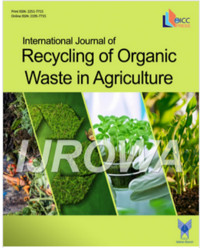

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Effects of biochar on the chemical properties of soils and the volume of wood in a plantation of *Acacia mangium* Willd in the Colombian Orinoquía (highlands)

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Original Research

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Abstract:

Purpose: Exploring alternatives to mitigate soil degradation has been gaining importance in recent years. Biochar promises to improve properties such as soil fertility and soil conditioning. This research involved an experiment with different levels of biochar in associating it with some chemical properties and the wood yield of *A. mangium*.
Method: We used a design including nine treatments and three repetitions of each treatment, employing two materials: biochar from *Acacia mangium* W. (BAM) and synthetic fertilizer (SF). We used a Bayesian principal component analysis to reduce dimensionality, and the two extracted dimensions were labeled by treatment to visualize their grouping. We validated the grouping using cluster analysis algorithms. Volume in wood was used as the response, and the same soil variables were used to run a regression by partial least squares where the explanatory variables were characterized by relative importance.
Result: We found an increase in the different chemical variables of the soil analyzed in treatments with BAM and BAM + SF and an increase in the volume of the stem of the trees in treatments with BAM + SF. The analysis by partial least squares showed how the EC and SOC variables were the most important in explaining the volume of wood.
Conclusion: Responses of the different variables analyzed increased with the addition of biochar, either alone or mixed with synthetic fertilizer. It was also possible to determine that the volume of *A. mangium* wood was influenced by soil chemical variables.

Keywords: Wood volume; Soil nutrients; Organic residues; Biochar; Bayesian statistics; Least squares

1. Introduction

Different anthropic activities and natural processes that intervene in the soil can lead to land degradation, which can cause progressive deterioration of soil quality. In the establishment of agroecosystems, there has been a continuous deterioration of the soil, especially from the point of view of its chemical properties, which translates into losses of agricultural productivity reflected in lower yields and more significant environmental problems (Jensen et al., 2020).

Land degradation, represented by erosion, desertification, salinization, cementation, and compaction, has all increased in recent years, especially in areas close to large cities and areas of agricultural and mining development (Pacheco et al., 2018). The Colombian Orinoquía, with an approximate area of 25 million hectares, occupies 22.16% of the national territory and has soils with a predominance of Oxisols and Ultisols (Rodriguez-Hernandez et al., 2023), characterized by a high degree of evolution and high quantities of iron and aluminum, all of which promote phenomena such as cementation and acidity. In the herbaceous savannas, the biomass input is scarce (2.2 to 3.8 tons ha^{-1} $year^{-1}$) (Rao et al., 2001). But for about five decades, the possibility has been described that it could be increased to 28 tons ha^{-1} $year^{-1}$ or more, depending on other coverages depending on the rainy regime, length of the dry season and available nutrients (Lamotte, 1987). In addition, the same could happen when agronomic practices are established to improve plant varieties for adaptability purposes. In terms of the main colloid of the soils, in kaolinic clay, as the main exchanger, the oxyhydroxides of Fe and Al predominate, integrated 2:1:1, with interlaminar aluminum, pyrophyllite, and gibbsite, which come from dominant processes of ferralization (formation of Oxisols: Haplustox (19.6%), Hapludox (14.5%), as prototypes, and some Haplaquox and Haploperox), which leads to high acidity, transformation and loss of elements: Ca, Mg, K, Na, and Si, among others (IGAC, 2007).

Such unfavorable conditions to produce food and fiber make it necessary to look for alternatives, such as adding organic materials that can improve the soil's physical, chemical, and biological properties. These components are a fundamental part of the different stages of soil evolution, where through aggregation and a vast metabolic network, the biodiversity increases, and a continuous flow of matter and energy is ensured to ensure a homeostatic system (Abujabhah et al., 2016).

Regarding applying these organic materials in the soil, biochar emerges as an alternative with great potential for fertility and soil conditioning with a high recovery of organic waste that can be used to increase agricultural production and mitigate climate change. Particularly in developing countries, this technology could help increase fiber production and contribute to the recovery of soils (Bernal et al., 2014). The basic process of pyrolysis in lignified materials such as wood includes the heating of organic materials in the absence of oxygen above 400 °C. With these temperatures, the materials decompose thermally releasing two phases; a vapour and a solid residual phase (biochar). The production yield in pyrolysis, such as the slow one, is approximately in the order of 35% for biochar, 30% bio-oil, and 35% for gas (Laird et al., 2009).

This research's objective was to study the effects of biochar obtained through pyrolysis of pruned biomass of *Acacia mangium* on the chemical properties of soils and the volume of wood in a plantation of *Acacia mangium* Willd in the Colombian Orinoquía.

2. Materials and methods

Experimental site

The study was conducted between 2017 (a) (b) and 2018 (a). This research was carried out in a plantation of *A. mangium* located in the village of Planas, department of Meta (Colombia), whose coordinates lie between 3°05′ and 4°08′ N and between 71°05′ and 72°30′ W. The study area is in the Colombian Orinoquía (highlands), specifically in the savanna with a modified area of a forest agroecosystem of *A. mangium* with an area of 2000 ha. The area has an average annual temperature of 30 °C. The climate is seasonal, with a dry season from 2 to 5 months (between November and March-April) (Armenteras et al., 2021). The climates of the region are characterized by having a bimodal regime of drought from January to May with high rainfall in the subsequent months of June to December (Table 1).

Soil sampling and test setup

Sampling was carried out as follows: a) the establishment of a rigid grid of 72 × 30 m; b) within the grid, the establishment of 27 plots of 8 m × 10 m, each plot established as a treatment with three repetitions; c) in each of these, batches of 6 samples taken [1]; d) the points where the soil samples were taken were located 20 cm from the *A. mangium* trees; e) an initial sample was collected (without the addition of any material) and used as a comparison control in the statistical analysis; f) samples were taken at a depth of 20 – 40 cm and then taken to the laboratory for analysis; g) a sample from each batch was considered as the experimental unit for the application of the different doses of the two materials to be evaluated in the treatments.

Allometric measurements of the *A. mangium* plants were taken one year after adding the treatments in the soil to evaluate the dry weight and volume of the trees. Dry weight was calculated by drying (in an oven at 70 °C) the branches, stems, and foliar parts (aerial part) of two trees chosen randomly in each treatment. After 72 hours of drying, the plant material was weighed (Fonseca et al., 2009).

For volume, a methodology was chosen based on the irregular shape of the trees. Volume was calculated using the truncated cone volume equation (Villegas and Marlats, 2005). For this estimate, measurements of the height and radii of the lower and upper bases of the stem were taken. A caliper and diameter tape were used for the measurements of the radii and the height.

To avoid excessive estimations of the stem's volume and compensate for measurement errors, the diameter was measured in centimeters and adjusted in a decreasing or increasing direction depending on the case (for example, 16.2 cm becomes 16 cm for more precision in the result).

Experimental design

For this research, we established a design of 9 treatments and three repetitions for each one, using two materials: 1) Acacia mangium biochar (BAM) (Table 2) and 2) synthetic fertilizer (SF), generating nine mixtures: T1) control, without application of both materials, T2) 50% of SF and 0 ton ha^{-1} of BAM, T3) 100% of SF and 0 ton ha^{-1} of BAM, T4) 0% of SF and 40 ton ha^{-1} of BAM, T5) 50% of SF and 40 ton ha^{-1} of BAM, T6) 100% of SF and 40 ton ha^{-1} BAM, T7) 0% of SF and 80 ton ha^{-1} of BAM, T8) 50% of SF and 80 ton ha^{-1} BAM, T9) 100% of SF and 80 ton ha^{-1} of BAM. The BAM came from residues from thinning and pruning the *A. mangium* plantation. BAM

1. ten months after the planting of *A. mangium* plants transfer to the text

Table 1. Climatic variables from the period 2013a-2018a taken at the Carimagua station. Municipality of Puerto Gaitán. Department of Meta*.

	Solar brightness average (hours)						Precipitation (mm)						Temperature (°C)					
	2013	2014	2015	2016	2017	2018	2013	2014	2015	2016	2017	2018	2013	2014	2015	2016	2017	2018
Jan	274.2	207.7	198.5	225.3	205.4	196.3	0	4	30	0	3	5	27.9	27.6	28	27.5	28	27.5
Feb	156.4	204.5	205.4	200.1	206.4	203.8	15	3	3	2	4	3	28.7	29.3	27.6	28.4	27.8	27.5
Mar	141.4	159.3	143.5	150.4	146.3	153.2	30	NA	50	30	60	45	28.1	29	28.5	28.6	28.5	28
Apr	149.8	118.8	146.3	127.3	136.4	133.4	140	55	70	50	55	60	27.8	25.9	26	26.5	27	27.5
May	133.2	144.2	155.6	142.8	147.5	146.4	62	NA	30	20	40	35	27.1	26.3	26.5	27	27.5	27.8
Jun	NA	79.3	86	87.4	90.6	88.4	NA	75	35	20	10	25	26.2	25	25.5	26.5	27	27.2
Jul	99.7	114.6	118.5	110.4	112.5		108	80	40	45	15		25.2	24.9	25	26	25.8	
Aug	130.1	129.2	134.6	129.5	127.5		62	20	40	45	40		25.3	24.8	25	26	25	
Sep	151.6	NA	NA	162.8	153.7		99	60	40	50	NA		26	25.5	26.5	26	26.8	
Oct	NA	NA	97.5	98	95.7		128	80	30	54	40		26.8	NA	26	27	26.7	
Nov	206.4	145.7	166.5	156.7	159.7		115	70	100	30	NA		27	27.4	26.5	27	26.8	
Dec	155.7	NA	160.6	164.8	160.4		NA	55	20	30	30		26.9	NA	28	28	28	

* NA: Non-Available.

Table 2. *Acacia mangium* W. biochar (BAM) analysis.

Variable	Units	Results
Cation Exchange Capacity (CEC)	$cmol^{+}\ kg^{-1}$	10.87
Organic Carbon	%	42.29
Organic Matter	%	91.78
Carbon: Nitrogen ratio	p:p	52.99
pH	$-\log[H^{+}]$	7.10
Electrical conductivity	$dS\ m^{-1}$	0.37
Total Nitrogen (N)	%	0.80
Ammoniacal Nitrogen (NH):	%	0.005
Nitric Nitrogen (NO)	%	0.003
Phosphorus (P)	%	0.04
Potassium (K)	%	0.25
Calcium (Ca)	%	0.20
Magnesium (Mg)	%	0.03
Sulfur (S)	%	0.38
Sodium (Na)	%	0.028
Manganese (Mn):	ppm	83.5
Iron (Fe)	ppm	2309.9
Cooper (Cu)	ppm	10.4
Zinc (Zn)	ppm	13.6
Boron (B)	ppm	9.1

was prepared under slow pyrolysis with residence times of 14 hours and temperatures between 350 and 400 °C in a pyrolysis oven located at the plantation. BAM levels were based on Jeffery et al. (2011) and Wolf et al. (2013), who estimated an average of 50 tons ha^{-1} for applying this material for an increase of 18%–28% in crop yield on a global scale. The recommended application for acacia biochar was 47 tons ha^{-1} (Eyles et al., 2015). The SF was triple-fifteen: 15% total nitrogen, 15% soluble phosphorus and neutral ammonium citrate, and 15% water-soluble potassium. The equivalent in kilograms for the doses of BAM (40 and 80 ton ha^{-1}) in each plot was 320 and 640, and in grams for the (SF) was 100 g $plant^{-1}$ for 100% and 50 g $plant^{-1}$ for 50% (Fig. 1).

Laboratory analyses were performed for the soil chemical variables initially and for the treatments at the end of the study (Table 3). The data matrix was made up of a series of 20 response variables (CEC -Cation Exchange Capacity-, Al, Ca, B, EC, Cu, Fe, SOC -Soil Organic Carbon-, OM -Organic Matter-, K, Mg, Mn, total N, Na, P, Zn, DM -Dry Mat-ter-, Pw, saturation, and volume) measured on the experimental units where the nine treatments were randomized with their respective repetitions. The design used was associated with a simple factorial arrangement (unifactorial) with nine treatments in a completely randomized arrangement.

Many responses in the data matrix made it necessary to reduce the dimensionality to work with, at most, two Bayesian principal components (PCAB), which is another variant of the "usual" linear principal component analysis

Figure 1. (A). Culture of *A. mangium*; (B). Slow pyrolysis oven; (C) Biochar of *A. mangium* residues.

Table 3. Initial soil analysis*.

pH	CE	N total %	P	K	Ca	Mg	Na	Al	Fe	Mn	Cu	Zn	B
4.7	0.1	11.5	1.6	13.3	11.3	5	7.3	0.79	14.5	0.31	0.2	0.1	0.1

* Units for major and minor elements in mg kg^{-1} or ppm. Al in $cmol^{+}$ kg^{-1}.

(PCA); only now a priori is imposed, and the base selection mechanism is codified. The "do.bpca" function of the Rdimtools R library follows Bishop's original article stating that the effective dimensionality of the latent space (number of retained principal components) can be determined automatically by Bayesian inference.
An advantage of PCBA over conventional PCA is that a probability distribution is defined by a maximum likelihood solution of a specific latent variable model, first introducing a q-dimensional latent variable x whose prior distribution is Normal with mean zero, that is, $p(x) = N(0, I_q)$, where I_q is an identity matrix of dimension $q \times q$. Next, the observed variable t is defined as a linear transformation of x with additive Normal noise, that is:

$$t = Wx + \mu + \varepsilon \quad (1)$$

Where W is dimension $d'q$, μ is a vector of length d, and ε is a vector of null means and covariance $s^2 I_d$, thus.

$$p(t) = \int p(t|x)p(x)\,dx = N(\mu, C) \quad (2)$$

With $C = WW' + s^2 I_d$, where W' is the transpose of W. By applying the maximum likelihood estimate (ML), the estimators μ_{ML}, W_{ML}, and σ^2_{ML} are obtained. The density in (2) represents the probabilistic formulation of the usual PCA. Finally, the Bayesian treatment is obtained by establishing the prior as $p(\mu, W, \sigma^2)$, thus obtaining the posterior with the observed data D as $p(\mu, W, \sigma^2|D)$ and with the multiplication of the prior (hierarchical in this case) with the likelihood, thus the predictive density to be marginalized on the parameters.
Effective dimensionality is selected based on the number of wi vectors extracted with the library's *mp.w* attribute. In the case of the current investigation, it was obtained with two dimensions since all the vectors became null with three.
Once the two dimensions of the BPCA were extracted, they were labeled by treatment to visualize the grouping of the treatments with only the application of the algorithm. These initial clustering results were validated with two additional techniques, namely cluster analysis, for which four classification algorithms, CLARA, K-means, PAM, and FUNNY, were used. All these suggested seven clusters as obtained in the BPCA. A graph was made to visualize agreement in the number of suggested clusters, and the clusters per response were represented only using the CLARA method (but any of the others could be used). Finally, validation was closed with a univariate analysis of variance (after review-ing the necessary assumptions of variance homogeneity using the Barlet test and normality of residuals using the Shapiro test). The two extracted BPCAs were not used due to their perfect linear relationship, so only univariate analysis was performed. Subsequently, the treatments were compared a posteriori of the analysis of variance with the Tukey test with p values adjusted for the number of comparisons. The final graph for the comparison represents all the pairs of comparisons and their distance to a null difference between each pair.
The final analysis involved the volume of wood as a response and the remaining soil variables as explanatory. Partial least squares regression (PLS regression) was used to find a linear regression by projecting the predictor and observable variables to a new space. Partial least squares regression was used to model the covariance structure in these two spaces (response and explanatory). The method builds new predictor variables known as special-form components, considering the response variable. The technique allows the construction of a graph of the importance of the variables to explain the answer that can guide a discussion of the results. It should be noted that the measure of the importance of the variables is based on the weighted sum of the absolute regression coefficients. Weights are a function of the reduction in sums of squares between the number of PLS components, and they are calculated separately for each outcome, so the contribution of the coefficients is weighted proportionally to the reduction in sums of squares (Kuhn, 2008).

3. Results and discussion

Soil chemical properties

The diagram of the first two dimensions automatically selected by the algorithm was obtained from the BPCA. In this case, the dimensions were labeled by the respective treatments. Fig. 2 shows two pairs of treatments, T4 (0% SF and 40 ton ha^{-1} BAM) and T7 (0 SF and 80 ton ha^{-1} BAM) (group 4) and T5 (50 SF and 40 ton ha^{-1} BAM) and T6 (100% SF and 40 ton ha^{-1} BAM) (group 5). What corresponds to the T4 (0 SF and 40 ton ha^{-1} BAM) and T7 (0 SF and 80 ton ha^{-1} BAM) treatments can be interpreted by the direct influence of BAM since these are composed only of this material in its two application levels. In T5 (50% SF and 40 ton ha^{-1} BAM) and T6 (100 SF and 40 ton ha^{-1} BAM), the relationship is conditioned by the lowest level of BAM (40 ton ha^{-1}).
The two dimensions of Fig. 2 were extracted to validate their concordance with other techniques. Because of a lack of training and test data, they corresponded to an experiment with three repetitions per treatment. The embedded observations corresponded to the values of the axes. The matrix of dimension $27'2$ was used as an input in four classification algorithms: K-means, PAM (K-mediodes),

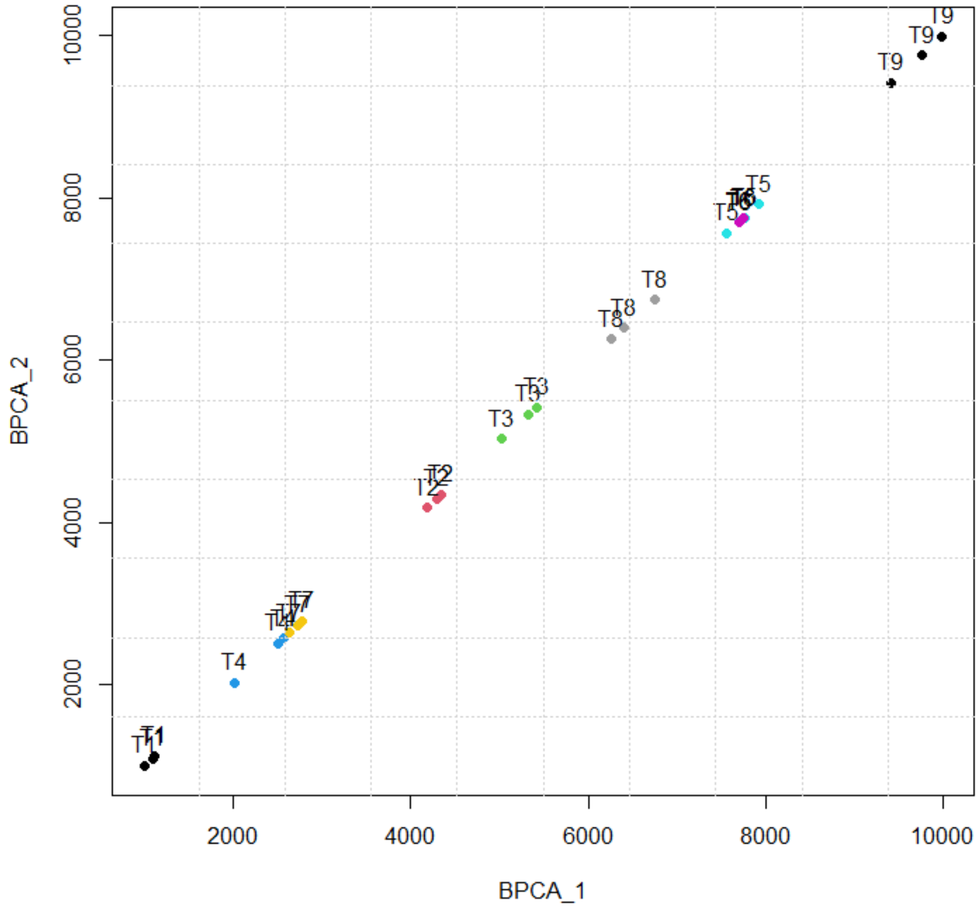

Figure 2. Two first extracted Bayesian principal components.

CLARA (Clustering Large Applications), and FANNY. The four suggested seven clusters corresponded to the groups that are formed in Fig. 1. Fig. 3 shows the silhouette diagrams of each classification algorithm and the number of clusters suggested with the dotted line.

The CLARA algorithm was selected, which randomly creates multiple fixed-size subsets from the original dataset and applies the same medoid-based algorithm (PAM), thus using each observation in the dataset of the closest medoid to generate the mean of the dissimilarity of the observations concerning the closest medoids used as a measure of goodness of fit using the Euclidean distance (Kaufman and Rousseeuw, 1990).

The cluster analysis results using CLARA and for the seven groups formed according to Fig. 3 can be seen in Fig. 4. The grouping was generated for each response to describe it individually. The clear grouping obtained with BPCA is evident; however, in some answers, it is more evident than in others.

Finally, continuing with the validation, this time using analysis of variance, only one of the embedded observations in the Fig. 4 was used as a response (since the linear relationship between the two was evident enough to perform a bivariate analysis of variance). Thus, a univariate analysis of variance was performed with the nine treatments after reviewing the assumptions of normality (Shapiro R test) and equality of variances (Bartlet R test). The results once again allowed us to assert that the data provided evidence against the null hypothesis of null effect. So, Tukey's mean comparison method was finally applied with the Tukey HSD function of R. Fig. 5 shows the results of this comparison, where again, the excellent concordance obtained with BPCA, cluster analysis, and ANOVA on the first dimension of the BPCA can be seen.

The greatest difference in the treatments was between T1 (control) and T9 (100 SF and 80 tons ha^{-1} BAM), corresponding to the control and the treatment with higher levels of BAM and SF. Other significant differences were found between treatments T6 (100 SF and 40 tons ha^{-1} BAM), T5 (50 SF and 40 tons ha^{-1} BAM), and the control. These differences mark a clear trend between the increase in the different variables with a mixture of BAM and SF concerning the control (without applying the two materials). In comparisons between the different treatments that contain BAM, the greatest significant difference was found between treatments T9 (100 SF and 80 tons ha^{-1} BAM)

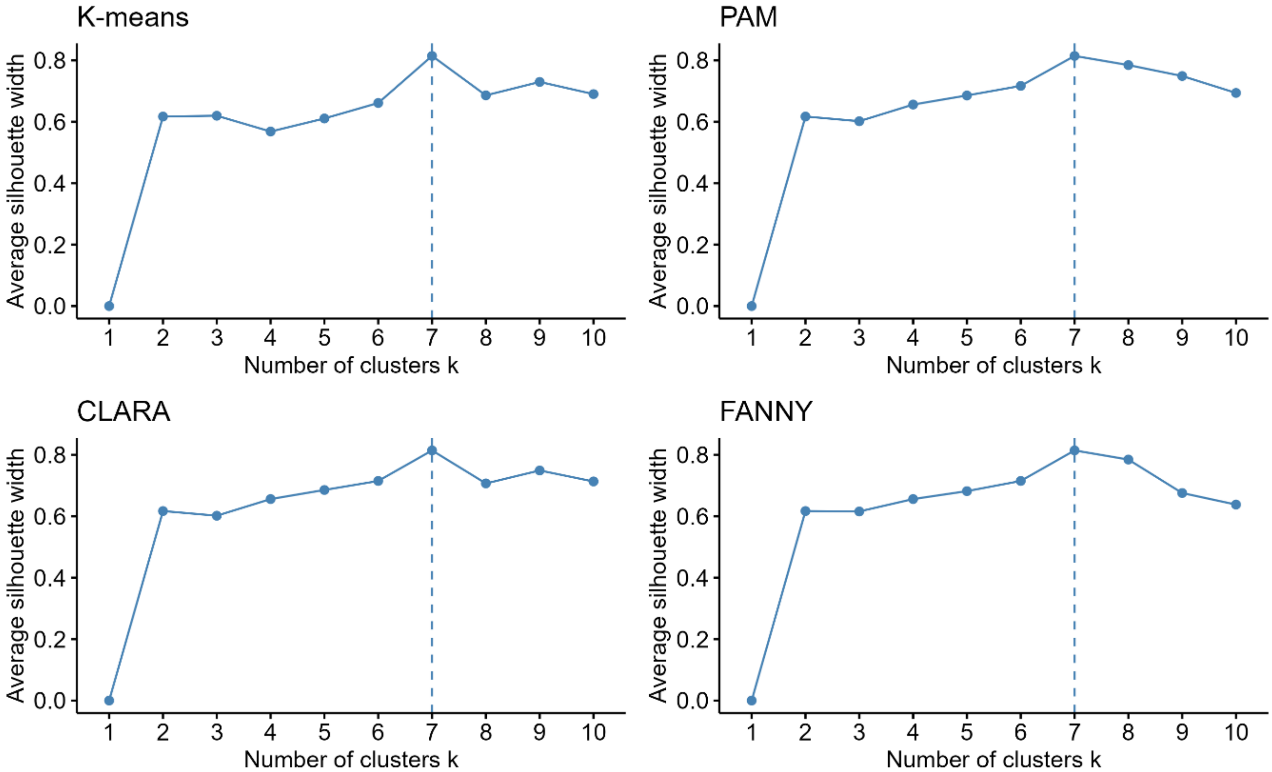

Figure 3. Classification algorithms used in the dimensions extracted by BPCA.

and T4 (0 SF and 40 tons ha^{-1} BAM) (Fig. 5). Surely, this difference was marked by the addition of SF in T9 (100 SF and 80 tons ha^{-1} BAM) concerning T4 (0 SF and 40 tons ha^{-1} BAM), to which only BAM was applied at its lowest level.

In the analysis of variables such as OM and SOC responses with a greater increase were found in the T4 (0 SF and 40 tons ha^{-1} BAM) and T7 (0 SF and 80 tons ha^{-1} BAM) treatments that would correspond to a causal relationship of the application of BAM to the soil since biochar itself is "dehydrated" organic material (Fig. 4). Likewise, OM can indirectly contribute to soil fertility through better soil structure, which improves germination, optimal plant root growth, improved water relations, and reduced erosion (Rasul et al., 2022).

High CEC concentrations of the T4 (0 SF and 40 tons ha^{-1} BAM), T7 (0 SF and 80 tons ha^{-1} BAM), and T9 (100 SF and 80 tons ha^{-1} BAM) treatments may be associated with an increase in OM (Fig. 4). Heitkotter and Marschner (2015) find positive associations between organic matter and CEC, a significantly higher trend per unit of organic carbon in the soil, compared to adjacent forest soils. In addition to higher CEC potential associated with higher organic matter content, trends of significantly higher CEC per unit of soil organic C are also observed in these soils compared to adjacent forest soils (Heitkotter and Marschner, 2015).

The increase in CEC in these treatments could be attributed to adding biochar. Evidence suggests that biochar application increases some soil properties. Lin et al. (2012) and Rajkovich et al. (2012) suggest this increase (particularly with biochars produced from slow pyrolysis) that organic functional groups are maintained that increase the CEC in the soil. Yamato et al. (2006) found an increase in CEC in corn and soybean crops after including the biochar in soil from *A. mangium*. If, in the present investigation, CEC was increased in treatments with biochar, the retention and availability of nutrients in the soil would be improved, influencing the volume and yield in the plants of these treatments.

One might think that plant residues are of little nutritional value through the action of microorganisms for the plant when they are included in the soil since they are degraded and transformed by chemical reactions that give rise to simpler products such as ammonium, nitrate, and nitrous and nitric oxides (Gonawala and Jardosh, 2018). Biochar plays a fundamental role by contributing or retaining elements by finding the highest amount of total N in the substrate in the treatments with BAM (T4 (0% SF and 40 tons ha^{-1} BAM) and T7 (0% SF and 80 tons ha^{-1} BAM)) in this research (Fig. 4). During the biochar pyrolysis process, three nutrient-related scenarios can be generated: 1) elements such as N and compounds such as different oxides -NO- found on the surface can be volatilized; 2) other nutrients can be concentrated in the biochar matrix; or, 3) soluble oxides can be released (Gundale and DeLuca, 2006).

Some authors find that biochar could be more linked to the transformation of nutrients than to their delivery to the soil. Prendergast-Miller et al. (2011), Spokas et al. (2012), Taghizadeh-Toosi et al. (2012), Ventura et al. (2013) established that biochar, due to its high surface area, can

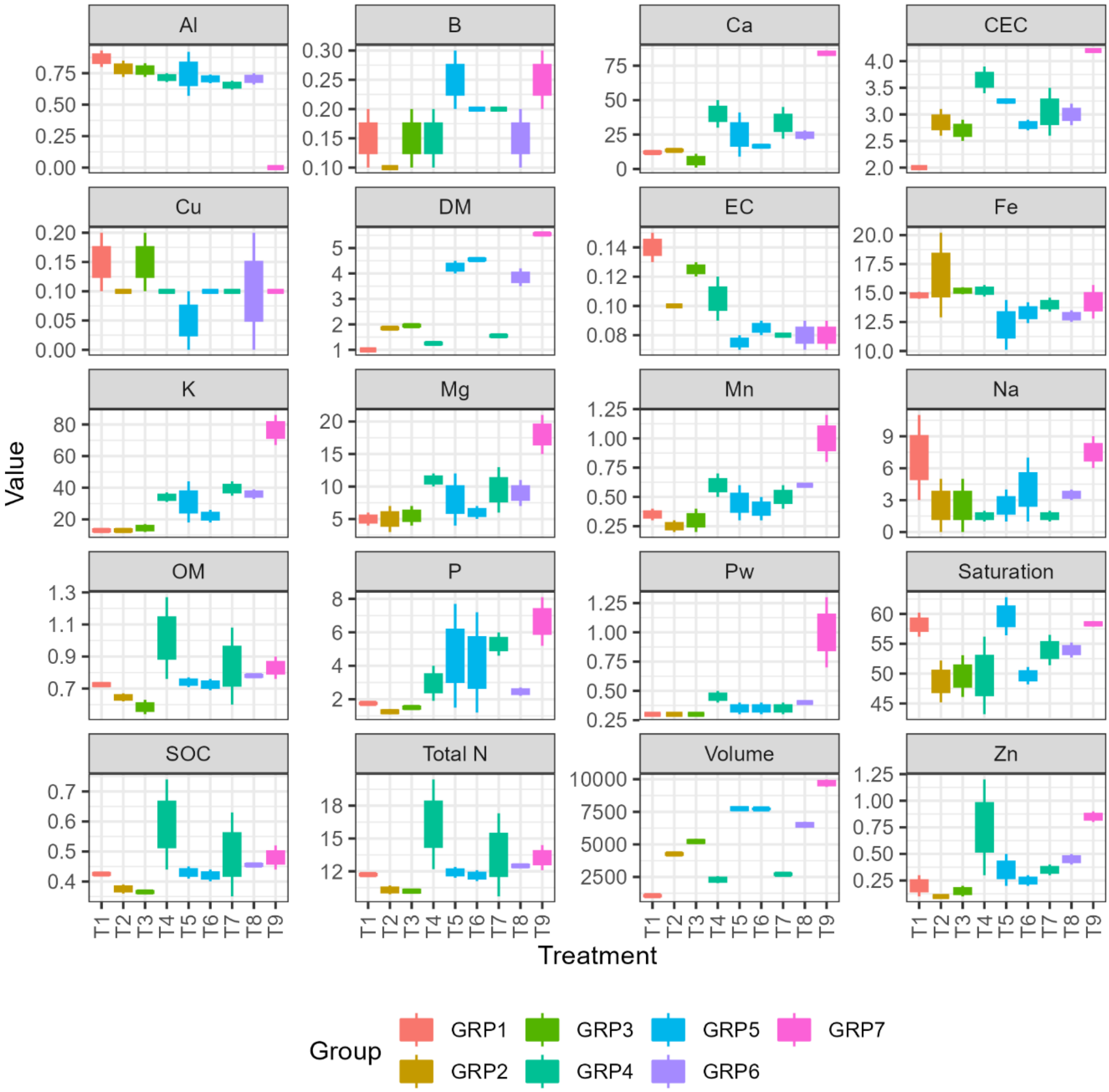

Figure 4. Classification using the CLARA algorithm into seven groups per response.

reduce the leaching and volatilization of elements that would increase the availability of nutrients available in the soil. In the case of this research and considering that the T4 (0% SF and 40 tons ha^{-1} BAM) and T7 (0% SF and 80 tons ha^{-1} BAM) treatments were made up of only BAM, we assumed that the biochar could act by retaining (through its retention through a high surface area) the N found naturally in the ground. The application of biochar helps the transformation of nitrogen and improves its availability. Palviainen et al. (2018) showed that with the addition of biochar in forest and agricultural soils, there is a greater increase of nitrification in the forest soils. The percentages of total N found in the biochar treatments could be due to the immobilized N. In some research, it has been possible to establish a great capacity of biochar to immobilize N for the plant initially, which could have three causes: 1) mineralization of the weakest or most labile parts, 2) ammonium adsorption, or 3) carbon sequestration by biochar micropores.

Biochar may contain ashes that have elements that are more soluble and accessible to plants than those included in the residues of the biochar. These elements could explain the favorable contribution in the short term to the production of different crops (Bernal et al., 2014). These ashes mainly contain a considerable number of exchangeable cations. Cations with higher valences are retained more strongly. The most dehydrated will be the most strongly fixed; K fixes stronger than Na and Ca more than Mg (Solly et al., 2020). In our research, higher values of K were found in treatments with BAM compared to treatments without this material, while similar values were found for Ca and Mg, both in treatments with and without BAM. Consistent with

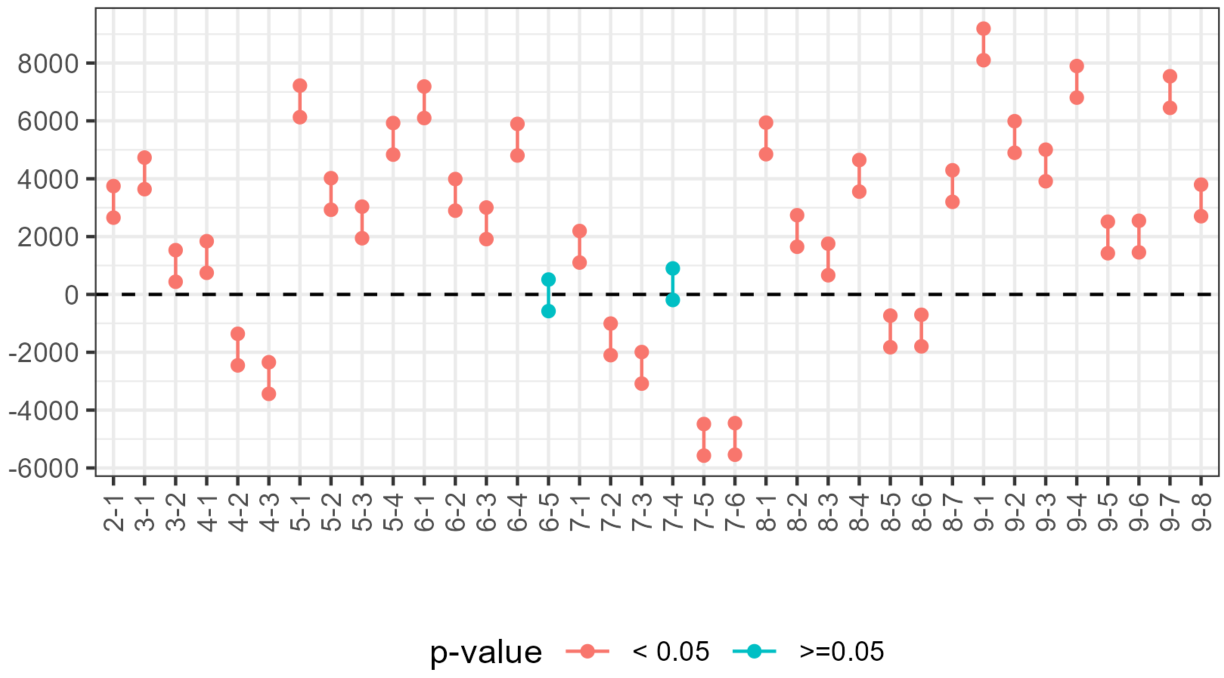

Figure 5. Comparison of treatments.

our research, Li et al. (2021) found that wood biochar's contain high amounts of metal oxides such as CaO, MgO, Fe_2O_3, TiO, and CrO in their ashes, which could be explained by the fact that once the biochar encounters soil water, these ashes become solubilized. The catalytic oxides remain attached to the active surfaces of the biochar (Blanco-Canqui, 2017). However, these surfaces with oxidized elements can adsorb NH_4^+ or NH_3. This increase in base retention could be mainly because, as the biochar ages, its surface begins to lose positive exchange sites while the negative sites increase (Duan et al., 2019).

Another factor that would be linked to the increase in nutrients in biochar treatments in the substrate is the type of pyrolysis. Slow pyrolysis (lower temperatures) increases the availability of nutrients (N, Ca, P, Mg, B, and Zn, in our research) compared to fast pyrolysis. In this sense, Spokas et al. (2012) established that slow pyrolysis produces biochars with higher amounts of available N, S, P, Ca, Mg, and CEC than fast pyrolysis. The reason why these elements remain in the biochar could be related to the volatilization rates with increasing temperature. In wood biochar, the beginning of the volatilization of the elements is estimated as follows: C at 100 °C, N above 200 °C, S and K above 375 °C, P between 700 and 800 °C and Ca, Mg, and Mn above 1000 °C (Beyers et al., 2005). In this sense, the biochar produced in the present study (through slow pyrolysis) could maintain nutrients such as K, P, Ca, and Mg.

Treatments with mixtures of BAM and SF and with only BAM represented the highest levels of P (Fig. 3). Laboratory studies suggest that biochar induces an increase in the addition of phosphates (Yang et al., 2021). The P can be controlled by cations such as Al, Fe, Ca, and Mg when the biochar increases or decreases the pH (Sarfraz et al., 2020). The availability of P is between 0.4% and 34% in the total biochar. In general, in the present study, elements such as N, P, Ca, Mg, and Ca were increased in treatments with biochar (T4 (0% SF and 40 tons ha^{-1} BAM), T5 (50% SF and 40 tons ha^{-1} BAM), T6 (100% SF and 40 tons ha^{-1} BAM), T8 (50% SF and 80 tons ha^{-1} BAM), and T9 (100% SF and 80 tons ha^{-1} BAM)) compared to those that contained only SF. With these results, Lehmann et al. (2021) observed an increase in the adsorption of elements such as P, K, Ca, Zn, and Cu when biochar is added to the soil in tropical crop soils.

Reyes et al. (2021) estimated that when biochar mixtures with synthetic fertilizers are used, the same crop yields can be obtained with a lower dose of conventional fertilization than in crops where the conventional or optimal fertilization dose is applied. Steiner et al. (2008) found higher yields in crops fertilized with the mixture than in control, represented by plots with only synthetic fertilizer, in studies of different plots with sustained additions of biochar and NPK. Rechberger et al. (2017) stipulated that applying biochar to the soil can improve certain chemicals and physical properties (CEC, pH increase, water retention). Our research shows a positive correlation between the volume and variables such as K, P, Mg, Mn, and CEC, as high values are also found in T5 (50 SF and 40 tons ha^{-1} BAM), T6 (100 SF and 40 tons ha^{-1} BAM), and T9 (100 SF and 80 tons ha^{-1} BAM) (Fig. 3).

One of the causes where the BAM could provide a greater capacity for photosynthesis, increased assimilation in the phloem, greater stomatal opening, and increased C is a greater amount of K in part of the plant, which is because this element is fundamental in stomatal movements and the

osmotic potential of the plant (Marschner, 2011).
Nutrient retention could be relative in terms of time; it would depend on long- or short-term oxidation once the biochar is introduced into the soil and interacts with the environment (Duan et al., 2019). Contrasting results in studies of fresh and aged biochars by (Jindo et al., 2020) show that aged biochars have higher retention of inorganic nitrogen, for example. Similarly, biochar can, directly and indirectly, influence the behavior of P in the soil through factors such as the alteration of enzymes for its solubilization, the formation of organomineral complexes that increase P solubility, and changes in the microbiological community (Bornø et al., 2018).

Correlation of wood volume and soil chemical properties

In the final analysis, the graph of the importance of the explanatory variables to explain the volume of wood can be seen in the following Fig. 6.
It is essential to specify that the importance graph does not interpret the highest values of the variables. These can be subjective values, i.e., these values can act positively or negatively. Contrasting these variables with their value in the different treatments is necessary. In this sense, we consider that the importance (within the variable-volume correlation) of EC in this study is negative concerning volume since T9 (100% SF and 80 tons ha^{-1} BAM), T5 (50% SF and 40 tons ha^{-1} BAM), and T6 (100% SF and 40 tons ha^{-1} BAM) have the lowest values of EC, but high-volume levels of wood (Fig. 6). This can be interpreted as a detriment in water relations from high electrical conductivities in treatments with low values of wood volume (Fig. 4 and Fig. 6). Hossain et al. (2011), Jones et al. (2012), and Ventura et al. (2013) found increases in EC with the addition to the soil. In the analysis of SOC in the correlation with the volume of wood and the different treatments, the graph of importance suggests that it has a positive interpretation in those treatments such as T5 (50% SF and 40 tons ha^{-1} BAM), T6 (100% SF and 40 tons ha^{-1} BAM), and T9 (100% SF and 80 tons ha^{-1} BAM) have high values for SOC and the volume of wood. Likewise, the SF at its application level (100%) could also be a determinant for the increase in volume in the stem of the trees. Without values lower than 70% concerning T5 (50% SF and 40 tons ha^{-1} BAM), T6 (100% SF and 40 tons ha^{-1} BAM), and 100% at T9 (100% SF and 80 tons

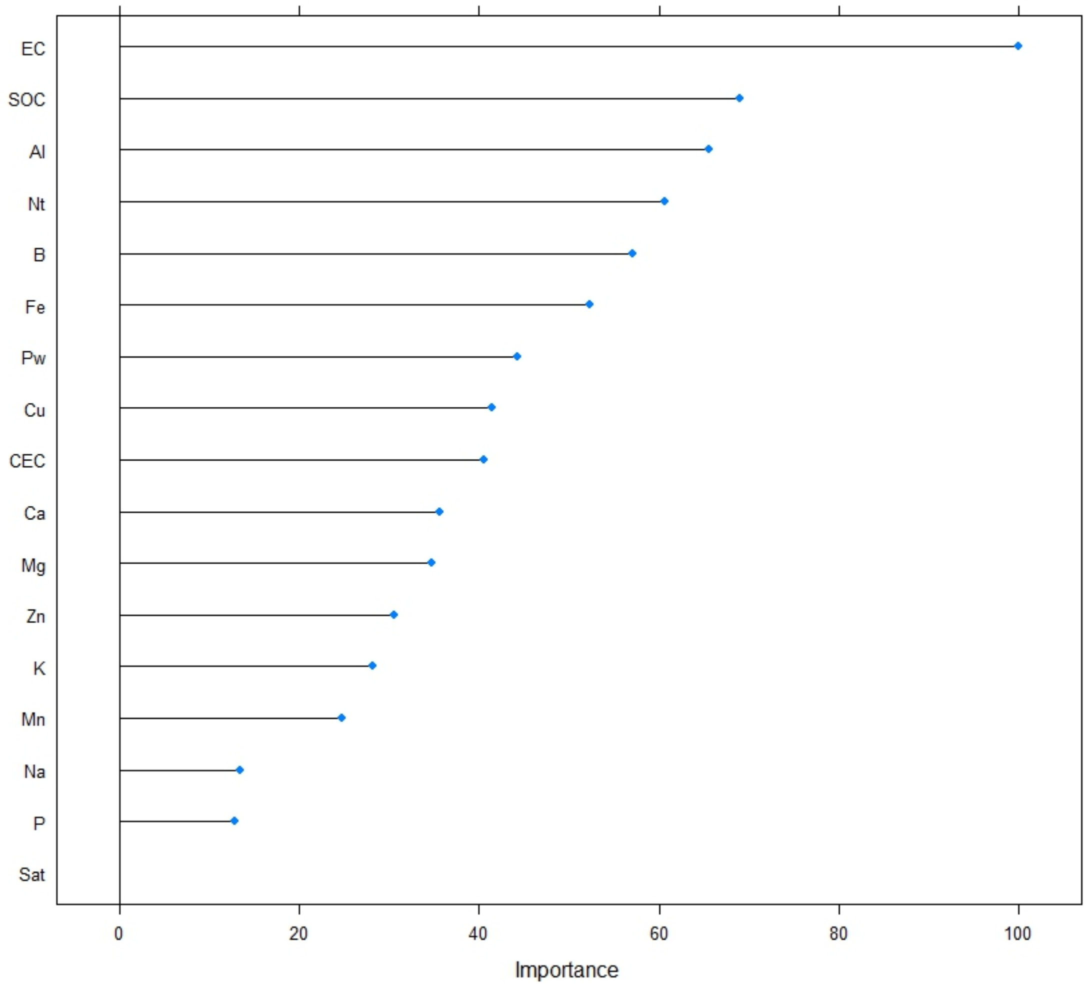

Figure 6. Partial least squares regression importance plot for wood volume in *A. mangium*.

ha^{-1} BAM) being possible, however, in the comparison of these treatments with T3 (100% SF and 0 tons ha^{-1} BAM) (where it is found to indicate that biochar also plays a fundamental role in the increase of volume and dry weight given the mixtures that make up the treatments), which may be correlated with the high presence of organic carbon, high porosity, and hydroxyl and carboxyl groups in the biochar from *A. mangium* waste (Khan et al., 2021).

4. Conclusion

When finding the grouping in the BPCA of compound treatments with BAM alone or in mixtures, this material influences the increase of the evaluated variables. Likewise, the greatest differences between the response's point of view and the statistical analysis results were favorably found in those treatments with mixtures of BAM and SF concerning the control. These mixtures, especially those composed of the higher levels, can cause an increase in the response of the set of variables considered. Higher values found in the different variables of chemical properties may be associated with an increase in stem volume and dry weight in *A. mangium* trees established in plantations in the region.

Ethical Approval
This manuscript does not report on or involve the use of any animal or human data or tissue. So the ethical approval is not applicable.

Authors Contributions
Giovanni Reyes-Moreno: Conceptualization, methodology, and writing-original draft. Aquiles Enrique Darghan: Formal analysis, methodology supervision, and writing-original draft. Carlos Rivera-Moreno: software, review, and editing. All authors reviewed and approved the final manuscript.

Availability of Data and Materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interests
The authors declare that there are no conflicts of interest associated with this study.

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