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Biochar and chicken manure improve soil chemical properties and nutritional status of rosewood seedlings grown in clay soil

El biocarbón y el estiércol de pollo mejoran las propiedades químicas del suelo y el estado nutricional de las plántulas de palo de rosa cultivadas en suelo arcilloso

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ABSTRACT

Studies on the effects of biochar and chicken manure on soil chemical properties and initial growth of rosewood under field conditions in the Amazon are rare; therefore, a field experiment was carried out to evaluate the effects of biochar, chicken manure, and mineral fertilizer on the chemical properties of the soil, nutrient concentrations in the leaves, and on the initial growth of rosewood (*Aniba rosaeodora*) grown in clay soil. The study was conducted in causal blocks, with five treatments (control, biochar, biochar plus chicken manure, biochar plus mineral fertilizer, and biochar plus chicken manure plus mineral fertilizer) and three replications. In general, we observed that the application of biochar and chicken manure, alone or in combination, increased soil pH, calcium, phosphorus, zinc, and manganese content, as well as foliar potassium and calcium concentrations. However, despite fertilization, we did not observe significant gains in the growth of *A. rosaeodora* seedlings until ten months after planting. The combination of biochar and chicken manure exhibited the greatest impact, and is therefore important for soil sustainability and plant development in tropical soils.

Keywords: Aniba rosaeodora, plant nutrition, amazon soils, forestry.

RESUMEN

Los estudios sobre el efecto del biocarbón y el estiércol de pollo sobre las propiedades químicas del suelo y el crecimiento inicial del palo de rosa en condiciones de campo en el Amazonas son escasos, por lo que se llevó a cabo un experimento de campo para evaluar los efectos del biocarbón, el estiércol de pollo y los fertilizantes minerales sobre las propiedades químicas, propiedades del suelo, concentraciones de nutrientes en las hojas y sobre el crecimiento inicial del palo de rosa (*Aniba rosaeodora*) cultivado en suelo arcilloso. El estudio se realizó en bloques causales, con cinco tratamientos (testigo, biocarbón, biocarbón y gallinaza, biocarbón y fertilizante mineral, biocarbón, gallinaza y fertilizante mineral) y tres repeticiones. Observamos que, en general, la aplicación de biocarbón y estiércol de pollo, solos o en combinación, aumentó el pH del suelo, los contenidos de calcio, fósforo, zinc y manganeso, así como las concentraciones foliares de potasio y calcio. Por otro lado, a pesar de la fertilización, no observamos ganancias significativas en el crecimiento de las plántulas de *A. rosaeodora* hasta diez meses después de la siembra. La combinación de biocarbón y estiércol de pollo mostró el mayor impacto y, por lo tanto, es un aliado importante para la sostenibilidad del suelo y el desarrollo de las plantas en suelos tropicales.

Palabras clave: Aniba rosaeodora, nutrición vegetal, suelos amazónicos, silvicultura.

INTRODUCTION

Rosewood (*Aniba rosaeodora* (Ducke)), which belongs to the Lauraceae family, is a tree species commonly found in dry land forests in the Brazilian and International Amazon regions. This species has great economic importance in the region because of its different tree compartments. An essential oil rich in linalool is extracted by distillation, which is widely used in the cosmetics and perfumery industries worldwide (Amusant *et al*. 2016, Krainovic *et al*. 2018).

Currently, this plant is in danger of extinction, and cultivation in plantations is beginning to be viewed as a financially viable commercial option. In addition, plantations can be a means of reducing exploitation pressure on natural rosewood populations. The management of planted trees is the only way to meet the demand for this product and guarantee the conservation of this species in its natural habitat (Krainovic *et al*. 2017).

However, despite the agro-industrial potential and economic expression, little is known about the nutritional requirements for the establishment of plantations, which may compromise the initial development of plants in the field, since they occur exclusively in dry land ecosystems, where Latosols and Argissolos predominate, soils characterized by low nutrient content, high acidity, and high aluminum saturation (Moreira and Fageria 2009), and fertilization, when performed, is performed empirically, with no published studies in this regard (Valencia *et al*. 2010).

In recent years, efforts have been made to increase the productivity and sustainability of agricultural production systems, which has stimulated the search for technologies that enhance soils and reduce production costs. Biochar, a product of biomass pyrolysis, has great potential for improving soil fertility and plant growth, especially in regions under humid tropical conditions, including the Amazon (Kloss *et al*. 2014, Falcão *et al*. 2019).

Biochar can be generated from a variety of different raw materials (Singh *et al*. 2022), including organic and industrial wastes (*e.g.* sludge and manure) and plant-based materials (*e.g.* leaves, bark, seeds, cobs, wood chips, and bark). Biochar can also be produced at different pyrolysis temperatures and durations. The combination of feedstock type and pyrolysis conditions allows the production of biochar with diverse physical and chemical properties (Mukherjee and Zimmerman 2013, Mašek *et al.* 2018).

Several studies have reported improvements in soil properties in addition to carbon sequestration related to biochar application. However, the effects of biochar application on soil properties vary depending on the feedstock source and pyrolysis temperature used in pyrolysis (Mukherjee and Zimmerman 2013). In general, several studies have reported that soil chemical properties, such as soil pH (Oliveira *et al.* 2020, Ke *et al.* 2022), cation exchange capacity, organic carbon, electrical conductivity (Beusch *et al.* 2019, Singh *et al*. 2022) and extractable nutrients, increase in response to different types of biochar (Petter *et al*. 2012, Glaser and Lehr 2019, Hossain *et al*. 2020).

However, some studies (Lima *et al*. 2015, Glaser and Lehr 2019) argue that the improvement in soil fertility and plant development provided by BC is greater when it is combined with additional nutrient sources. Therefore, studies using biochar alone or in combination with other sources of nutrients under field conditions in the silvicultural environment are necessary, as there are few published works in the area and, from a practical point of view, much still needs to be studied. The use of biochar in forestry is a technological proposal that aims to capture carbon in the soil and improve its agronomic quality.

In this way, this study has provided information on the management of fertilization of young *A. rosaeodora* plants when planted in field conditions and on the effects of biochar produced from plant residues combined with other fertilizer sources as an environmentally friendly and low-cost innovation to promote plant growth and the quality of soils with low natural fertility. Our results contribute to the appropriate and sustainable management of *A. rosaeodora* in tropical soils, as the use of agro-industrial waste is an important recycling strategy in the search for more sustainable agriculture.

In this study, we hypothesize that (i) biochar, alone or in combination with chicken manure and/or mineral fertilizer, alters soil acidity and promotes plant growth, improving soil chemical properties, and (ii) young *A. rosaeodora* plants respond well to fertilization in the initial growth phase. Therefore, we investigate the effects of biochar, chicken manure, and mineral fertilization on the chemical properties of the soil, concentrations of nutrients in the leaves, and initial growth of *A. rosaeodora* grown under field conditions on a dystrophic Yellow Latosol in Central Amazonia.

METHODS

Study site. The present experiment was conducted at the Tropical Fruticulture Experimental Station of the National Institute for Amazonian Research-INPA, located in the municipality of Manaus, State of Amazonas (latitude 02° 37’ 12’’ S and longitude 60° 02’ 27’’ W, at an altitude of 92 m a.s.l.). According to the Köppen classification, the dominant climate in the region is of the *Af* type (Alvares *et al*. 2013), humid, and rainy tropical. The monthly rainfall distribution and water balance of the study region during the period in which the test was carried out are described in (figure 1).

The soil in the experimental area was classified as LATOSSOLO AMARELO distrófico (Santos *et al*. 2018a), corresponding to the Ferralsol (IUSS Working Group WRB 2014) and Oxisol (Survey Staff 1999), with 352, 550, and 98 g kg^{-1} clay, sand, and silt, respectively, in the 0 - 20 cm layer, and 409, 500, and 91 g kg^{-1} clay, sand, and silt, respectively, in the 20 - 40 cm layer. Soil samples were collected prior to plantation to be chemically characterized at depths of 0 - 20 and 20 - 40 cm (table 1).

Experimental design and conduction of the experiment. The experimental design was in randomized blocks, with five treatments: T1- Control (with no fertilization), T2- 10 t ha^{-1} biochar, T3- 10 t ha^{-1} biochar + 3 kg $plant^{-1}$ chicken manure, T4- 10 t ha^{-1} biochar + 300 g $plant^{-1}$ of formulated N-P-K (04 % - 14 % - 08 %) at planting and 200 g $plant^{-1}$ formulated N-K (18 % - 18 %) in top dressing at 120 days after planting, T5- 10 t ha^{-1} biochar + 3 kg $plant^{-1}$ chicken manure + 300 g $plant^{-1}$ (formulated NPK (04 % - 14 % - 08 %, respectively at planting and 200 g $plant^{-1}$ of (formulated N-K (18 % - 18 %) in top dressing at 120 days after planting) and three replicates.

The experimental plot consisted of three rows of six plants with a spacing of 3 m between rows and 1.5 m between plants. The assessment plot consisted of a central row of four plants. The trial was installed in a second growth vegetation area previously planted with perennial crops, and

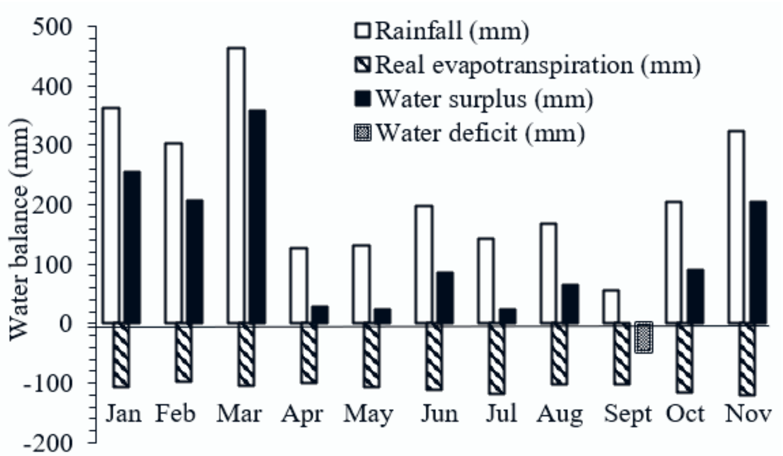

Figure 1. Water balance of the experiment study region from January to November 2021. Source: Data from the National Institute of Meteorology – INMET, Manaus-AM.

Balance hídrico de la región de estudio del experimento de enero a noviembre de 2021. Fuente: Datos del Instituto Nacional de Meteorología – INMET, Manaus-AM.

Table 1. Experimental area soil chemical characterization at 0 - 20 and 20 - 40 cm layers.

Área experimental de caracterización química del suelo en capas de 0 - 20 y 20 - 40 cm.

Depth	pH	Total N	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	P	K	Fe	Zn	Mn	OM	V
(cm)	(H_2O)	g kg^{-1}	$cmol_c$ kg^{-1}				mg kg^{-1}					%	
0 - 20	4.78	1.15	0.99	0.15	0.56	4.86	5.15	15.64	194	3.43	2.09	2.45	24.2
20 - 40	4.63	0.84	0.23	0.09	0.93	4.55	4.20	11.73	222	2.39	0.90	1.79	7.6

pH in H_2O 1:2.5, Ca, Mg and Al: extracted by KCl, H+Al: extracted by calcium acetate, P, K, Fe, Zn and Mn: extracted by Mehlich 1, total nitrogen: determined by the Kjeldahl method, organic matter (OM): determined by the Walkley-Black method, V: saturation percentage by bases.

40 × 40 × 40 cm pits were prepared manually two months prior to planting at the beginning of the rainy season by employing seedlings produced from seeds proceeding from the Adolpho Ducke Forest Preserve. Plants were taken to the field when they were nearly 12 months old, with an average height of 35 cm, 6.3 mm a collar diameter and 10 fully expanded leaves. *A. rosaeodora* plants were covered with palm straw to protect them from direct solar radiation.

During the experiment, cultural treatments, such as control of weeds and pest insects, including locusts (*Schistocera* spp.), whiteflies (*Aleurodicus cocois* (Curtis), and caterpillars (Lepidoptera), were carried out using specific insecticides to controlling these pests. Whenever necessary, the plants were irrigated manually until the field capacity was reached.

Organic Material. Biochar was collected from the tailings deposit of a thermoelectric plant that consumes wood residues located in the metropolitan region of Manaus-AM. The material was produced from sawmill residual biomass with a chemical composition of 47 % ash, 0.62 % K_2O, 0.19 % P_2O_5, 5.16 % CaO, 1.87 % MgO, 28 % Mn, and 0.76 % Zn residual, which was used as the burning fuel in a boiler at a temperature of 900 °C. Chicken manure was obtained from an egg farm and presented the following chemical composition: 1.2 % N, 8.2 % P_2O_5, 3.3 % K_2O, 26.8 % CaO, and 2.15 % MgO. Material chemical property analyses were performed according to the methodology proposed by the Empresa Brasileira de Pesquisa Agropecuária (Embrapa 1999).

Soil fertility. At the end of the experiment, in each treatment, soil samples were collected from 0 to 20 cm depth right near the plant, in the triangular sampling scheme, for their subsequent homogenization and removal of a sample composed of a useful plot.

Samples were crushed, air-dried, and passed through 2.0 mm mesh sieves to determine pH (water), total N (determined by the Kjeldahl method), P, K, Fe, Zn, Mn (Mehlich 1 extractor), and Ca^{2+}. Mg^{2+} and Al^{3+} (KCl extractor 1.0 mol L^{-1}). All analyses were carried out in the thematic laboratory of soils and plants of the National Institute for Amazonian Research and were determined according to the methodology described by Embrapa (1999).

Nutritional status of plants. Concomitantly with soil collection, leaf samples formed by four newly mature leaves per plant, taken at the four cardinal points in the median portion of *A. rosaeodora* were collected in the useful plot. Following collection, they were dried in a forced circulation oven at 65 °C, ground, and chemically analyzed to determine their foliar nutrient concentrations (Malavolta *et al*. 1997).

Total N was extracted by sulfuric digestion, followed by distillation in a micro Kjeldahl apparatus and titration. Macro (P, K, Ca, and Mg) and micronutrients (Fe, Zn, and Mn) were extracted by nitro-perchloric digestion, P was determined by visible spectrophotometry, and macro (K, Ca, and Mg) and micronutrients (Fe, Mn, and Zn) were determined using atomic absorption spectrophotometry (Embrapa 1999).

Growth variables and statistical analyses. The assessed growth variables included height growth (cm), height growth rates (cm $month^{-1}$), growth in stem diameter (mm), stem diameter growth rates (mm $month^{-1}$), and foliar gain. These variables were determined ten months after planting in the field according to the methodology described by Bugbee (1996).

Data were subjected to the Shapiro-Wilk normality test and then to the analysis of variance F test; when there was a significant difference between the means, the Scott-Knott test ($P < 0.05$) was applied using the software statistician R Development Core Team (2022).

RESULTS

Soil fertility. The pH values in H_2O increased in the treatments that received biochar with chicken manure and isolated biochar compared to the control treatment (figure 2A). This increase in pH resulted in a significant decrease in the exchangeable aluminum (Al^{3+}) content in the soil (figure 2B). However, the combination of biochar with mineral fertilizer was similar to that of the control; consequently, there was greater solubility of Al in the soil (figure 2B).

An exploratory analysis of the data revealed that, in general, nutrient content increased in treatments in which biochar was added together with chicken manure (figure 3A-H). The total nitrogen (N) content significantly increased in the treatments with manure and mineral fertilization, whereas in the control (T1) and biochar (T2) treatments, the total N content was considered low (figure 3A). There was greater availability of available P and Ca in the soil in the treatments in which manure and biochar were added in relation to the other treatments (figure 3B and 3D), and these latter treatments showed no statistical difference between themselves; however, it was observed that although there were no significant increases, the treatments that contained only biochar and biochar combined with mineral fertilizer raised the levels of these nutrients to adequate levels, considering their low availability in Argisols and Latosols in the Amazon.

K and Mg contents (figure 3C and 3E) were generally considered "low to medium" according to the criteria of Moreira and Malavolta (2002). However, they were high in all treatments where biochar was applied, although there was only a significant difference in Mg when compared to the control. Regarding micronutrients, Zn and Mn contents were only significantly increased in treatments with the addition of manure (figure 3G and 3H). On the other hand, the Fe content was above the adequate levels in all treatments (figure 3F). According to Cochrane *et al*. (1985), when above 45, they are considered to be "high."

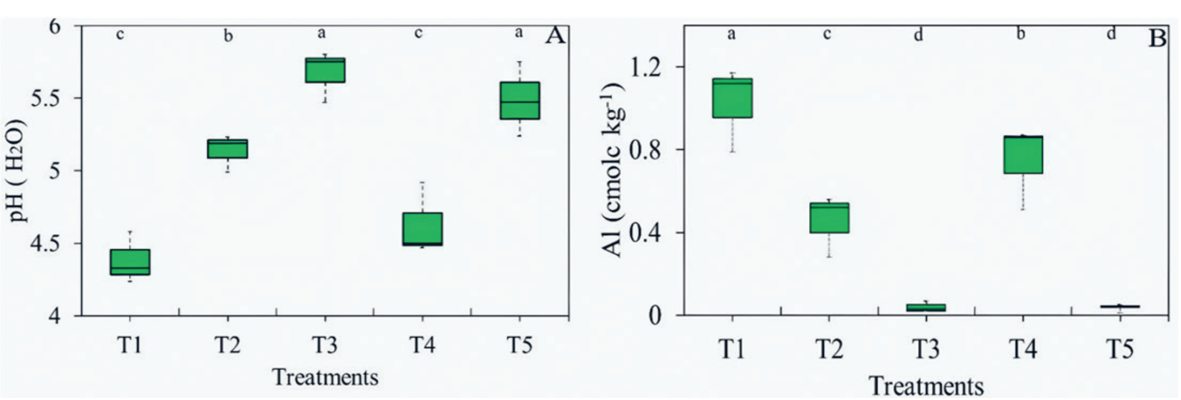

Figure 2. A) pH (H_2O) and B) exchangeable aluminum (Al^{3+}) contents in the soil, 12 months following the treatment application (layer 0 - 20 cm). Treatments: T1: control, T2: biochar, T3: biochar + chicken manure, T4: biochar + NPK and T5: biochar + NPK + chicken manure. Different letters indicate significant values among treatments (Scott-Knott test $P < 0.05$).

Contenido de A) pH (H_2O) y B) aluminio intercambiable (Al^{3+}) en el suelo, 12 meses después de la aplicación del tratamiento (capa 0 - 20 cm). Tratamientos: T1: control, T2: biochar, T3: biochar + gallinaza, T4: biochar + NPK y T5: biochar + NPK + gallinaza. Letras diferentes indican valores significativos entre tratamientos (prueba de Scott-Knott $P < 0,05$).

Visual Characteristics of the Plant and Growth Variables. The growth of *A. rosaeodora* after planting occurred for ten months, and in general, fertilization did not provide significant gains in plant growth (figures 4A-E and figure 5). Based on the visual appearance of the aerial parts of the plants, the control treatment (without fertilization) did not contrast negatively with the plants that received some type of fertilization (figure 4A).

During this period, the plants showed an average increment in absolute growth in height ranging from 29 to 41 cm and in diameter from 4.5 to 5.8 mm (figure 5A and 5C), with an average monthly growth rate in height and diameter between 3 and 4.1 cm and 0.5 to 0.7 mm, respectively (figure 5B and 5D).

Nutritional status of plants. We observed that there was a significant increase in leaf concentrations of K and Ca

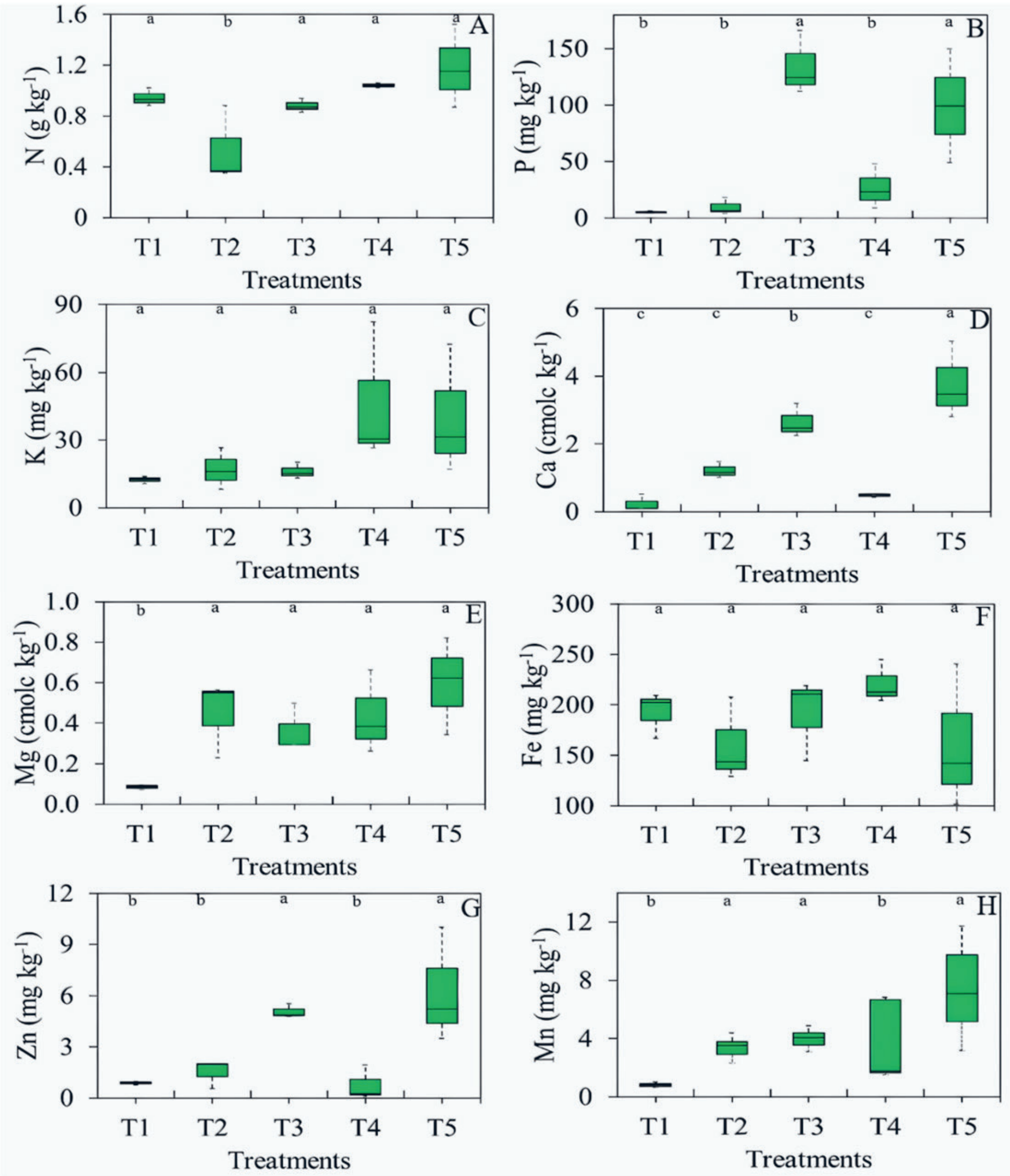

Figure 3. Nutrient contents: A): total nitrogen (N), B): phosphorus (P), C): potassium (K), D): calcium (Ca), E): magnesium (Mg), F): iron (Fe), G): zinc (Zn) and H): manganese (Mn) in the soil after 12 months of treatment application (layer 0 - 20 cm). Treatments: T1: control, T2: biochar, T3: biochar + chicken manure, T4: biochar + NPK and T5: biochar+ NPK+ chicken manure. Different Letters indicate significant values among treatments (Scott-Knott test $P < 0.05$).

Contenido de nutrientes: A): nitrógeno total (N), B): fósforo (P), C): potasio (K), D): calcio (Ca), E): magnesio (Mg), F): hierro (Fe), G): zinc (Zn) y H): manganeso (Mn) en el suelo después de 12 meses de aplicación del tratamiento (capa 0 -20 cm). Tratamientos: T1: control, T2: biochar, T3: biochar + gallinaza, T4: biochar + NPK y T5: biochar+ NPK+ gallinaza. Letras diferentes indican valores significativos entre tratamientos (prueba de Scott-Knott $P < 0,05$).

(figure 6C and 6D) in the treatments with manure and in Mn concentrations in the treatment (T4) (figure 7C). The concentrations of other nutrients were not significantly affected by the treatment**.** Among the macronutrients, N presented higher concentrations in the rosewood leaves than in the other nutrients, with 13.84 - 17.02 g kg^{-1} variation (figure 6A). Regarding P levels, this species showed low extraction of this macronutrient, with concentrations ranging from 0.72 to 1.36 g kg^{-1} in the biochar treatments combined with mineral fertilization and the control treatment, respectively (figure 6B).

K concentrations were significantly influenced by the treatments, with values varying between 4.50 and 10.28 g kg^{-1} (figure 6C). Ca showed high absorption and proved to be a very important element for this species having a similar behavior to that of K (figure 6D). On the other hand, significant increases in Mg concentrations were not observed with concentrations ranging from 1.63 to 2.08 g kg^{-1} (figure 6E).

As for micronutrients, high Fe concentrations ranging from 925 to 1,300 mg kg^{-1} were found in leaves (figure 7A), and Zn concentrations did not significantly increase in treatments with fertilization (figure 7B), whereas, for Mn concentrations, a greater amount of this nutrient was extracted from plants in treatments with high acidity (figure 7C).

DISCUSSION

Soil Fertility. The Increases in pH and Al content neutralization in treatments T2, T3, and T5 can be attributed to both chicken manure and ash contained in biochar, which are rich in potassium, calcium, and magnesium oxides, among other ions, which can change soil pH by substituting H^{+} and Al^{3+} ions in the soil exchange complex, contributing to the formation of precipitates in the case of Al^{3+}. Increases in pH due to application to the soil of biochar, isolated or combined with other material sources, were observed by Petter *et al*. (2012) and Oliveira *et al*. (2020), ratifying the potential of biochar as a soil acidity corrector to be employed as an alternative to higher-cost limestone compounds in highly acidic soils.

However, the low efficiency of the combination of biochar and mineral fertilizer in reducing soil acidity is

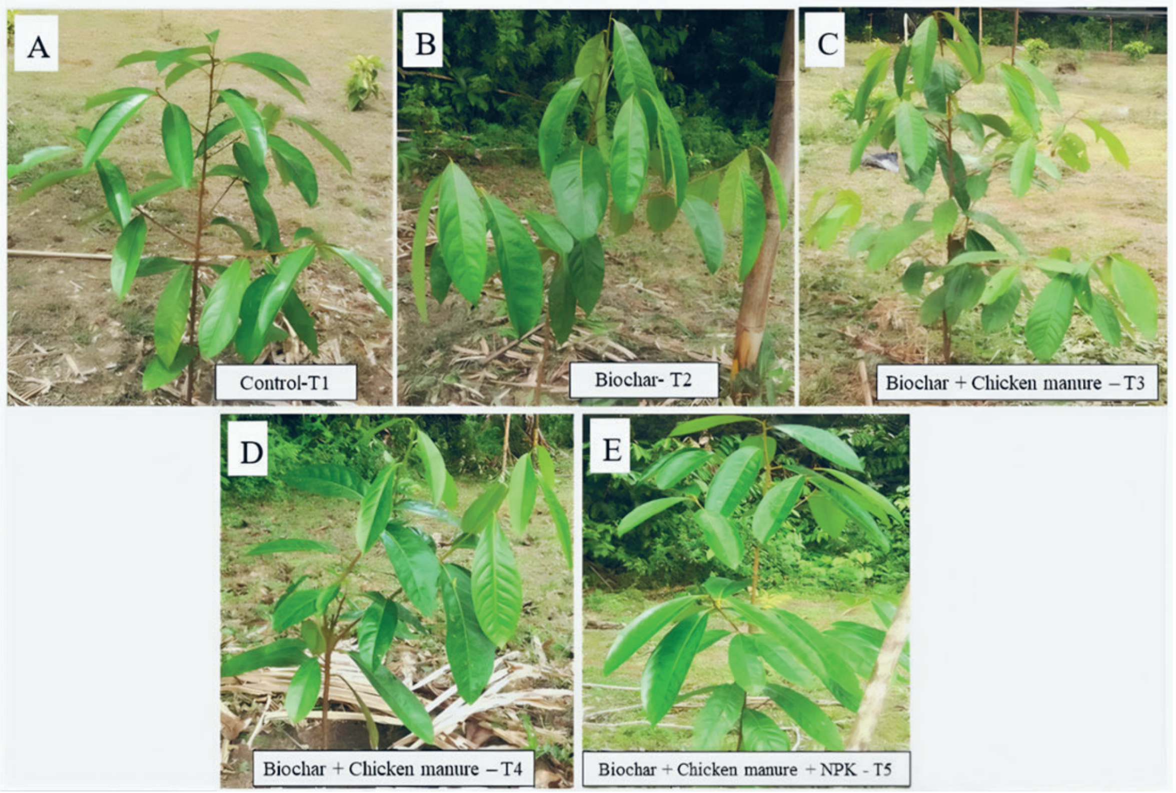

Figure 4. Visual appearance of *Aniba rosaeodora* plants subjected to different fertilization treatments: A) T1: control, B) T2: biochar, C) T3: biochar + chicken manure, D) T4: biochar + NPK and E) T5: biochar + NPK + chicken manure. Plant images were recorded 300 days after planting.

Aspecto visual de plantas de *Aniba rosaeodora* sometidas a diferentes tratamientos de fertilización: A) T1: control, B) T2: biochar, C) T3: biochar + gallinaza, D) T4: biochar + NPK y E) T5: biochar + NPK + gallinaza. Las imágenes de las plantas se registraron 300 días después de la siembra.

probably due to the application of mineral fertilizer at high doses, since the use of nitrogen fertilizers causes soil acidification as they release H^+ ions in their reaction with the soil. Van Zwieten *et al*. (2010) observed that the application of biochar increased the soil pH considerably, whereas the combination of biochar and mineral fertilizer decreased it further.

The increase in N levels in treatments T4 and T5 probably occurred as a result of the application of mineral fertilization in these treatments and the total N found in chicken manure in the latter. However, there was a lower N concentration in the T2 treatment; a similar behavior was found by Alburquerque *et al.* (2013), who observed biochar presence-induced N availability losses. According to these authors, this may be related to the very nature of biochar, which has a low nitrogen content, high adsorption capacity, and low mineralization rates.

There was an increase in K levels in treatments that received mineral fertilization; however, no statistical difference was noted for the other treatments. In general, the application of both biochar and chicken manure was insufficient to increase the levels of this macronutrient. One of the factors that may account for this behavior may be the low concentration of this nutrient in biochar due to its high temperature causing these losses. Keiluweit *et al*. (2010) reported that low-temperature pyrolysis (< 550 °C)

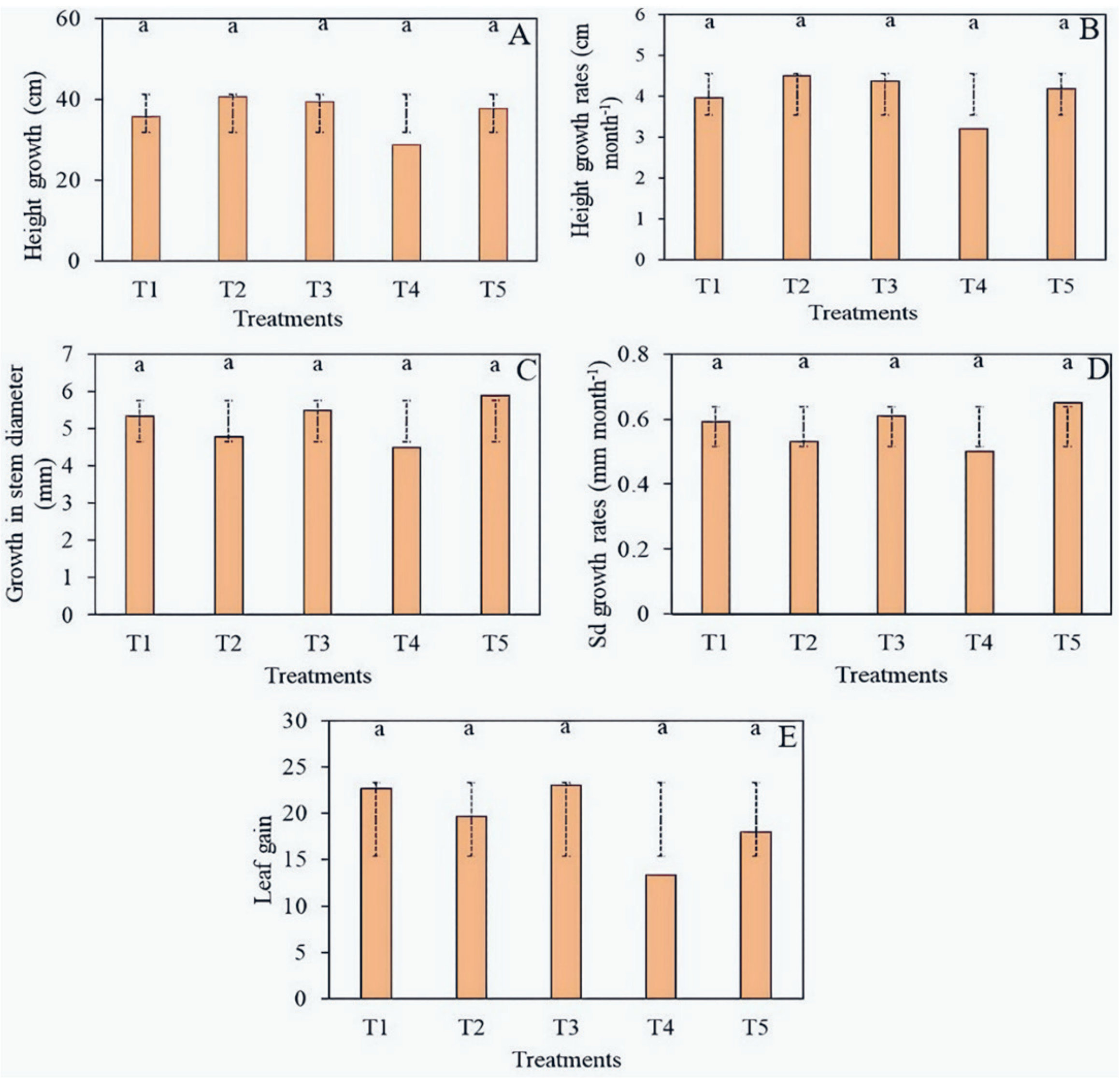

Figure 5. Mean values and standard deviation of A) height growth (cm), C) growth in stem diameter (mm), B) height growth rates (cm month^{-1}), D) stem diameter growth rates (mm month^{-1}) and E) leaf gain of *Aniba rosaeodora* plants under different fertilization treatments (T1: control, T2: biochar, T3: biochar + chicken manure, T4: Biochar + NPK and T5: Biochar + NPK + chicken manure).

Valores medios y desviación estándar del A) crecimiento en altura (cm), C) crecimiento en diámetro del tallo (mm), B) tasas de crecimiento en altura (cm mes^{-1}), D) tasas de crecimiento del diámetro del tallo (mm mes^{-1}) y E) ganancia de hojas de plantas de *Aniba rosaeodora* bajo diferentes fertilizaciones tratos (T1: testigo, T2: biochar, T3: biochar + gallinaza, T4: Biochar + NPK y T5: Biochar + NPK + gallinaza).

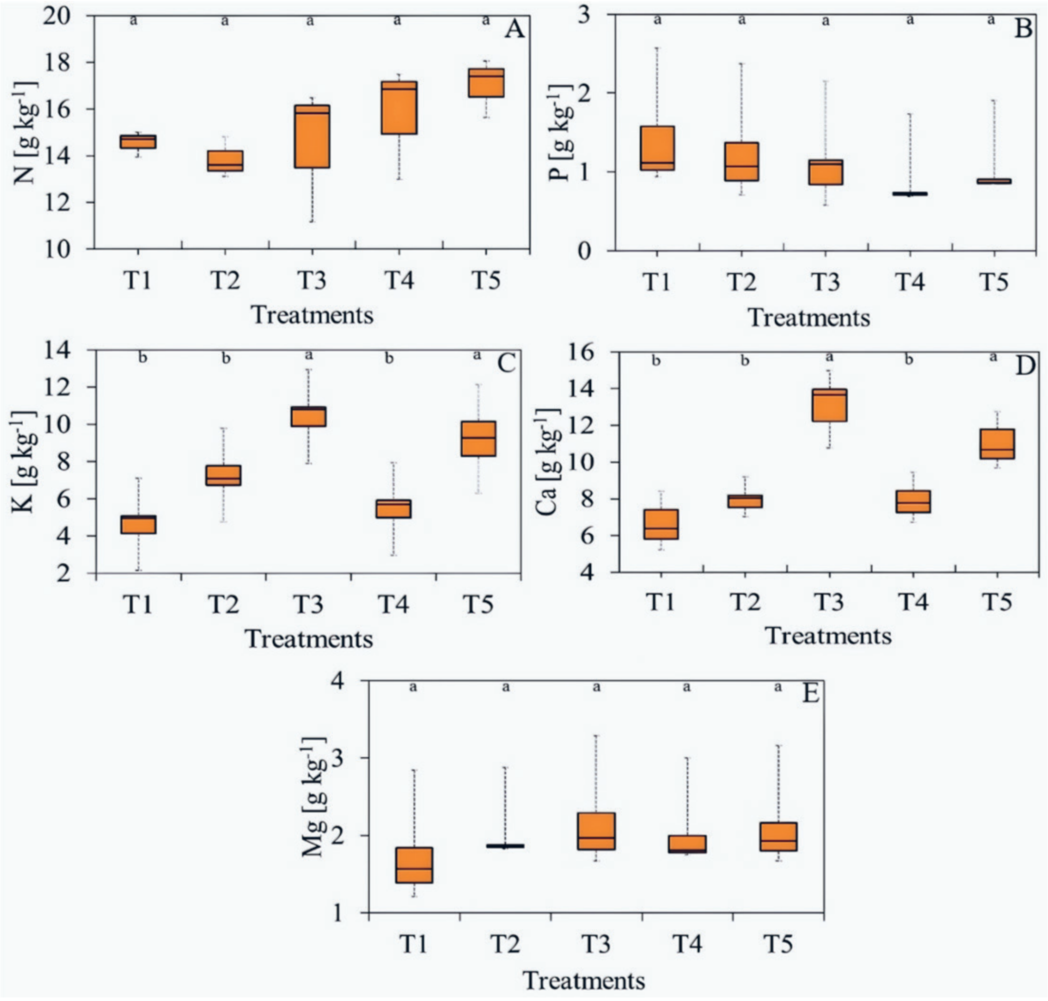

Figure 6. Mean nutrient concentrations in *A. rosaeodora* leaves at ten months following planting with application of different fertilization treatments. Treatments: T1: control, T2: biochar, T3: biochar + chicken manure, T4: biochar + NPK and T5: biochar+ NPK+ chicken manure. Different letters indicate significant values among fertilization treatments (Scott-Knott Test $P < 0.05$).

Concentraciones medias de nutrientes en hojas de *A. rosaeodora* a los diez meses de la siembra con aplicación de diferentes tratamientos de fertilización. Tratamientos: T1: control, T2: biochar, T3: biochar + gallinaza, T4: biochar + NPK y T5: biochar+ NPK+ gallinaza. Letras diferentes indican valores significativos entre tratamientos de fertilización (Prueba de Scott-Knott $P < 0,05$).

favors a greater recovery of C and several nutrients, which are increasingly lost as the temperature increases. A second explanation for the low availability of K in the soil in the treatments that contained sources of this nutrient may be related to leaching, since this macronutrient, when present in the soil solution, moves vertically, mainly by mass flow, and can be transported to depth, mainly during periods of high rainfall (see figure 1).

The significant increases in available P and Ca in treatments T3 and T5 can be explained by the significant amounts of these nutrients present in the chicken manure added to that found in biochar. Regarding the T2 treatment, it was noted that, although not statistically different, there was an increase of 89 and 426 % in P and Ca contents, respectively, compared to the control, which can be attributed to the application of biochar. Glaser and Lehr (2019) suggested that biochar could be considered a phosphorus source for low-fertility soils.

Petter *et al.* (2012) state that the application of eucalyptus biochar under field conditions positively affected soil fertility, mainly increasing the availability of Ca and P. Considering that approximately 80 % of the P applied, through soluble phosphate fertilizers, on Brazilian soils, are adsorbed into colloidal soil particles, resulting in its low agronomic efficiency (Raij 2011), biochar can be an important "ally" in the process by reducing costs with these fertilizers.

The application of both biochar and manure increased Mg levels relative to those of the control, however, they were still classified as "low" to "medium" according to the criteria of Moreira and Malavolta (2002). These low levels are possibly due to the low concentrations detected in the

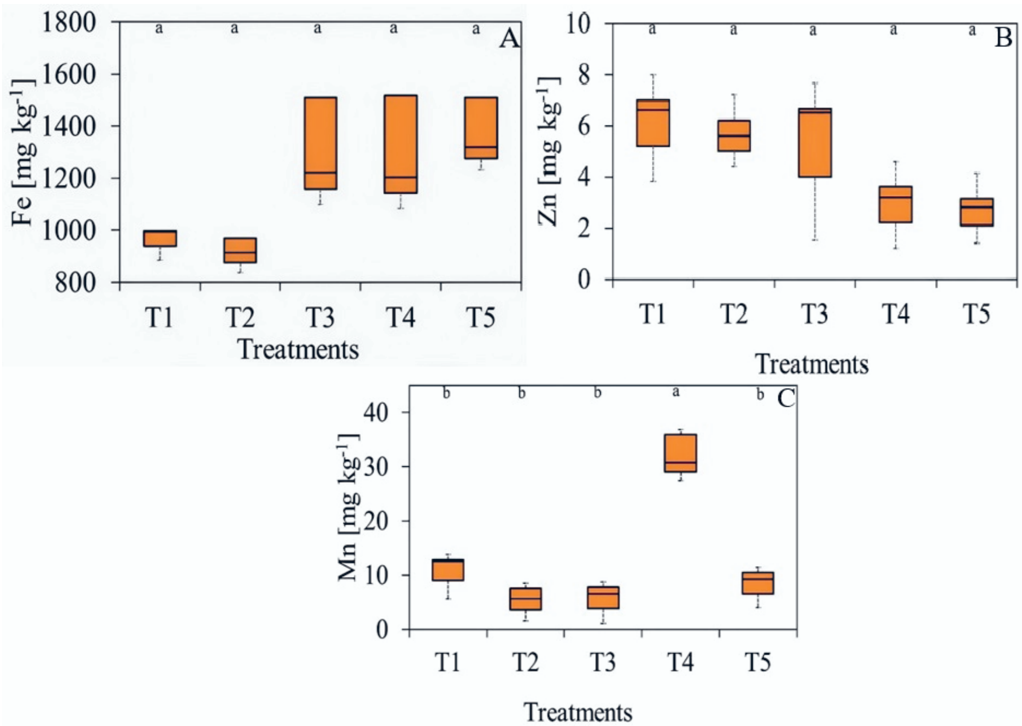

Figure 7. Mean nutrient concentrations in *A. rosaeodora* leaves at ten months following planting with application of different fertilization treatments. Treatments: T1: control, T2: biochar, T3: biochar + chicken manure, T4: biochar + NPK and T5: biochar+ NPK+ chicken manure. Different letters indicate significant values among fertilization treatments (Scott-Knott Test $P < 0.05$).

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organic material, in addition to its possible leaching due to the intense rains that occurred during this period. The quality of BC depends on the type and source of the raw material used for its production, as well as on the conditions used for heat treatment (Mendez *et al*. 2013).

Regarding micronutrients, the highest Zn and Mn levels observed in treatments with the addition of BC and chicken manure, in general, may have been provided by the application of organic materials, especially manure. However, the high Fe values observed in all treatments may reflect the high content present in both natural soil (control) and organic material sources. High iron oxide levels are not desirable in tropical soils, as according to Fink *et al*. (2016), they confer high phosphorus adsorption capacity.

Growth variables. The absence of significant gains in growth is evidence of the low responsiveness of this species to fertilization during the initial growth phase. This may have been due to the low species nutritional requirement, which is only supplied with the nutrients present in the soil organic matter. Despite their contents being in the medium class, according to the Soil Fertility Commission of the State of Minas Gerais (CFSEMG 1999), its mineralization would be sufficient to maintain the initial growth of the plant in the field. Another explanation is that, in contrast to pioneer species, which have reduced growth potential when developing in loa fertility soils, the climax shade-tolerant ecological group, to which *A. rosaeodora* species belong to, has the growth stimulus provided by the less pronounced and sometimes non-existent fertilization, which is attributed, in part, to the slower growth of the species belonging to this group. This difference in behavior between climax and pioneer species is partly due to the fact that pioneer species have a more developed root system and a greater density of fine roots ≤ 2 mm in diameter (Addo-Danso *et al*. 2020), which provides higher rates of growth and nutrient absorption.

However, Valencia *et al.* (2010) in a study with omission of nutrients in a greenhouse and in different fertility environments, observed the *A. rosaeodora* growth to be affected in the absence of N, Ca and Mg. In contrast they observed no significant response to P and K, Neves (2019), evaluating the effect of increasing N doses on the production of *A. rosaeodora* seedlings in a controlled environment, noticed their response to this nutrient. These results are in contrast to those of the present assay. Nevertheless, according to the same author, the best results occurred with low nitrogen doses when the negative effects of high nitrogen fertilization doses were observed.

On the other hand, when comparing species with some successional group similarity and native to the Amazon region, such as mahogany (*Swietenia macrophylla* King) submitted to fertilization with increasing doses of N, P, and K in increasing doses, (Tucci *et al*. 2011) observed no significant growth gain was observed in any of the treatments, when compared to the control. These authors report that slow-growing species bear a low response to the supply of nutrients, a characteristic, in some cases, related with the mechanism of adaptation to the Amazon region's poorly fertile soils. Similar results were found by Ferreira *et al*. (2012), who, when working in a field with *Bertholletia excelsa* Bonpl., observed that they failed to differ from those of the control during eight months of testing with chemical fertilization treatment.

This latter species behavior corroborates that found in the present study, confirming a general, low response potential trend for climax species in the initial growth phase. However, this work should be considered a pioneer in field conditions for this species, and to confirm this premise, more work should be carried out under these conditions, which would allow for a more consistent inference regarding the fertilization management of this species.

Plant nutritional satus. The high N concentration in rosewood plants compared to other nutrients may result from the functions of this nutrient in the plant. Normally, N is the most demanded nutrient because it acts on amino acids, proteins, enzymes, and secondary product molecules (Bang *et al*. 2020). The N foliar concentrations found in these treatments, despite there being no known standard adequate sufficiency range values for *A. rosaeodora*, were below the values found by Valencia *et al*. (2010) and Neves (2019) in work with this species seedlings in a greenhouse.

Regarding P concentrations, one notes that *A. rosaeodora* did not seem to demand much of this nutrient. In a study on nutrient omission in a greenhouse, Valencia *et al*. (2010) observed that the P suspension failed to compromise plant performance compared to the treatment with complete fertilization. These authors suggest that species have a low nutritional requirement for this nutrient-evincing characteristic of plant adaptability to low, natural fertility soils. Marschner (1991) stated that P is poorly available in tropical soils, and the growth efficiency with this low availability is the resource the plant uses for adapting to these soils.

The present study shows that K and Ca absorption is significantly favored and precisely follows the increase in the levels of these macronutrients in the soil, as detected in the soil analysis. Kerbauy (2004) claimed that K foliar concentrations, which are considered adequate for forest species growth, should be around 10 g kg^{-1}, whereas Malavolta (2006) suggested that for Ca, the minimum foliar concentration indicated as suitable for forest species should be 5.0 g kg^{-1}. Considering these references, one notes that plants only presented ideally considered concentrations in treatments containing chicken manure.

Leaf concentrations of Mg failed to differ among the studied treatments for up to ten months after planting. Low absorption was likely due to its limited availability in the soil, as observed in (soil fertility) section. Valencia *et al*. (2010) observed that the absence of Mg limits the growth of the species during the seedling phase in a controlled environment.

Among the micronutrients, *A. rosaeodora* was demonstrated to be very demanding of Fe, since it presented high foliar concentrations in all the studied treatments. This high extraction rate can probably be attributed to the high values present in the sources of organic fertilization and soil of the experimental area prior to planting, indicating the non-limitation of this nutrient, which is involved in the biosynthesis of cytochromes, coenzymes, and chlorophyll. Assuming that the average amounts for adequate plant development are between 50 and 100 mg kg^{-1} (Kerbauy 2004, Dechen and Nachtigall 2006), Fe concentrations were above these values in all treatments.

In general, foliar Zn and Mn concentrations decreased in treatments in which the soil acidity was reduced. Similar behavior has already been found in some studies, which related soil acidity to foliar micronutrient concentration reduction, since the absorption of these elements by plants decreases with increasing pH due to the formation of low-solubility oxides and hydroxides formation (Roque *et al*. 2004).

Despite adequate nutrient concentrations being adequate (Dechen and Nachtigall 2006), in some treatments, no apparent symptoms of visual impairment of these nutrients were observed during the experimental period in some treatments. Furthermore, it is important to highlight the lack of studies in the scientific literature that point to critical nutritional deficiency levels for this species.

The results of this study revealed the absence of or low response potential of this species to fertilization in the initial growth phase, which suggests that it has adaptation mechanisms to the low natural fertility soil conditions of the region. In addition, since this is a climax species and a work in progress, more time for evaluation and studies are needed to verify the greater effect of fertilization on plant development. On the other hand, BC proved to be an excellent soil conditioner, helping improve its chemical characteristics.

CONCLUSIONS

In this study, the use of sawmill residual biomass (10 t ha^{-1}) had a positive effect on the behavior of different soil properties for the production of *A. rosaeodora*. In addition, our results showed that the combination of biochar and chicken manure led to an increase in pH and neutralization of Al^{3+} as well as an increase in soil levels of Ca, P, Zn, and Mn. It also increased foliar concentrations of K, Ca, and Fe in *A. rosaeodora*. Our findings expand our knowledge of how biochar improves soil quality, particularly in tropical soils.

In contrast, *A. rosaeodora* showed little response to fertilization up to ten months after planting. However, it is necessary to provide essential elements for plant growth, given the metabolic damage caused by their absence.

This study suggests that the use of biochar produced from sawmill waste biomass (10 t ha^{-1}) combined with chicken manure (6.66 t ha^{-1}) could be an alternative to improve the quality of soils with low natural fertility and help with solid waste management. Finally, this combination also offers a complementary option for the nutrition of this crop, which would reduce the levels of chemical fertilizer applications.

AUTHOR CONTRIBUTIONS

JCCF: Experimental setup and data collection, laboratory analysis, formal analysis, interpretation of results, and writing; ABPS and RPR: experimental setup, data collection, and laboratory analysis; RBA: laboratory analysis and writing; HMSR: Contributed to the setup of the experiment and formal and statistical analyses; DMO and NPSF: Guidance and supervision of work; discussion and interpretation of results.

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