



## Effect and viability of *Guadua angustifolia* Kunth biochar on soil conditions and the development of *Zea mays* L.

Efecto y viabilidad del biochar de *Guadua angustifolia* Kunth en las condiciones del suelo y el desarrollo de *Zea mays* L.

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### RESUMEN

La demanda mundial de alimentos ha generado un aumento en el uso de los fertilizantes, los cuales tienen impactos ambientales negativos en el suelo, el agua y el aire. En este contexto se propone el biochar como una alternativa sostenible para mejorar la salud del suelo disminuyendo la dependencia de insumos agrícolas. Este estudio evaluó la viabilidad ambiental, productiva y económica del biochar elaborado con *Guadua angustifolia* Kunth en plantas de *Zea mays* L. en el municipio de Pitalito, Huila, Colombia. Aplicando cinco tratamientos: T1 (fertilización sintética convencional), T2 y T3 (fertilización sintética con 80 y 160 g de biochar), T4 y T5 (80 y 160 g de biochar), se utilizó un diseño completamente aleatorio con tres réplicas. Los resultados mostraron que T2 (5 t/ha de biochar) presentó un aumento del 10% en biomasa aérea comparado con T1, mejoró parámetros del suelo como el pH, la capacidad de intercambio catiónico y redujo del aluminio intercambiable (~63%). El biochar logró una captura de carbono de 2 135 a 2 155 kg CO<sub>2</sub>eq/t, con posibilidad de generar certificados de captura (CORCs). El costo de producción por tonelada estimado fue USD 303, el costo total de aplicación por hectárea estimado fue USD 1 816 con la dosis de 5t/ha.

**Palabras clave:** Agricultura sostenible; Enmiendas para suelos; Fertilización balanceada.

### ABSTRACT

Global demand for food has led to an increase in the use of fertilisers, which have negative environmental impacts on soil, water and air. In this context, biochar is proposed as a sustainable alternative to improve soil health and reduce dependence on agricultural inputs. This study evaluated the environmental, productive, and economic viability of biochar made from *Guadua angustifolia* Kunth in *Zea mays* L. plants in Pitalito, Huila (Colombia). Five treatments were applied: T1 (conventional synthetic fertilisation), T2 and T3 (synthetic fertilisation with 80 and 160 g of biochar per plant), T4 and T5 (80 and 160 g of biochar per plant), using a completely randomised design and three replicates. The results showed that T2 (equivalent to 5 t/ha of biochar) presented a ~10% increase in above-ground biomass compared to T1, improved soil parameters such as pH, cation exchange capacity and reduction of exchangeable aluminium (~63%). Biochar also showed a carbon capture potential of 2 135–2 155 kg CO<sub>2</sub>eq/t, with the possibility of generating removal certificates (CORCs). The production cost per tonne was estimated at USD 303, and total application cost per hectare was estimated at USD 1 816 at a dose of 5 t/ha.

**Keywords:** Sustainable agriculture; Soil amendment; Balanced fertilisation.

## 1. Introduction

The excessive application of fertilisers to the soil is a current problem that causes serious environmental impacts such as acidification and degradation of soil properties, leaching of nutrients into water bodies, and an increase in greenhouse gases in the atmosphere. The use of fertilisers is justified by the growing global demand for food, which is why there is a need to identify and evaluate sustainable alternatives that increase the efficiency of these inputs.

Biochar is becoming an alternative solution to this problem, as it is an organic soil amendment produced by mixing charcoal with nutrients and microorganisms. Several studies have been conducted to evaluate its properties and demonstrate its environmental, economic, and productive benefits for crops. One raw material that can be used to produce high-quality biochar is *Guadua angustifolia* Kunth (Orozco-Gutiérrez and de Lira-Fuentes, 2020), which has high biomass generation, a high lignocellulosic content and a porous cell structure that gives biochar larger specific surface area and water retention capacity compared to other lignocellulosic raw materials such as pine (Masís-Meléndez et al. 2020).

The high temperature of pyrolysis makes biochar alkaline, Hossain et al. (2020) show that this is due to the large number of alkalis and alkaline metals that are not volatilised, allowing biochar to have a pH close to 10, and found that applying doses of 50 and 100 t/ha to soils with a pH of 5.25 can generate an increase of up to 4.5 units. Biochar also stabilizes the pH of soil, Jiang et al. (2025), found that the application of biochar increases the soil's acid buffering capacity, preventing the application of fertilisers such as urea from lowering the pH again. Biochar also helps prevent soil degradation by reducing the amount of fertiliser needed to obtain the same yield. Saharudin et al. (2024) analysed multiple studies and found that for various crops, biochar allows for a consistent reduction of 10% in nitrogen ( $\text{CO}(\text{NH}_2)_2$ ) application, a 5% reduction in phosphorus ( $\text{P}_2\text{O}_5$ ) application, and a 5% reduction in potassium ( $\text{K}_2\text{O}$ ) application.

The decrease in the inputs required for crops is also due to the reduction in the risk of nutrient leaching and their physical and chemical fixation on the surface of the biochar, as well as positive impacts on the rhizosphere microbiota (Ayaz et al. 2021, Jiang et al. 2025). The literature indicates that, by reducing the use of fertilisers, biochar generates a reduction in crop production costs. In

response to this, authors such as Patel and Panwar (2024) emphasise that the economic benefits of biochar should be quantified in the medium to long term, a statement supported by Latawiec et al. (2021), who find profitability within three to four years with doses of 40, 60, and 80 t/ha.

Based on the above context, the potential of *G. angustifolia* biochar as an amendment capable of positively impacting soil properties and crop yields is evident, generating economic and environmental benefits by reducing the need for synthetic chemical fertilisers and capturing carbon in the long term. However, despite this information, there is a knowledge gap, as there are no studies evaluating the feasibility of applying *G. angustifolia* biochar in Colombia, including its environmental, economic, and productive aspects together.

## 2. Methodology

### 2.1 Type of study and methodological approach

The experiment was conducted using a quantitative experimental approach, employing a completely randomised design (CRD). Agronomic variables were measured for *Z. mays* plants (above-ground and root biomass accumulation, foliar analysis) and edaphic variables (through soil analysis). In addition, variables related to the economic aspects of biochar production were measured, from the crop of *G. angustifolia* to the final application of biochar.

### 2.2 Location and site conditions

The experiment was carried out at El Vergel farm, located in the Honda Porvenir district of the municipality of Pitalito, Huila (Colombia). The area is situated at an altitude of 1 288 metres above sea level, with geographical coordinates  $1^{\circ}49'11.67''\text{N}$  and  $76^{\circ}2'53.18''\text{W}$ . With average temperatures of  $17^{\circ}\text{C}$  to  $25^{\circ}\text{C}$ , the area used for the study was a 200 m<sup>2</sup> plot with flat topography and no shade.

### 2.3 Preparation of biochar

The biochar was produced by pyrolysis of *G. angustifolia*, harvested at maturity, three to four years old. The culms were dried naturally for one month, and the final moisture content of the biomass was measured with a hygrometer, with an average result of less than 20%. The material was subjected to pyrolysis at a temperature of  $500^{\circ}\text{C}$  for a period of four hours in a retort-type kiln with a capacity for 250 kg of biomass. The charcoal obtained was ground using a hammer mill and mixed with composted chicken manure (detailed

in Table 1) in a 1:1 ratio, 300 mL of water was added for each kg of the mixture, which was left to ferment for 15 days. The temperature and humidity of the mixture were monitored daily to ensure that it did not exceed 70°C, aiming to prevent the death of microorganisms and increasing nutrient mineralisation.

## 2.4 Experimental design and treatments

Following the methodology proposed by Cargua Chávez (2020), four treatments and one control were established, each with three replicates. These were randomly distributed in an area of 200 m<sup>2</sup> in plastic bags containing 10 kg of substrate, which had been previously characterised (Table 1). Two seeds of *Z. mays*, variety ICA V-305, were sown in each bag. The treatments applied were: T1: Synthetic fertiliser NPK (15g) (Control); T2: fertiliser NPK (15g) + biochar (80g); T3: fertiliser NPK (15g) + biochar (160g); T4: biochar (80g); T5: biochar (160g).

The fertiliser used was a commercial mixture (Nutrimon®, Monómeros, Colombia) of N-P-K (15-15-15), which was applied in two stages: five grams on the fifth day after the emergence of the coleoptile and an additional 10 grams 15 days later, while the biochar was mixed with the substrate before bagging. 46 days after coleoptile emergence, data were collected on above-ground biomass and root biomass, and a foliar nutrient analysis and a physicochemical soil analysis were performed.

## 2.5 Statistical Analysis

An analysis of variance (ANOVA) and Tukey's multiple comparison test were performed for each of the variables in the previous section, with a significance level ( $P < 0.05$ ). Analysis software Real Statistics (V2) and R (V 4.4.1) were used.

## 3. Results and discussion

The initial soil characterisation shows a sandy loam texture with a pH of 4.03 and a high content of exchangeable aluminium. There is a low percentage of nitrogen and organic matter and medium to high concentrations of phosphorus, potassium, magnesium, calcium, sodium, iron and sulphur. On the other hand, there is evidence of low concentrations of boron, copper, manganese and zinc (Table 1).

Based on the data, it is interpreted that the soil has good aeration and drainage, but low water and nutrient retention capacity (Abiala and Blackwood, 2024). The pH is very low and may limit the availability of nutrients such as calcium,

magnesium, and phosphorus. In addition, the acidity causes a high content of exchangeable aluminium, which is phytotoxic and negatively impacts root and plant growth (Chen et al. 2023). Also, it is evident that there is low biological fertility due to low levels of nitrogen and organic matter, which can affect plant development and soil microbiota. This is compounded by low levels of boron, copper, manganese, and zinc, which have an impact on enzyme activity in plants (Gerke, 2022).

**Table 1**

Characterisation of initial conditions of the materials used in the experiment

Variable	Result		
	Soil	Chicken manure	Biochar
pH (units)	4.03	7.6	9.53
Conductivity (µs/cm)	66.90	332	46.19
C.E.C (meq/100g)	34.40	41.5	40.18
Organic nitrogen (%)	0.08	1.60	0.32
Organic matter (%)	2.49	-	18.04
Available phosphorus (ppm)	18.03	3.60	2 740.68
Potassium (ppm)	0.52	2 800	19.06
Magnesium (meq/100g)	4.23	1.09	24.26
Calcium (meq/100g)	10.73	162	33.79
Exchangeable aluminium (meq/100g)	1.62	-	0
Sodium (meq/100g)	0.18	15.49	6.06
Iron (ppm)	77.32	4 010	75.48
Boron (ppm)	0.17	35.6	31.94
Copper (ppm)	0.81	53.2	34.84
Manganese (ppm)	10.52	412	18.58
Zinc (ppm)	1.13	366	32.98
Sulphur (ppm)	17.05	4 220	6.16

On the other hand, the characterisation of biochar (Table 1) shows a high pH (9.63), which is suitable for reducing soil acidity. It also has low electrical conductivity, indicating that there is no risk of soil salinisation. Furthermore, its high cation exchange capacity can help in the retention and release of nutrients to plants.

## 3.1 Changes in soil health

The analysis of variance shows that there were no significant changes ( $p > 0.05$ ) in the granulometric variables, percentage of sand, silt and clay (Table 2). This result is consistent with that reported by Toková et al. (2020) and Li et al. (2021), who found that physical changes in the soil are only evident at high doses above 20 t/ha, whereas in this experiment a maximum dose of 10 t/ha was used.

Significant differences ( $p < 0.05$ ) were identified in all treatments regarding the pH variable, where the treatments with biochar recorded a higher pH (Table 2). Hossain et al. (2020) and Jiang et al. (2025) explain that biochar displaces acid cations in the soil and reduces the risk of cationic base leaching, which adds to the presence of functional groups with oxygen and other organic anions that, through protonation and deprotonation reactions, allow the anchoring of iron oxides and hydroxides, increasing the soil's acidity buffering capacity and helping to prevent pH from decreasing when nitrogen fertilisers are applied.

Authors such as Hossain et al. (2020) report that an increase in pH leads to a decrease in phytotoxicity caused by exchangeable aluminium in acidic soils, which was reduced by 64.17% (95% CI: 60.00% - 66.11%;  $p < 0.05$ ) in the treatments with biochar (T2 to T5) compared to the treatment without biochar (T1) (Table 2).

Electrical conductivity also showed significant differences ( $p < 0.05$ ) between all treatments, with T1, T3, and T5 showing the highest conductivity, which may indicate that the ionic salt content decreases when biochar is applied in low quantities (Abiala & Blackwood, 2024).

In terms of cation exchange capacity, the highest values were found in the treatments with the highest dose of biochar. This is similar to the results of Chen et al. (2020) who found an increase in cation exchange capacity in two soil

types when applying four different doses of biochar, showing a significant increase  $p < 0.05$ ) between treatments, with the highest doses of biochar presenting a higher cation exchange capacity. In contrast, studies such as those by Li et al. (2021) report that biochar had no impact on this parameter, so it can be inferred that this effect does not always occur.

Regarding the major elements in the soil, there is no significant difference ( $p > 0.05$ ) in nitrogen concentration, considering that it is an element that volatilises during biomass pyrolysis in the form of ammonia (Rathyanake et al. 2023). For potassium, there are significant differences between treatments, with the highest concentrations found in those with the highest doses of biochar. These results are consistent with those reported by Rathyanake et al. (2023). For phosphorus, the authors indicate that it accumulates in biochar at pyrolysis temperatures above 650 °C. A lower concentration is evident in the biochar treatments (T2 to T5) compared to the control (T1), which may indicate that there was greater bioavailability of the element when biochar was applied.

For minor elements, the analysis of variance shows that there is no significant difference in the concentration of sodium, iron, copper, manganese, and zinc. On the other hand, there were significant differences in the content of magnesium, calcium, boron, and sulphur (Table 2).

**Table 2**

Soil analysis results 46 days after coleoptile emergence in *Z. mays* cultivation

Treatment	pH	Conductivity ( $\mu\text{S}/\text{cm}$ )	CEC ( $\text{meq}/100\text{g}$ )	Exchangeable Al ( $\text{meq}/100\text{g}$ )	K ( $\text{meq}/100\text{g}$ )
	Mean $\pm$ SE	Mean $\pm$ SE	Mean $\pm$ SE	Mean $\pm$ SE	Mean $\pm$ SE
T1	4.51 <sup>a</sup> $\pm$ 0.00	94.22 <sup>a</sup> $\pm$ 0.00	18.68 <sup>a</sup> $\pm$ 0.02	1.80 <sup>a</sup> $\pm$ 0.00	0.70 <sup>a</sup> $\pm$ 0.02
T2	4.74 <sup>b</sup> $\pm$ 0.00	68.93 <sup>b</sup> $\pm$ 0.00	20.36 <sup>b</sup> $\pm$ 0.01	0.65 <sup>b</sup> $\pm$ 0.01	0.91 <sup>b</sup> $\pm$ 0.02
T3	5.09 <sup>c</sup> $\pm$ 0.00	81.90 <sup>c</sup> $\pm$ 0.01	23.07 <sup>c</sup> $\pm$ 0.05	0.61 <sup>b</sup> $\pm$ 0.00	1.12 <sup>c</sup> $\pm$ 0.02
T4	5.02 <sup>d</sup> $\pm$ 0.00	46.83 <sup>d</sup> $\pm$ 0.00	18.28 <sup>a</sup> $\pm$ 0.39	0.68 <sup>b</sup> $\pm$ 0.01	0.70 <sup>a</sup> $\pm$ 0.02
T5	5.30 <sup>e</sup> $\pm$ 0.00	71.58 <sup>e</sup> $\pm$ 0.03	23.92 <sup>c</sup> $\pm$ 0.05	0.62 <sup>b</sup> $\pm$ 0.00	1.51 <sup>d</sup> $\pm$ 0.02
p-value ANOVA	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Treatment	Mg ( $\text{meq}/100\text{g}$ )	Ca ( $\text{meq}/100\text{g}$ )	P (ppm)	B (ppm)	S (ppm)
	Mean $\pm$ SE	Mean $\pm$ SE	Mean $\pm$ SE	Mean $\pm$ SE	Mean $\pm$ SE
T1	2.56 <sup>a</sup> $\pm$ 0.01	6.1 <sup>a</sup> $\pm$ 0.05	99.08 <sup>a</sup> $\pm$ 0.1	0.56 <sup>a</sup> $\pm$ 0.11	15.94 <sup>a</sup> $\pm$ 0.16
T2	2.96 <sup>b</sup> $\pm$ 0.01	6.97 <sup>b</sup> $\pm$ 0.01	62.08 <sup>b</sup> $\pm$ 0.08	0.61 <sup>a</sup> $\pm$ 0.06	7.76 <sup>b</sup> $\pm$ 0.19
T3	3.61 <sup>c</sup> $\pm$ 0.01	7.86 <sup>c</sup> $\pm$ 0.03	64.42 <sup>c</sup> $\pm$ 0.05	0.53 <sup>a</sup> $\pm$ 0.01	13.35 <sup>c</sup> $\pm$ 0.16
T4	2.24 <sup>d</sup> $\pm$ 0.01	6.95 <sup>b</sup> $\pm$ 0.01	43.75 <sup>d</sup> $\pm$ 0.05	0.49 <sup>ab</sup> $\pm$ 0.00	10.62 <sup>d</sup> $\pm$ 0.18
T5	2.54 <sup>a</sup> $\pm$ 0.00	7.71 <sup>c</sup> $\pm$ 0.01	45.85 <sup>e</sup> $\pm$ 0.1	0.17 <sup>b</sup> $\pm$ 0.00	18.90 <sup>e</sup> $\pm$ 0.16
p-value ANOVA	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05

Different letters in each column indicate significant differences between treatments ( $p < 0.05$ ; Tukey's test).

In terms of calcium content, T1 had the lowest concentration, the treatments with the lowest dose of biochar (T2 and T4) had intermediate concentrations, and the treatments with the highest dose (T3 and T5) had the highest concentrations. For magnesium, T3 had the highest content, while for boron there was no significant difference between treatments, except for T5, which had a lower concentration. Finally, in relation to sulphur content, all treatments were statistically different, and T5 had the highest content (Table 2).

### 3.2 Carbon capture measurement

The carbon capture calculation was performed using the methodology proposed by Puro.earth (2025) which has been used by authors such as Fawzy et al. (2022).

The amount of carbon permanently fixed in the soil is calculated based on a minimum projection of 200 years, which is determined using the equation (1) proposed by Puro.earth (2025):

$$PF = M - A(H/C_{org}) \quad (1)$$

Where PF is the persistence factor of carbon present in biochar, M and A are regression parameters to include the effect of soil temperature, which are reported by Puro.earth. For a soil temperature of 17 °C, M = 90.96 and A = 31.39 were found. H is the hydrogen content of biochar, which was found in the studies by Césaire et al. (2019) and Ardila et al. (2019) to be 5.96% and 6.7%, respectively. Finally,  $C_{org}$  is the percentage of organic carbon in *G. angustifolia* biochar, which was taken from the study by Cañon-Tafur et al. (2025), who reported a value of  $46.323\% \pm 1.513$ .

Using the above data, a PF = 86.27% to 87.05% was calculated. This result is higher than that reported by Fawzy et al. (2022), who found values ranging from 59.82% to 81.52% for oil palm biochar. However, percentages ranging from 80% to 87% were reported for other raw materials (Ayaz et al. 2021; Saharudin et al. 2023).

To calculate the amount in kg CO<sub>2</sub> equivalent captured per tonne of biochar applied to the soil, the Puro.earth methodology was followed, applying the equation (2):

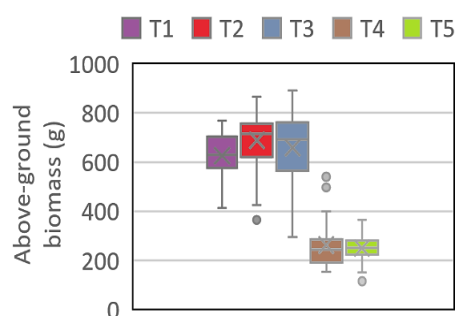
$$C_{loss} = C_{stored}(100 - PF) \quad (2)$$

Where  $C_{loss}$  is the amount of carbon released back into the atmosphere and  $C_{stored}$  is the gross amount of carbon captured by biochar, which was taken from the analysis reported by Cañon-Tafur et al. (2025) and quantified at 66.92%. For one tonne of biochar,  $C_{stored} = 2\,475.04$  kg CO<sub>2</sub>eq and  $C_{loss} = 320.67 - 340.05$  kg CO<sub>2</sub>eq, resulting in a

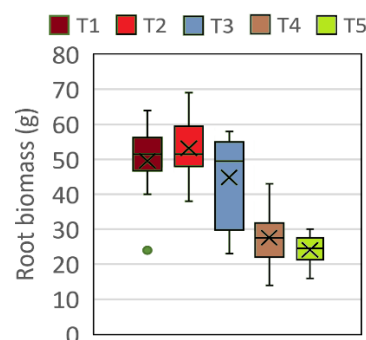
carbon capture amount of 2 135.99 to 2 155.37 kg CO<sub>2</sub>eq per tonne of *G. angustifolia* biochar applied to the soil. This value is like that reported by other authors such as Yin et al. (2022), who calculated a range of 2 408–2 682 kg CO<sub>2</sub>eq/t, Saharudin et al. (2024), with values of 2 063 to 3 900 kg CO<sub>2</sub>eq/t, and Fan et al. (2021), who found 900 to 6 600 kg CO<sub>2</sub>eq/t. The results obtained show a high carbon capture potential in *G. angustifolia* biochar.

### 3.3 Changes in plant growth

Analysis of the results for above-ground biomass accumulation shows that there is a significant difference ( $p < 0.05$ ) between treatments, with T2 showing the highest accumulation (Figure 1). On the other hand, the results for root biomass showed differences only between the group with additional fertilisation (T1 to T3) and the group to which only biochar was applied (T4 and T5) (Figure 2).



**Figure 1.** Above-ground of *Z. mays* accumulated over 46 days after coleoptile emergence.



**Figure 2.** Root biomass of *Z. mays* accumulated over 46 days after coleoptile emergence.

Regarding above-ground biomass, T2 showed the highest accumulation, being 10.05% higher (95% CI 3.60%–16.51%  $P < 0.05$ ) than control (T1). This phenomenon is confirmed by authors such as Ayaz et al. (2021) and Yang et al. (2022), who indicate that the change produced by biochar in soil properties, such as increased pH and reduced

exchangeable aluminium, frees up cation exchange spaces that increase the bioavailability and nutrient retention capacity of the soil. The result obtained in T3 is consistent with that reported by Yang et al. (2022), who indicate that high doses of biochar do not represent substantial improvements and that exceeding the optimal dose (5 t/ha in this case) can generate zero or adverse additional effects.

The biomass accumulation results are compared with those reported by Khan et al. (2024), who conducted a meta-analysis (114 studies) in which they identified an average increase of 20% in the yield of the crops analysed, being more pronounced in acidic soils, similar to the pH conditions in which this study was conducted. On the other hand, Ullah et al. (2024) and Jiang et al. (2024) report that the increase in crop yield remains in the range of 3% to 16% in the long term.

The results of root biomass accumulation (Figure 2) indicate that the application of biochar did not have an impact on root growth, given that there is no significant difference ( $p > 0.05$ ) between treatments T1, T2, and T3, a result corroborated by authors such as González-Marquetti et al. (2020), who found that the application of biochar can inhibit root growth.

### 3.4 Changes in foliar nutrition

The results of the foliar analysis show that there is no significant change ( $p > 0.05$ ) in the concentration of zinc, chlorine, boron, potassium, sulphur, calcium, sodium, and copper. These results are like those reported by González-Marquetti et al. (2020), who highlight the findings of various studies showing that biochar did not increase nutrient content at the leaf level but did have a positive impact on plant growth and crop yields, especially in combination with additional fertilisation. However, in the present study, significant differences ( $p < 0.05$ ) were found in the contents of nitrogen, phosphorus, magnesium, iron, and manganese, as shown in Table 3.

**Table 3**

Characterisation of *Z. mays* leaves 46 days after coleoptile emergence

Treatment	Nitrogen (%) Mean $\pm$ SE	Phosphorus (%) Mean $\pm$ SE	Magnesium (%) Mean $\pm$ SE	Iron (PPM) Mean $\pm$ SE	Manganese (PPM) Mean $\pm$ SE
T1	2.92 <sup>a</sup> $\pm$ 0.05	0.38 <sup>a</sup> $\pm$ <0.05	0.18 <sup>a</sup> $\pm$ <0.05	113.0 <sup>ab</sup> $\pm$ 4.54	59.00 <sup>ab</sup> $\pm$ 2.16
T2	2.91 <sup>a</sup> $\pm$ 0.12	0.44 <sup>a</sup> $\pm$ <0.05	0.16 <sup>ab</sup> $\pm$ <0.05	121.0 <sup>a</sup> $\pm$ 11.14	67.67 <sup>b</sup> $\pm$ 7.51
T3	2.15 <sup>ab</sup> $\pm$ 0.28	0.39 <sup>a</sup> $\pm$ <0.05	0.13 <sup>ab</sup> $\pm$ <0.05	98.0 <sup>ab</sup> $\pm$ 13.49	54.67 <sup>ab</sup> $\pm$ 4.25
T4	1.24 <sup>bc</sup> $\pm$ 0.08	0.26 <sup>b</sup> $\pm$ <0.05	0.09 <sup>b</sup> $\pm$ <0.05	64.3 <sup>b</sup> $\pm$ 5.17	39.00 <sup>b</sup> $\pm$ 1.69
T5	1.13 <sup>c</sup> $\pm$ 0.11	0.25 <sup>b</sup> $\pm$ <0.05	0.09 <sup>b</sup> $\pm$ <0.05	60.0 <sup>b</sup> $\pm$ 2.16	36.33 <sup>b</sup> $\pm$ 1.18

Different letters in each column indicate significant differences between treatments ( $p < 0.05$ ; Tukey's test).

There are no significant differences ( $p > 0.05$ ) between T1, T2, and T3 for any of the variables, so it can be inferred that biochar did not have a significant impact on the foliar content of the elements analysed, which has been reported in other cases by authors such as González-Marquetti et al. (2020), who found that biochar has an indeterminate impact on foliar nutrition when analysing various studies.

Furthermore, González-Marquetti et al. (2020) confirm the findings in treatments T4 and T5, where implementing biochar without additional fertilisation compromises productivity, resulting in low yields due to phytotoxic effects. However, Naeem et al. (2024) reported that applying doses of 5 t/ha and 10 t/ha of *Acacia nilotica* L. biochar without additional fertilisation resulted in a 26% increase in grain and stubble and a 29% increase in total seed weight in a maize crop.

### 3.5 Production and application costs of biochar

To calculate the costs of producing and applying biochar, the methodology proposed by Saharudin et al. (2024) was followed, which included the acquisition and transport of biomass to the production plant, drying and preparation of the material, the pyrolysis process, grinding, and packaging. The costs of activating the biochar by loading it with nutrients and microorganisms from chicken manure were added (Table 4). The production costs resulted in a value of USD 303 per tonne of biochar (produced and packaged).

**Table 4**

Production and application costs of biochar

Production costs per ton of biochar	(USD)
Biomass acquisition and transport	33
Preparation and drying	22
Pyrolysis and milling	88
Activation of biochar	149
Packaging	11
Total	303
Application costs per hectare	(USD)
Transport	71
Application	230
Total	301

To calculate application costs per hectare a planting density of 62 500 corn plants per hectare was considered, applying 80 g dose per plant (which yielded the best results), the necessary amount of biochar per hectare is calculated to be five tonnes, which costs USD 1515 (using the calculated value of USD 303 per tonne) and adding the costs associated with transport and application, which were calculated at USD 301 per hectare (Table 4), the total cost of biochar production and application for the year 2025 is estimated at USD 1 816 per hectare.

The final application value far exceeds the estimated cost of conventional chemical fertilisation for *Z. mays* crop in Colombia, which was calculated at USD 566 per hectare in 2025. According to Liu et al. (2025), the application of biochar should be considered a medium- and long-term investment, as the benefits of biochar remain in the soil for up to 12 years after application, thereby increasing profitability. Similarly, Zhang et al. (2023) have documented a reduction of up to 40% in the need for synthetic chemical fertilisers over several harvests, which increases economic security in an environment where there is high price volatility.

According to Patel & Panwar (2024) and Latawiec et al. (2021), returns increase over time, especially with moderate doses (< 10 t/ha), which maximises the net present value of the investment and the internal rate of return.

### 3.6 Economic benefits of biochar

Given the economic benefits that can be obtained from the application of biochar, Saharudin et al. (2024) consider the reduction in the quantity of fertilizers required for crops (up to 40% less) and the possible sale of CO<sub>2</sub> removal certificates (CORCs), which can generate significant additional income for farmers. Fawzy et al. (2024) propose the calculation based on the following equation (3):

$$\text{CORC} = E_{\text{stored}} - E_{\text{biomass}} - E_{\text{production}} - E_{\text{use}} \quad (3)$$

Where  $E_{\text{biomass}}$  considers the emissions generated by the acquisition of raw materials, which were measured in the field,  $E_{\text{production}}$  considers the emissions generated by the conversion of biomass, which were calculated using mass and energy balances, taking into account that the yield of the pyrolysis process was 25% at a temperature of 500°C, which is very similar to the 27% yield at 550°C obtained by Orozco-Gutiérrez and de Lira-Fuentes (2020) during the production of biochar from *G. angustifolia*.  $E_{\text{use}}$  refers to the emissions associated with the transport and application of

biochar, which were calculated using the methodology of Sahoo et al. (2021) methodology, considering less than 100 km from the *G. angustifolia* crop to the processing plant and the final application point. The result is 0.589–0.623 CO<sub>2</sub> CORCs per tonne of *G. angustifolia* biochar applied.

The experimental results suggest that the application of *G. angustifolia* biochar is viable from an environmental perspective, thanks to its carbon capture capacity and its properties in improving the physicochemical conditions of acidic soils. In terms of plant growth, an increase in accumulated above-ground biomass was observed during the early growth stage. Finally, it was noted that the low production costs and economic benefits from carbon capture certificates make this amendment a sustainable alternative for agriculture in areas where *G. angustifolia* is available.

### 4. Conclusions

The application of 5t/ha of *G. angustifolia* biochar to *Z. mays* crops together with NPK fertilisation (T2) showed superior or similar properties compared to the conventional fertiliser treatment (T1) and the other biochar treatments. Biochar also showed a high carbon capture capacity, which opens the possibility for further studies applying this amount under commercial-scale field conditions and bringing the crop to harvest to determine yield. Applying biochar is a high investment but the selling of CORCs and reduction of fertiliser need over the years can minimize or negate this cost.

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