
Mg	ppm	262.83	259.07	1350	1201.5
Na	ppm	2.83	50.83	33	34.48
Cu	ppm	1.7	1.35	12.93	12.02
Fe	ppm	35.08	26.9	57.31	42.6
Zn	ppm	3.22	2.31	16.96	27.39
B	ppm	0.421	0.32	17.11	50.84

BBV = *Bambusa vulgaris*; BBVV = *Bambusa vulgaris vittata;* EC = Electrical conductivity; CEC = Cation exchange capacity; OM = Organic matter; P = Phosphorus; K = Potassium; Ca = Calcium; Mg = Magnesium; Na = Sodium; Cu = Copper; Fe = Iron; Zn = Zinc; B = Boron.

Biochar characterization research indicates that the pH range of most biochars varies between 6.2 and 13.0 (Chan and Xu, 2009; Srinivasarao *et al*., 2013). In the present test, the pH of the different bamboo biochars was similar to that of oak wood (6.38) and Acai palm (6.3) (Lehmann *et al*., 2011; Nunes *et al*., 2019). Both species have components such as cellulose and hemicellulose, which are common in all woody plants and in some bamboo species, such is the case of the genus *Bambusa*. Therefore, the utilization of biochar from *Bambusa vulgaris* and *Bambusa vulgaris vittata* are alternatives that alkalinize the pH of the soil.

According to Jia *et al.* (2013), the pH of biochar is related to the amount of organic and phenolic acids derived from the thermal decomposition of cellulose and hemicellulose. Similarly, Gul *et al.* (2015) point out that one reason for the increase in the pH of soil with biochar is the presence on its surface of negatively charged carboxyl and hydroxyl groups that bind H+ ions from the soil solution, which reduces the concentration of H+ ions in the soil solution and increases its pH.

The electrical conductivity of the biochars was 2.35 dS m^{-1} in BBV and 1.290 dS m^{-1} in BBVV; i.e. they were moderately saline (Brady and Weil, 2008). Therefore, according to Hernández-Hernández (2015), there is no risk of salinity issues for the cultivation sugar cane when biochar is used as an amendment agent. The results of the present investigation coincide with those cited by Concilco *et al*. (2018), who reported that the EC of biochar was 2.55 dS m^{-1} in *Bambusa vulgaris* var. *vulgaris* and *Bambusa oldhammi* Munro.

The total carbon content of BBVVV was 53.55 %, which was higher than that of BBV (50.54 %); however, it was higher than that of gliricidia biochar (33 %) (Hernández-Godínez, 2015), but lower than the total carbon (84.2 %) of a biochar of *B. vulgaris vittata* and that of *B. vulgaris* (86.3 %), both at a temperature of 650 °C (Brito and Filho, 1987). It should be noted that the carbon content is closely related to the pyrolization temperature (Demirbas, 2004; Uchimiya *et al*., 2010).

Phosphorus content was 8 532.8 mg kg^{-1} for BBV, which was higher than that of BBVVV (6 836.1 mg kg^{-1}) —an excellent result for bamboo biochar. Both values exceed the 743 mg kg^{-1} of a biochar from sugarcane bagasse (Hernández-Godínez, 2015). Castellanos *et al*. (2000); Jia*et al*. (2013) and Yao *et al*. (2013) propose that biochar with high phosphorus concentration can be used as slow-release fertilizers, but highlight the need to correctly establish the dosage, frequency and time of application, since phosphorus is a slow-release fertilizer (Hernández-Hernández, 2015).

The phosphorus content of the soil increased considerably, due to the release by the utilized biochar. Yao *et al*. (2013) suggests applying biochar directly to the soil, as a fertilizer, for sustainable crop production, and as a carbon sequestrator.

The organic matter content was higher in BBVV, with 92.28 %, compared to 86.44 % in BBV. Both results are superior to those indicated by Domínguez (2013) for a biochar used as organic substrate for the growth of sugarcane seedlings, in which 60.50 % and 63.50 % organic matter was obtained, and to those reported by Concilco *et al.* (2018) in a commercial biochar of *B. vulgaris* and *B. oldhammi*, which had a mere 0.25 %.

Table 1 shows the total concentration of Mg: 1 350 mg kg^{-1}, 1 201 mg kg^{-1}; Ca: 2 122.5 mg kg^{-1}, 631.1 mg kg^{-1}; Na: 33, 34.48 mg kg^{-1}; Cu: 12.93 mg $kg^{-}kg^{-1}$, 42.6 mg kg^{-1}; Zn: 16.96 mg kg^{-1}, 27.39 mg kg^{-1}, and B: 17.11 mg kg^{-1}, 50.84 mg kg^{-1} of BBVV and BBVVV*.* The results for both biochars in these elements were higher than that cited by Rojas (2017) for a coffee husk biochar, and by Concilco *et al.* (2018) for a commercial biochar from *B. vulgaris* and *B. oldhamii*.

Effect of biochar on soils

According to the results of the soil analysis before and after the application of biochar, the pH increased from 6.93 to 7.69, so it is classified as moderately alkaline. According to other studies, biochar with alkaline pH can be used in acid soils as liming material for pH improvement (Rojas, 2017), as pH is related to nutrient availability for plant growth and development (Gul *et al.,* 2015)*.*

The electrical conductivity (EC) increased from 0.76 to 1.56 dS m^{-1} (Table 1), which is considered moderately low, indicating that the soil is free of the presence of salts, an ideal condition for sugarcane growth. In addition, the cation exchange capacity (CEC) increased from 12.85 to 24.69 mEq 100 g^{-1}. Studies have shown that biochar can alter soil fertility, either by direct nutrient supply or by increasing the CEC (Liang *et al.*, 2006), which favors nutrient retention and avoids leaching losses (Liang *et al.*, 2006).

The organic matter (OM) content decreased from 6.09 to 5.91 %. According to the parameters of NOM-021-RECNAT-2000 (Semarnat, 2002) volcanic soils are of medium OM content, and non-volcanic soils are very high in OM; therefore, the soil used in the experiment documented herein is of medium content. OM has an important effect on the CEC, because it potentially retains and exchanges nutrients, in addition to promoting soil microbiological activity (Lehman and Joseph, 2009; Abujabhah *et al*., 2016). With the application of bamboo biochar, there was an increase in phosphorus, potassium, calcium, magnesium and sodium, while some micronutrients such as copper, iron, zinc, and boron decreased (Table 1).

Table 2 summarizes the physical properties of the soil before and after biochar application. The bulk density (Da) was 1.60 g cm^{-3}; based on the texture, it corresponds to a sandy loam soil (Semarnat, 2002). Likewise, there was a change in the physical properties of the soil, since it exhibited a greater moisture retention in those treatments where biochar was applied, which was enhanced by the field capacity and the permanent wilting point (Table 2).

Table 2. Analysis of soil physical properties before and after biochar application.

Determinations	Before biochar application	After biochar application
Field capacity %	40.00	42.50
Permanent wilting point %	21.31	22.00
Usable moisture %	19.19	20.00
Bulk density g cm^3	1.60	1.60

Effect of biochar on the sugarcane plant height

The analysis of variance carried out on the results of the height variable (Table 4), establishes that the addition of biochar to the soil with the different treatments had a significant effect on the height of the plants. According to the comparison of means between treatments with the Tukey test (Table 3), it indicates that when treatment 4 (20 t ha^{-1} BBVV) was applied, the height of the sugarcane plants was significantly higher than with treatment 2 (BBV 20 t ha^{-1}). There was no significant statistical difference between the control (S-AB), treatment 1 (BBVV with 10 t ha^{-1}), and treatment 3 (BBVV with 10 t ha^{-1}). This indicates that the plant height variable alone does not represent a solid criterion for determining a particular superior treatment, but that the rest of the agronomic variables must be taken into consideration.

Table 3. Effect of biochar on the growth variables in the sugar cane crop variety CP 72-2086.

Growth variables	Treatments				
	S-AB	**BBV_10**	**BBV _20**	**BBVV_10**	**BBVV_20**
Height (cm)	60.06±1.53 ab	62.90±1.53 ab	59.24±1.53 b	63.66±1.53 ab	66.86±1.53 a
Diameter (mm)	6.53±0.18 a	6.74±0.18 a	6.17±0.18 a	6.89±0.18 a	6.91±0.18 a
No. of shoots	8.37 ±0.51 b	11.00±0.51 ab	11.20±0.51 a	9.41±0.51 ab	11.62±0.51 a
Root volume (cm^3)	76.62±8.44 c	84.81 ±8.44 bc	110.91±8.44 ab	110.40±8.44 ab	117.00±8.44 a

T0 (S-AB) = Without biochar application; T1 = 10 t ha^{-1} of BBV; T2 = 20 t ha^{-1} of BBV; T3 = 10 t ha^{-1} of BBVV; T4 = 20 t ha^{-1} of BBVV. Means that do not share a letter are significantly different, Tukey's test (P≤0.05).

Table 4. Analysis of variance of response variables.

Source	GL	Variable	Ajusted SC	Ajusted MC	*F* Value	*p* Value
Treatment	4	Height	148.34	37.085	3.97	0.028
		Diameter	1.511	0.377	2.68	0.083
		Shoots	28.014	7.003	6.53	0.005
		Root volume	5173.1	1293.28	9.08	0.001
Block	3	Height	45.71	15.238	1.63	0.812
		Diameter	0.174	0.058	0.41	0.741
		Shoots	2.993	0.997	0.93	0.456
		Root volume	125.0	41.68	0.29	0.830
Error	12	Height	112.08	9.340		
		Diameter	0.6917	0.140		
		Shoots	12.875	1.0729		
		Root volume	1710.0	142.50		
Total	19	Height	306.13			
		Diameter	3.377			
		Shoots	43.882			
		Root volume	70008.1			
Variables	S	Squared R	(Adjusted) square R	(Pred.) square R		
Height	3.05608	63.39%	42.03%	0.00%		
Diameter	0.61	49.91%	20.69%	0.00%		
Shoots	1.03582	70.42%	53.54%	18.50%		
Root volume	11.9373	75.60%	61.37%	32.22		

Effect of biochar on the diameter

The analysis of variance carried out on the variable stem diameter (Table 4) and the Tukey's mean comparison between treatments, establishes that the addition of biochar to the soil with the doses used at 70 days did not have a significant effect on this variable, since the effect attributed to all treatments is equal. The variable stem diameter during the development or growth of the sugarcane crop shows few pronounced increases, i.e., it is a particular characteristic of this hybrid.

Effect of biochar on the stem number population

The variable number of milling stalks per hectare is one of the most relevant variables, since it directly impacts the yield potential in the field. The analysis of variance carried out on the results of the variable number of stems (Table 4) establishes that the addition of biochar to the soil with each of the various treatments had a significant effect on this variable. According to Tukey's test mean comparison of means between treatments (Table 3), when treatment 2 BBV-20 t ha^{-1} (a) and treatment 4 BBVV-20 t ha^{-1} (a) are applied, the stem population is statistically superior to that of the control treatment (b). In treatments 1 BBVV-10 t ha^{-1} (ab), 3 BBVV-10 t ha^{-1} (ab) the means were the same.

Effect of biochar on the root volume

The comparison of treatment means with Tukey's test (Table 3) indicates that when treatment 4 (BBVV-20 t ha^{-1}) was applied, there was a statistically significant increase in the root volume with respect to the control treatment (S-AB).

The analysis of variance carried out on the root volume variable (Table 4) establishes that the addition of biochar to the soil in the different treatments had a significant effect on this variable.

Conclusions

The application of biochar had a positive effect on the height, number of shoots and root volume of sugarcane plants. A higher dose of biochar promoted a higher growth rate in these plants, with the biochar from *Bambusa vulgaris vittata* at a concentration of 20 t ha^{-1}. *Bambusa vulgaris* biochar at a concentration of 20 t ha^{-1} only influences the number of shoots. The use of bamboo biochar as an organic amendment option improves soil fertility and nutrient cycling, which favorably affects plant growth. In this study, bamboo biochar improved most of the growth traits of sugarcane plants, such as height, diameter, number of total shoots and root volume, since biochar prevents the leaching of nutrients and increases water retention due to its high surface area and porous nature; consequently, nutrients are available for plant consumption. In general, the physical and chemical properties of the soil are improved by the application of biochar. The positive results of the study suggest a potential benefit for enhancing soil fertility and the growth of such crops as sugar cane, thereby contributing to the development of agriculture and the economy in the country.

Acknowledgments

The authors wish to thank the INIFAP fiscal project for the feasibility and viability in the propagation, conservation, establishment and sustainable management of five native species of woody bamboo in the Pacific-Central region of Mexico. We would also like to thank *Ingenio Quesería S.A. de C.V*. And, finally, the operating staff, as well as the Soil, Plant and Water laboratory of the INIFAP *Tecomán* Experimental Field.

Conflict of interest

The authors declare no conflicts of interest.

Contributions by author

Gabriela Orozco Gutiérrez: fieldwork, analysis, drafting of the manuscript, and integral project management; Laura Medina Telez: fieldwork, statistical analysis, laboratory and fieldwork, data analysis, data analysis; Antonio Elvira Espinosa: support in edaphic analyses; Jeovani Francisco Cervantes Preciado: sugarcane growth analysis.

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