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Characterization of the nutrient contents and properties of biochars for agricultural use in the state of Pernambuco

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ABSTRACT

Biochar comes from organic biomass and is used to improve agricultural productivity. However, its variable chemical composition limits its classification and effective use. Thus, the objective of this study was to characterize the nutrient contents and properties of different biochars produced in the southern Agreste region of Pernambuco. The research was developed at the Federal University of Agreste de Pernambuco (UFAPE), where biochars are produced from sewage sludge (B1), grape fermentation (B2), cashew wood (B3), chicken litter (B4) and beans (B5) via a slow pyrolysis process. Standard Embrapa and Iac methodologies were followed in the chemical analyses. Principal component analysis (PCA) was used to identify specific characteristics that made them suitable for use in different soil types. PCA revealed that the first four main components (PC1, PC2, PC3 and PC4) explained 100% of the total data variability. PC1 was defined by variables such as C, H and pH. PC2 was positively correlated with nutrient content and CEC. PC3 and PC4 were positively correlated with K, N, P and Mg. On this basis, the use of B1 is indicated for soils with high levels of organic matter, B2 is indicated for soils deficient in elements such as N and K, B3 and B5 are indicated before its use, its association with other sources of nutrients is necessary, and B4 is recommended for soils poor in P and Ca.

Keywords: principal component analysis, soil fertility, pyrolysis.

Caracterização dos teores de nutrientes e propriedades de biochars para uso agrícola no estado de Pernambuco

RESUMO

O biochar é proveniente da biomassa orgânica, sendo utilizado na melhoria da produtividade agrícola. Entretanto, a composição química variável limita sua classificação e uso eficaz. Desta forma, objetivou-se caracterizar os teores de nutrientes e propriedades de diferentes biochars produzidos na região do Agreste Meridional de Pernambuco. A pesquisa foi desenvolvida na Universidade Federal do Agreste de Pernambuco (UFAPE), onde foram produzidos biochars de lodo de esgoto (B1), fermentação de uva (B2), madeira de cajueiro (B3), cama de frango (B4) e casca de feijão (B5) em processo de pirólise lenta. Foram seguidas metodologias padrões da Embrapa e Iac nas análises químicas. A análise de componentes principais (ACP) foi utilizada para identificar apresentavam características específicas que os tornavam adequados para uso em distintos tipos de solo. Por meio da ACP foi possível identificar que as quatro primeiras

componentes principais (CP1, CP2, CP3 e CP4) explicam 100% da variabilidade total dos dados. A CP1 foi definida por variáveis como C, H e pH. A CP2 se correlacionou positivamente com teores de nutrientes e CTC. As CP3 e CP4 se correlacionaram positivamente com K, N, P e Mg. A partir disso, o uso do B1 é indicado para solos com altos teores de matéria orgânica, B2 é indicado para solos com deficiência de elementos como N e K, B3 e B5 antes do seu uso, é necessária sua associação com outras fontes de nutrientes, e B4 é indicado para solos pobres em P e Ca.
Palavras-chave: análise de componentes principais, fertilidade do solo, pirólise.

Introduction

Biochar is a product resulting from the biomass pyrolysis process at high temperatures, generally ranging between 200 and 1200 °C under conditions of low oxygen input (Farhangi Abriz et al., 2021; Joseph et al., 2021). Under specific temperature conditions, cellulose, hemicellulose, and lignin undergo various reaction mechanisms, such as depolymerization, fragmentation, and bonding, which correspond to new states of charcoal, such as liquid, solid, and gaseous (Singh et al., 2021). Biochar can be produced using various types of reactors, such as paddle furnaces, bubbling fluidized beds, and stirred sand rotary kilns (Sakhiya et al., 2020). In more, this material can be prepared from various raw materials of organic waste, highlighting it can be rich in carbon (Wang & Wang, 2019; Barbhuiya et al., 2024; Gao et al., 2024 Liu et al., 2024; Rambhatla et al., 2025), being the subject of various studies (Ji et al., 2022; Xie et al., 2022; Yadav et al., 2023; Nie et al., 2024; Sadegh et al., 2024; Kang et al., 2025; Sheikh et al., 2025; Yuan et al., 2025).

The use of biochar in agricultural systems increases crop yields and mitigates the environmental externalities of intensive production, such as climate change or carbon loss from the system (Sohi et al., 2010; Jeffery et al., 2011; Wijitkosum & Jiwnok, 2019; Diatta et al., 2020; Alkharabsheh et al., 2021; Brockamp et al., 2021; Wu et al., 2024; Vicente et al., 2025; Waheed et al., 2025). This material can be used in a large number of applications, from heat and energy production to soil correction (Kloss et al., 2012; Weber & Quicker, 2018; Ortiz et al., 2020; Wang et al., 2020; Bolan et al., 2024; Zou et al., 2024). In general, this product has a high specific surface area, high porosity, and good cation exchange capacity, making it suitable for multiple applications, including the reduction of greenhouse gas emissions such as CO_2 and CH_4 (Qi et al., 2020; Lehmann et al., 2021).

The composition of biochar is variable, as it is a solid material of mineral or organic nature and can be used purely or in combination with other materials (Angın, 2013; Li et al., 2016; Muthusamy et al., 2019). Thus, the potential use of biochar in various applications depends on its properties (Qian et al., 2015). Among the factors affecting this product are the type of biomass, temperature, residence time, and thermal efficiency, which can significantly influence the yield and properties of biochar (Agrafioti et al., 2013; Zhang et al., 2015; Debiagi et al., 2018; Leng et al., 2021; Zhou et al., 2021). In this perspective, the higher the temperature in the pyrolysis process, the lower the yield of the biochar produced (Kim et al., 2012; Ippolito et al., 2015; Ponnusamy et al., 2020; Gotore et al., 2024). The increase in pyrolysis temperature can result in an increase in the pH of biochar as a result of the addition of ashes (Song & Guo, 2012; Leng et al., 2021). This increase, when temperatures are above 500 ºC, results in an increase in hydrophobicity, specific surface area and total volume of micropores, which makes biochar sensitive to the removal of organic pollutants (Lee et al., 2013; Sakhiya et al., 2020).

This variability is a factor that makes it difficult to determine their physical and chemical characteristics, as there is no standard classification in the literature (Islam et al., 2021). The multifaceted potential of biochar in different domains highlights its importance in contemporary studies (Santos et al., 2025).

In this context, it is necessary to analyze and study biochar classification parameters to favor the formulation process and facilitate production management.

One approach to examining the chemical attributes of biochar is through the use of multivariate analysis techniques (Neder et al., 2013). In multivariate analysis, principal component analysis (PCA) generates new variables from the original data, maximizing the proportion of uncorrelated variance in subsequent principal components. Furthermore, PCA also considerably reduces the size of the dataset (Silva & Sbrissia, 2010; Zhao et al., 2014). Being used in different research on biochar (Dai et al., 2014; Clemente et al., 2018; Janu et al., 2021; Quintana-Najera et al., 2023; Faloye et al., 2024).

PCA is applied to generate indices and group individuals. This technique groups individuals on the basis of their variations, that is, taking into account the variability of their characteristics that define each individual. In this way, PCA helps to remove unnecessary data and extract original information, reducing the size of the dataset (Yang et al., 2023). Although these techniques were initially used in problems related to biology and psychology, multivariate analysis techniques can also be applied in different areas of knowledge, such as soil science (Regazzi et al., 2000).

Therefore, the objective of this study was to characterize the nutrient content and properties of different biochars produced in the southern Agreste region of Pernambuco.

Material and Methods

Location of the search

The research was carried out under laboratory conditions at the Garanhuns Research Support Center (CENLAG), belonging to the Federal University of Agreste de Pernambuco (UFAPE), located in Garanhuns (Figure 1), in the Agreste Meridional region of Pernambuco, with geographic coordinates of 08° 53' 25" S latitude and 36° 29' 34" W longitude, from March 2022 to April 2023.

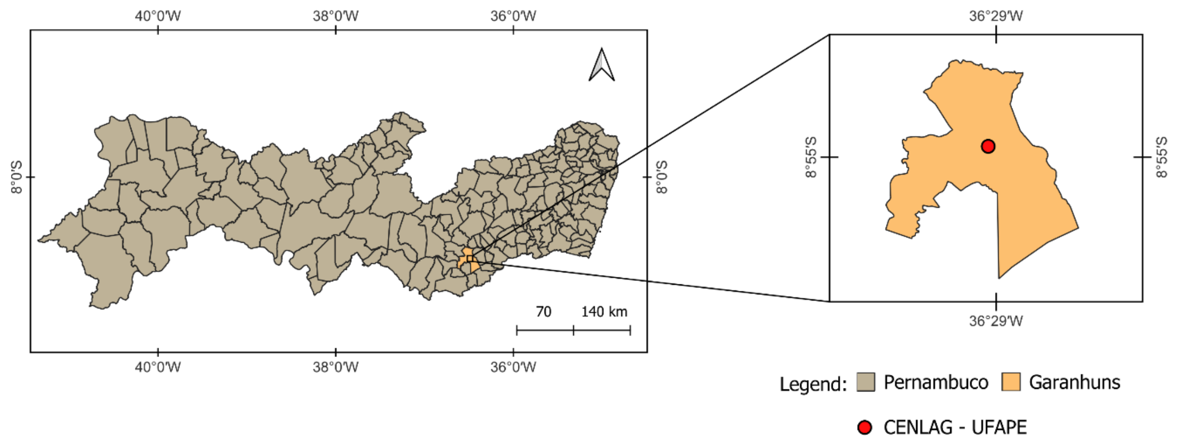

Figure 1. Location of CENLAG at the Federal University of Agreste de Pernambuco (UFAPE).

Biochar production

The selection of materials for biochar production was based on the availability of these materials in the aforementioned region. Biochars were produced from sewage sludge (B1), grape fermentation (B2), chicken litter (B4) and bean hulls (B5). This procedure was carried out through incomplete combustion via slow pyrolysis in a traditional oven at temperatures ranging between 400 and 500 °C for approximately 10 hours (Lima et al., 2018).

After the pyrolysis process, the biochars were sieved through a sieve with a 2 mm mesh opening. In contrast, cashew wood biochar (B3) is produced via slow pyrolysis of waste from cashew trees through earth charcoal ovens, which are commonly used in the production of charcoal in Northeast Brazil (Lima et al., 2019).

The oven temperature was monitored with a thermocouple and varied between 500–550 °C for 24–48 h (Lima et al., 2021).

After the pyrolysis process, B3 was crushed into forage to obtain a material with smaller particles, which was subsequently sieved through a 2 mm sieve. All the biochars were subsequently macerated, and samples of these materials were separated for analysis.

Methodological procedures

The biochar analyses were conducted in accordance with the standard methodologies of EMBRAPA (Brazilian Agricultural Research Corporation) and IAC (Agronomic Institute of Campinas). The chemical attributes of the biochars were determined on the basis of these analyses, as shown in Table 1.

Table 1. Chemical attributes of the biochars used.

Properties	Units	B1	B2	B3	B4	B5
C	%	19.06	60.43	77.49	36.83	49.0
H	%	1.53	2.78	3.59	2.25	2.2
N	%	2.02	6.40	2.78	3.04	2.5
C/N	adm.	9.44	9.44	27.87	12.11	19.7
pH	adm.	7.92	10.01	9.32	10.0	10.54
K	$cmol_c.kg^{-1}$	3.07	3.55	0.73	2.38	2.02
P	$mg.kg^{-1}$	18.41	230.53	230.13	450.86	180.7
Ca	$cmol_c.kg^{-1}$	50.9	3.4	1.9	55.80	7.4
Mg	$cmol_c.kg^{-1}$	13.16	0.32	0.51	0.17	0.15
Na	$cmol_c.kg^{-1}$	7.83	0.19	0.67	0.11	0.5
SO_4^{2-}	$hg.g^{-1}$	1.42	0.64	0.09	1.32	1.52 1
H+ Al	$cmol_c.kg^{-1}$	0.66	0.50	2.97	6.97	1.79
CTC	$cmol_c.kg^{-1}$	75.73	7.87	64.85	284.44	11.8

C: carbon. H: hydrogen. N: nitrogen. C/N: carbon/nitrogen ratio. pH: hydrogen potential. K: potassium. P: phosphorus. Ca: calcium. Mg: magnesium. Na: sodium. SO_4^{2-}: available sulfate. H + Al: potential acidity. CEC: cation exchange capacity.

Available phosphorus (P) was determined via the Olsen method described by (Irving & Mclaughlin, 1990) and analyzed according to (Teixeira et al., 2017a). The exchangeable sodium and potassium contents (Na and K) were determined according to (Teixeira et al., 2017b); the exchangeable magnesium (Mg) content was determined by atomic absorption according to (Teixeira 2017c); and the available sulfate () content was determined according to (Williams & Steinbergs, 1959) and analyzed according to the methodology of (Camargo et al., 2009a). The pH of the water at a ratio of 1:2.5 was obtained according to (Teixeira et al., 2017d), and the total nitrogen (N) content was obtained according to (Camargo et al., 2009b). The OM content was determined according to (Fontana, 2017) by dividing by the van Bemmelen factor (1.724) to determine the TOC content according to (Fageria et al., 1999).

The carbon (C), nitrogen (N) and hydrogen (H) contents of the samples were determined by combustion at a temperature of 925 °C in a CHNS-O elemental analyzer (Perkin Elmer PE-2400). Acetonalamide was used as a reference standard, with the following levels: C (71.09%), H (6.71%) and N (10.36%). The results obtained were used to calculate the cation exchange capacity (CEC) and the carbon–nitrogen ratio (C/N), according to (Teixeira et al., 2017c).

Principal component analysis

Statistical procedures for PCA were performed via PAST® software, version 4.03 (Hammer et al., 2001). The raw data were not entered into PAST®, as they were at different scales, and a transformation was carried out to balance the weights of the selected variables. For this, the following equation was used (Petersen et al., 1989):

$$\text{Score} - z = \frac{(Ci - x)}{\sigma} \qquad (1)$$

where Score-z is the standard score for each variable; Ci is the corresponding value of each standardized variable; x is the arithmetic mean of the variable; and σ is the sample standard deviation of the variable.

Jamovi® software version 2.4.11 (https://www.jamovi.org/download.html) was used for calculations of the eigenvalues.

Results and Discussion

In Table 2, the eigenvalues and variance in percentage of each main component of the chemical attributes of the biochars are presented.

Table 2. Characteristics of the main components of the biochar.

Components	Eigenvalue	% total variance	% accumulated variance
PC1	4.98	38.3	38.3
PC2	4.29	33.0	71.4
PC3	2.32	17.9	89.2
PC4	1.40	10.8	100.0
PC5	3.03e-15	2.33e-14	100.0
PC6	2.22e-15	1.71e-14	100.0
PC7	1.51e-16	1.16e-15	100.0
PC8	1.16e-16	8.91e-16	100.0
PC9	9.29e-17	7.15e-16	100.0
PC10	-2.51e−17	1.93e-16	100.0
PC11	-4.47e−17	3.44e-16	100.0
PC12	-2.71e−16	2.08e-15	100.0
PC13	-5.24e−16	4.03e-15	100.0

The table shows the percentage variances explained by the main components. The first component (PC1) explained 38.3% of the total data variability, whereas the second principal component (PC2) explained 33.0% of the remaining variance not explained by the first component, the third principal component (PC3) explained 17.9%, and the fourth principal component (PC4) explained 10.8% of the remaining variance not explained by PC1. The components together explain 100% of the total data variability. In the same table, the eigenvalues are verified. According to the criterion established by (Kaiser, 1960), which considers only the principal components with eigenvalues greater than 1 (> 1.0), we conclude that the principal components retained are PC1, PC2, PC3 and PC4.

In Table 3, the correlation coefficients between the variables used for each biochar (filler) and the main components are listed. The most significant correlation coefficients were highlighted for each component to identify the most important variable in the formation of the components. Therefore, loads above 0.3 meet the established minimum, loads of 0.4 are considered more relevant, and loads above 0.5 are statistically significant (Hair et al., 2005).

Table 3. Loadings of the main components by variables.

Variables	PC1	PC2	PC3	PC4
K	0.49415	0.51886	0.69461	-0.06422
Na	0.88592	-0.23762	-0.031183	-0.39712
P	0.31969	0.74657	-0.16155	0.56066
Ca	-0.089711	0.98523	-0.13216	0.061767
Mg	0.018457	-0.80343	-0.17219	0.56966
SO_4^{2-}	-0.62245	0.64211	0.29634	-0.3353
H + Al	0.50479	0.57281	-0.64498	0.032931
CTC	0.44344	0.76049	-0.40894	0.24041
pH	0.79504	0.45041	0.30888	-0.26386
C	0.94357	-0.2786	0.17564	-0.034846
N	0.43308	-0.016047	0.81569	0.38318
H	0.91965	-0.31993	0.026442	0.22624
C/N	0.67091	-0.3012	-0.55172	-0.3934

PC1: main component 1. PC2: main component 2. PC3: main component 3. PC4: main component 4. K: potassium; Na: sodium; P: phosphorus; Ca: calcium; Mg: magnesium; SO_4^{2-}: available sulfate; H+Al: potential acidity; CTC: cation exchange capacity; pH: hydrogen potential; C: carbon; N: nitrogen; H: hydrogen; C/N: carbon:nitrogen ratio.

PC1 is defined by most of the variables, namely, Na, SO_4^{2-}, H+Al, pH, C, H and the C/N ratio, with charge values (correlations) of 0, 88592, 0.62245, 0.50479, 0.79504, 0.94357, 0.91965, and 0.67091, reflecting most of the variability in the data. These results demonstrate that PC1 is highly influenced by variables that denote the efficiency of biochar as a material with potential for agricultural use. Biochars with high PC1 values strongly tend to be rich in C and H and contain considerable amounts of Na and SO_4^{2-}, in addition to having a high pH and a high C/N ratio, suggesting that these biochars can effectively improve soil structure (Edeh et al., 2020; Razzaghi et al., 2020) and increase nutrient and water retention capacity, acting as neutralization agents for acidic soils. The high C/N ratio indicates that these biochars are stable and have good durability in the soil, resulting in long-term benefits in the soil (De Jesus Duarte et al., 2019).

PC2 can be defined by the following variables: K, P, Ca, Mg, SO_4^{2-}, H+Al and CTC. The correlation values between PC2 and each of these variables are 0.51886, 0.74657, 0.98523, 0.80343, 0.64211, 0.57281, and 0.76049, respectively, capturing the second largest part of the data variability. PC2 is related to the nutrient content and cation exchange capacity of biochar. These factors are related to the applicability of biochar in terms of plant nutrition and soil fertility and are useful for improving nutrient retention in the soil (Agbede & Oyewumi, 2022; Zhang et al., 2022). Therefore, the choice of biochar to be used by the producer must take into account the ability of this product to improve CTC, increasing plant growth potential and increasing soil health.

PC3 is defined by the following variables: K, H+Al, N and the C/N ratio. The correlation values between PC3 and each of these variables are 0.69461, 0.64498, 0.81569, and 0.55172, respectively, capturing the third largest part of the data variability. These results demonstrate that PC3 can be used to understand how different types of biochar influence plant nutrition and nutrient dynamics in the soil. Furthermore, these results are important for choosing the most suitable biochar to improve soil fertility and soil quality (Lima et al., 2018; Zhang et al., 2021a).

PC4 is defined by the following variables, namely, P and Mg, with the following correlation values between the main component and each of these variables: 0.56066 and 0.56966, respectively, capturing the fourth largest part of the variability of the data. This high correlation of variables with PC4 reinforces that this main component is sensitive to variations in the levels of these nutrients in biochars. PC4 provides important information about the capacity of biochars to supply phosphorus and magnesium to the soil, identifying which biochars are most relevant in correcting specific nutrient deficiencies (Faria et al., 2018; Frišták et al., 2018).

Figure 2 shows the graphical representation of the correlation coefficients (biplot) demonstrating the distribution of the biochars used (B1, B2, B3, B4 and B5) as a function of the first two principal components (PC1 and PC2). The green lines, representing the variables analyzed, represent the correlations of the variables with the principal components. The data indicated that the parameters evaluated were sufficient to identify the correlations and multiple effects of the treatments with different variables. The multivariate analysis revealed complex patterns and relationships between the biochar components.

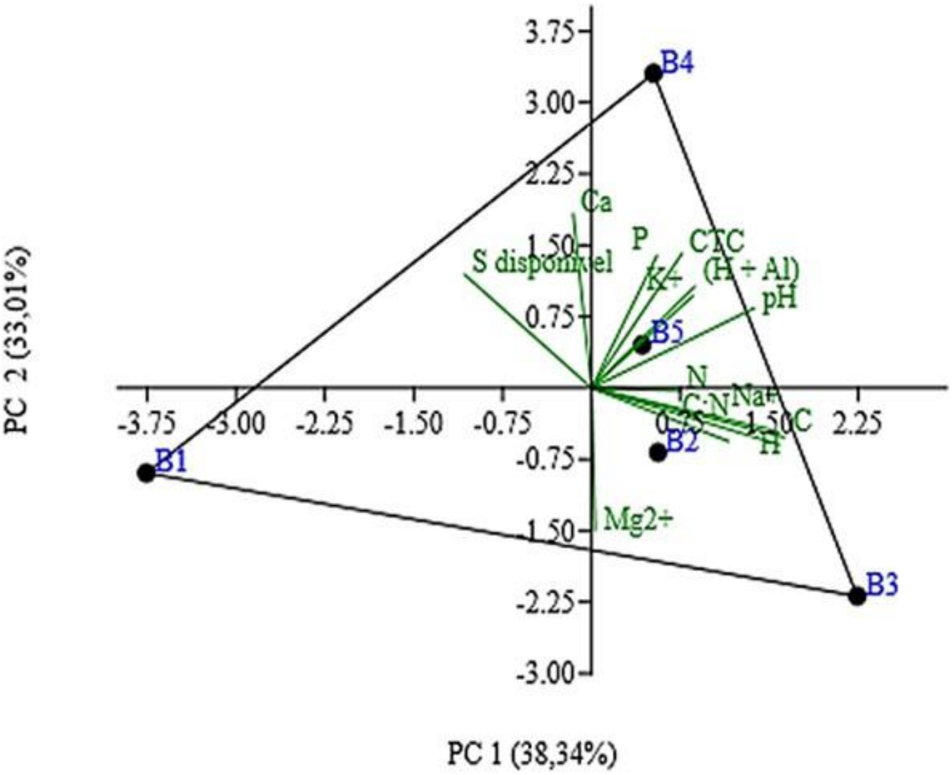

Figure 2. Biplot graph of PC1 and PC2 with correlation coefficients.

With respect to the specific interpretation of the biochars, B1 presented reduced values of the variables correlated with PC1, such as H+Al, pH, C, N, and the C/N ratio. This result indicates that B1 has lower acidity; lower contents of elements such as C and N; and a low C/N ratio. In contrast, B3 presents high acidity and a high C/N ratio, which occurs because its location is opposite to that of B1 along the PC1 axis. B4 presents high values of P and Ca, which reflects its positive position in relation to the PC2 axis. B2 and B5 present similar characteristics and are located in the center of the graph, indicating the absence of extreme values in relation to the variables analyzed.

In this context, B1, owing to its correlations, exerts less influence on the alteration of soil properties, making it more suitable for incorporation in soils with high levels of organic matter. B2 and B5 can be used in different types of soil without altering chemical properties. B3, owing to its correlations, is less efficient in providing nutrients in the short term, requiring adjustments to optimize its application as a soil conditioner. B4 improves the productivity of agricultural crops and is a potential source of nutrients. The observed variability highlights the importance of choosing the right type of biochar for agricultural crops, inducing efficient use and contributing to greater agricultural sustainability.

Figure 3 shows the graphical representation of the correlation coefficients (biplot) demonstrating the distribution of the biochars used (B1, B2, B3, B4 and B5) as a function of the first two principal components (PC3 and PC4). The green lines, representing the variables analyzed, represent the correlations of the variables with the principal components. This PCA provides new correlations on the characteristics and distribution of the biochars.

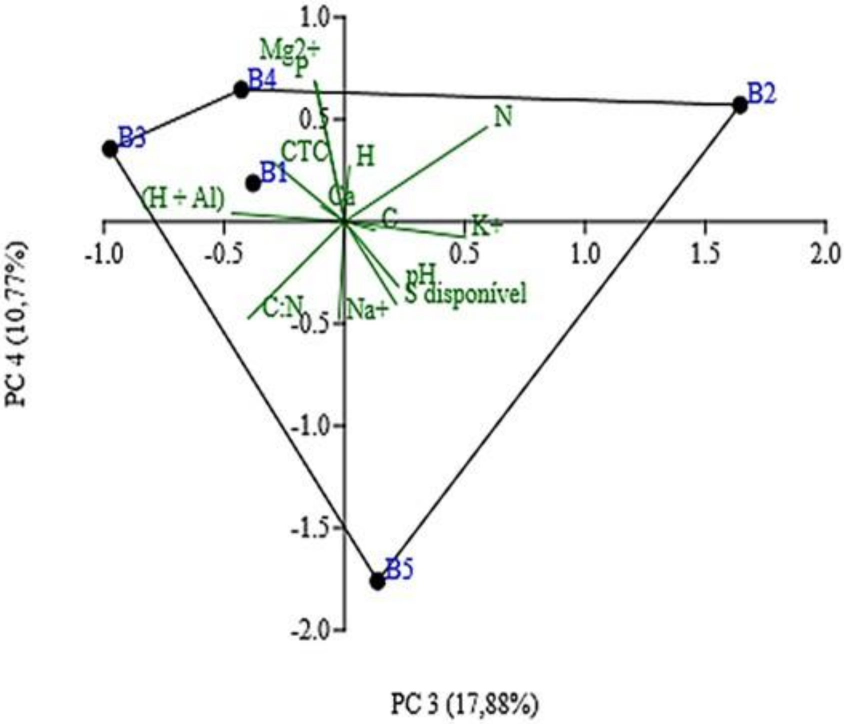

Figure 3. Biplot graph of PC3 and PC4 with correlation coefficients.

With respect to the specific interpretation of the biochars, B1 had little influence on PC3 and PC4 but had significant values and important correlations with PC1, indicating its high potential to be used as a source of organic matter and specific nutrients. For PC3, the biochars that presented the greatest correlation were B2 and B5. B2 was positively correlated with N and K, making this biochar a potential source of essential nutrients for vegetative growth. B5 had a negative correlation, with lower concentrations of these nutrients than the other biochars did. This result indicates that the use of this biochar may be limited by its effectiveness in relation to these elements or indicates the use of this biochar with nutrient supplementation.

For PC4, biochars B3 and B4 are located, indicating a positive correlation with P and Mg, indicating that these biochars have relatively high levels of these nutrients. These results demonstrate that these biochars are rich in P and Mg, which are elements that assist in the structure of the plant, in physiological functions such as the photosynthetic process and in the synthesis of ATP. These results help in understanding how different types of biochar can be used to improve soil fertility and vegetative growth and increase the sustainability of the system. In this context, chemically characterizing the biochars before their use to select them appropriately maximizes the benefits of this soil conditioner.

In general, the application of biochar has the potential to improve soil fertility by facilitating the biochemical cycling of nitrogen. The organic matter content of biochar provides plants with essential nutrients such as N, P, K, and C, among others (Guimarães et al., 2017; Lima et al., 2018; Zhang et al., 2021b). In addition, the potential of biochar to retain nutrients in the soil reduces the use of synthetic fertilizers in crops (Adekiya et al., 2022).

The chemical properties of the soil are also affected by the addition of biochar, which include pH and cation exchange capacity (El-Naggar et al., 2019; Palansooriya et al., 2019; Farkas et al., 2020). These properties are related to the raw material used to manufacture the biochar, as well as the production conditions. In general, biochar has an alkaline character, and high pH values directly affect the pH of the soil after incorporation, reducing the mobility of toxic nutrients (Fidel et al., 2017; Glaser & Lehr, 2019). After being added to the soil, biochar has the potential to exchange H^+ and Al^{3+} in the soil, with the aim of reducing the concentration of ions in the soil (Palansooriya et al., 2019).

Several studies have shown consistent and positive results for soil chemical attributes after the incorporation of biochar (Faria et al., 2018; Mensah & Frimpong, 2018; Sadeghi et al., 2018; Oni et al., 2019; Agbede & Oyewumi, 2022; Godlewska & Oleszczuk, 2022). These effects are due to the physical–chemical properties of biochar, such as its porous structure (Edeh et al., 2020; Razzaghi et al., 2020).

Conclusions

B1 (sewage sludge biochar) is more suitable for soils with high levels of organic matter because it is a biochar with lower acidity and has a low correlation with the contents of C and N and a reduced C/N ratio.

B2 (grape fermentation biochar) is more suitable for soils with N and K deficiency because it is a biochar with high levels of K and N.

B3 (cashew wood biochar) is not indicated for use in the short term, and it is recommended to complement it with other fertilizers because it is a biochar with high acidity and a high C/N ratio.

B4 (chicken bed biochar) is recommended for application in the soil to improve the productivity of agricultural crops because of its strong correlation with P and Ca, especially in soils poor in P and Ca.

The application of B5 (bean peel biochar) is complemented with other sources of nutrients because of its low correlation with N and K.

Future studies should focus on the long-term evaluation of these biochars and their recalcitrant effects on the soil, in addition to investigating the interaction of biochars with other sources of fertilizers.

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References

Adekiya, A. O., Adebiyi, O. V., Ibaba, A. L., Aremu, C., & Ajibade, R. O. (2022). Effects of wood biochar and potassium fertilizer on soil properties, growth and yield of sweet potato (Ipomea batata). *Heliyon*, 8(11). https://doi.org/10.1016/j.heliyon.2022.e11728

Agbede, T. M., & Oyewumi, A. (2022). Benefits of biochar, poultry manure and biochar–poultry manure for improvement of soil properties and sweet potato productivity in degraded tropical agricultural soils. *Resources, Environment and Sustainability*, 7, 100051. https://doi.org/10.1016/j.resenv.2022.10005

Agrafioti, E., Bouras, G., Kalderis, D., & Diamadopoulos, E. (2013). Biochar production by sewage sludge pyrolysis. *Journal of analytical and applied pyrolysis*, 101, 72-78. https://doi.org/10.1016/j.jaap.2013.02.010

Alkharabsheh, H. M., Seleiman, M. F., Battaglia, M. L., Shami, A., Jalal, R. S., Alhammad, B. A., ... & Al-Saif, A. M. (2021). Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: A review. *Agronomy*, 11(5), 993. https://doi.org/10.3390/agronomy11050993

Angın, D. (2013). Effect of pyrolysis temperature and heating rate on biochar obtained from pyrolysis of safflower seed press cake. *Bioresource technology*, 128, 593-597. https://doi.org/10.1016/j.biortech.2012.10.150

Barbhuiya, S., Das, B. B., & Kanavaris, F. (2024). Biochar-concrete: A comprehensive review of properties, production and sustainability. Case Studies in Construction Materials, 20, e02859. https://doi.org/10.1016/j.cscm.2024.e02859

Bolan, S., Sharma, S., Mukherjee, S., Kumar, M., Rao, C. S., Nataraj, K. C., ... & Bolan, N. (2024). Biochar modulating soil biological health: A review. Science of the Total Environment, 914, 169585. https://doi.org/10.1016/j.scitotenv.2023.169585

Brockamp, R. L., & Weyers, S. L. (2021). Biochar amendments show potential for restoration of degraded, contaminated, and infertile soils in agricultural and forested landscapes. In *Soils and Landscape Restoration* (pp. 209-236). Academic Press. https://doi.org/10.1016/B978-0-12-813193-0.00008-4

Camargo, A.O., Moniz, A.C., Jorge, J.A., Valadares, J.M.A.S. (2009a). Extração e determinação do sulfato. In: Camargo AO, Moniz AC, Jorge JA, Valadares JMAS. *Métodos de análise química, mineralógica e física de solos do Instituto Agronômico de Campinas*. IAC: Campinas (SP); 22-23.

Camargo, A.O., Moniz, A.C., Jorge, J.A., Valadares, J.M.A.S. (2009b). Determinação do nitrogênio total (orgânico mais amoniacal). In: Camargo AO, Moniz AC, Jorge JA, Valadares JMAS. *Métodos de análise química, mineralógica e física de solos do Instituto Agronômico de Campinas*. IAC: Campinas (SP);19-21.

Clemente, J. S., Beauchemin, S., Thibault, Y., MacKinnon, T., & Smith, D. (2018). Differentiating inorganics in biochars produced at commercial scale using principal component analysis. ACS omega, 3(6), 6931-6944.

Dai, Z., Li, R., Muhammad, N., Brookes, P. C., Wang, H., Liu, X., & Xu, J. (2014). Principle component and hierarchical cluster analysis of soil properties following biochar incorporation. Soil Science Society of America Journal, 78(1), 205-213. https://doi.org/10.2136/sssaj2013.05.0199

De Jesus Duarte, S., Glaser, B., Paiva de Lima, R., & Pelegrino Cerri, C. E. (2019). Chemical, physical, and hydraulic properties as affected by one year of Miscanthus biochar interaction with Sandy and Loamy tropical soils. *Soil Systems*, 3(2), 24. https://doi.org/10.3390/soilsystems3020024

Debiagi, P., Gentile, G., Cuoci, A., Frassoldati, A., Ranzi, E., & Faravelli, T. (2018). A predictive model of biochar formation and characterization. *Journal of analytical and applied pyrolysis*, 134, 326-335. https://doi.org/10.1016/j.jaap.2018.06.022

Diatta, A. A., Fike, J. H., Battaglia, M. L., Galbraith, J. M., & Baig, M. B. (2020). Effects of biochar on soil fertility and crop productivity in arid regions: a review. *Arabian Journal of Geosciences*, 13, 1-17. https://doi.org/10.1007/s12517-020-05586-2

Edeh, I. G., Mašek, O., & Buss, W. (2020). A meta-analysis on biochar's effects on soil water properties–New insights and future research challenges. *Science of the Total Environment*, 714, 136857. https://doi.org/10.1016/j.scitotenv.2020.136857

El-Naggar, A., Lee, S. S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A. K., ... & Ok, Y. S. (2019). Biochar application to low fertility soils: A review of current status, and future prospects. *Geoderma*, 337, 536-554. https://doi.org/10.1016/j.geoderma.2018.09.034

Fageria, N.K., Stone, F.F., & Santos, A.B. (1999). *Maximização da produção das culturas*. Embrapa: Santo Antônio de Goiás (GO).

Faloye, O. T., Ajayi, A. E., Kamchoom, V., Akintola, O. A., & Oguntunde, P. G. (2024). Evaluating impacts of biochar and inorganic fertilizer applications on soil quality and maize yield using principal component analysis. Agronomy, 14(8), 1761. https://doi.org/10.3390/agronomy14081761

Farhangi-Abriz, S., Torabian, S., Qin, R., Noulas, C., Lu, Y., & Gao, S. (2021). Biochar effects on yield of cereal and legume crops using meta-analysis. *Science of the Total Environment*, 775,145869.https://doi.org/10.1016/j.scitotenv.2021.145869

Faria, W. M., Figueiredo, C. C. D., Coser, T. R., Vale, A. T., & Schneider, B. G. (2018). Is sewage sludge biochar capable of replacing inorganic fertilizers for corn production? Evidence from a two-year field experiment. *Archives of Agronomy and Soil Science*, 64(4), 505-519. https://doi.org/10.1080/03650340.2017.1360488

Farkas, É., Feigl, V., Gruiz, K., Vaszita, E., Fekete-Kertész, I., Tolner, M., ... & Molnár, M. (2020). Long-term effects of grain husk and paper fibre sludge biochar on acidic and calcareous sandy soils–a scale-up field experiment applying a complex monitoring toolkit. *Science of the Total Environment*, 731, 138988. https://doi.org/10.1016/j.scitotenv.2020.138988

Fidel, R. B., Laird, D. A., Thompson, M. L., & Lawrinenko, M. (2017). Characterization and quantification of biochar alkalinity. *Chemosphere*, 167, 367-373. https://doi.org/10.1016/j.chemosphere.2016.09.151

Fontana A. (2017). Matéria orgânica. In: Teixeira PC.; Donagemma GK, Fontana A, Teixeira

WG. (eds). Manual de métodos de análises de solo. Embrapa: Brasília (DF); 397-400.

Frišták, V., Pipíška, M., & Soja, G. (2018). Pyrolysis treatment of sewage sludge: A promising way to produce phosphorus fertilizer. *Journal of Cleaner Production*, 172, 1772-1778.https://doi.org/10.1016/j.jclepro.2017.12.015

Gao, G., Yan, L., Tong, K., Yu, H., Lu, M., Wang, L., & Niu, Y. (2024). The potential and prospects of modified biochar for comprehensive management of salt-affected soils and plants: A critical review. Science of the Total Environment, 912, 169618. https://doi.org/10.1016/j.scitotenv.2023.169618

Glaser, B., & Lehr, V. I. (2019). Biochar effects on phosphorus availability in agricultural soils: A meta-analysis. *Scientific reports*, 9(1), 9338. https://doi.org/10.1038/s41598-019-45693-z

Godlewska, P., & Oleszczuk, P. (2022). Effect of biomass addition before sewage sludge pyrolysis on the persistence and bioavailability of polycyclic aromatic hydrocarbons in biochar-amended soil. *Chemical Engineering Journal*, 429, 132143. https://doi.org/10.1016/j.cej.2021.132143

Gotore, O., Masere, T. P., & Muronda, M. T. (2024). The immobilization and adsorption mechanisms of agro-waste based biochar: A review on the effectiveness of pyrolytic temperatures on heavy metal removal. *Environmental Chemistry and Ecotoxicology*. https://doi.org/10.1016/j.enceco.2024.04.002

Guimarães, R.S., Padinha, F.J, Cedano, J.C.C., Damaceno, J.B.D., Gama, R.T., Oliveira, D.M., Teixeira, W.G., & Falcão, N.P.S. (2017) Efeito residual de biocarvão e pó de serra nos teores de carbono e nitrogênio total em Latossolo Amarelo na Amazônia. Revista Virtual de Química. 9(5): 1944-1956.

Hair, J.F, Anderson, R.E., Tatham, R.L., & Black, W.C. (2005). *Análise multivariada de dados*. Bookman: Porto Alegre (RS).

Hammer, Ø., & Harper, D. A. (2001). Past: paleontological statistics software package for educaton and data anlysis. *Palaeontologia electronica*, 4(1), 1.24.

Ippolito, J. A., Spokas, K. A., Novak, J. M., Lentz, R. D., & Cantrell, K. B. (2015). *Biochar elemental composition and factors influencing nutrient retention*. In Biochar for environmental management (pp. 139-163). Routledge.

Irving, G. C. J., & McLaughlin, M. J. (1990). A rapid and simple field test for phosphorus in Olsen and Bray No. 1 extracts of soil. *Communications in Soil Science and Plant Analysis*, 21(19-20), 2245-2255. https://doi.org/10.1080/00103629009368377

Islam, M. U., Jiang, F., Guo, Z., & Peng, X. (2021). Does biochar application improve soil aggregation? A meta-analysis. *Soil and Tillage Research*, 209, 104926.https://doi.org/10.1016/j.still.2020.104926

Janu, R., Mrlik, V., Ribitsch, D., Hofman, J., Sedláček, P., Bielská, L., & Soja, G. (2021). Biochar surface functional groups as affected by biomass feedstock, biochar composition and pyrolysis temperature. Carbon Resources Conversion, 4, 36-46. https://doi.org/10.1016/j.crcon.2021.01.003

Jeffery, S., Verheijen, F. G., van der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, ecosystems & environment*, 144(1), 175-187. https://doi.org/10.1016/j.agee.2011.08.015

Ji, M., Wang, X., Usman, M., Liu, F., Dan, Y., Zhou, L., ... & Sang, W. (2022). Effects of different feedstocks-based biochar on soil remediation: A review. *Environmental Pollution*, 294, 118655. https://doi.org/10.1016/j.envpol.2021.118655

Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., ... & Lehmann, J. (2021). How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. Gcb Bioenergy, 13(11), 1731-1764. https://doi.org/10.1111/gcbb.12885

Kaiser, H. F. (1960). The application of electronic computers to factor analysis. *Educational and psychological measurement*, 20(1), 141-151.https://doi.org/10.1177/001316446002000116

Kang, H., Ren, H., Labidi, A., Liao, Y., Wang, Y., Zheng, H., ... & Wang, C. (2025). Fe3O4 loaded biochar to enhance persulfate activation for tetracycline degradation: Performance and mechanism. *Chemosphere*, 376, 144267. https://doi.org/10.1016/j.chemosphere.2025.144267

Kim, K. H., Kim, J. Y., Cho, T. S., & Choi, J. W. (2012). Influence of pyrolysis temperature on physicochemical properties of biochar obtained from the fast pyrolysis of pitch pine (Pinus rigida). *Bioresource technology*, 118, 158-162. https://doi.org/10.1016/j.biortech.2012.04.094

Kloss, S., Zehetner, F., Dellantonio, A., Hamid, R., Ottner, F., Liedtke, V., ... & Soja, G. (2012). Characterization of slow pyrolysis biochars: effects of feedstocks and pyrolysis temperature on biochar properties. *Journal of environmental quality*, 41(4), 990-1000. https://doi.org/10.2134/jeq2011.0070

Lee, Y., Ryu, C., Park, Y. K., Jung, J. H., & Hyun, S. (2013). Characteristics of biochar produced from slow pyrolysis of Geodae-Uksae 1. *Bioresource Technology*, 130, 345-350. https://doi.org/10.1016/j.biortech.2012.12.012

Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., ... & Whitman, T. (2021). Biochar in climate change mitigation. Nature Geoscience, 14(12), 883-892. https://doi.org/10.1038/s41561-021-00852-8

Leng, L., Xiong, Q., Yang, L., Li, H., Zhou, Y., Zhang, W., ... & Huang, H. (2021). An overview on engineering the surface area and porosity of biochar. *Science of the total Environment*, 763, 144204. https://doi.org/10.1016/j.scitotenv.2020.144204

Leng, L., Xiong, Q., Yang, L., Li, H., Zhou, Y., Zhang, W., ... & Huang, H. (2021). An overview on engineering the surface area and porosity of biochar. Science of the total Environment, 763, 144204. https://doi.org/10.1016/j.scitotenv.2020.144204

Li, S., Harris, S., Anandhi, A., & Chen, G. (2019). Predicting biochar properties and functions based on feedstock and pyrolysis temperature: A review and data syntheses. *Journal of Cleaner Production*, 215, 890-902. https://doi.org/10.1016/j.biombioe.2016.09.010

Lima, J. R. D. S., Goes, M. D. C. C. D., Antonino, A. C. D., Medeiros, E. V. D., Duda, G. P., Leite, M. C. D. B. S., ... & Hammecker, C. (2021). Biochar enhances Acrisol attributes and yield of bean in Brazilian tropical dry region. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, 71(8), 674-682. https://doi.org/10.1080/09064710.2021.1937691

Lima, J. R. S., da Silva Oliveira, J. E., dos Santos Moura, A., de Freitas Silva, C., De Medeiros, É. V., & Hammecker, C. (2019). Produção e eficiência no uso de água do feijão comum adubado com biochar. *Diversitas Journal*, 4(3), 1146-1155. https://doi.org/10.17648/diversitas-journal-v4i3.837

Lima, J. R. S., de Moraes Silva, W., de Medeiros, E. V., Duda, G. P., Corrêa, M. M., Martins Filho, A. P., ... & Hammecker, C. (2018). Effect of biochar on physicochemical properties of a sandy soil and maize growth in a greenhouse experiment. *Geoderma*, 319, 14-23.

Liu, X., Chen, Z., Lu, S., Shi, X., Qu, F., Cheng, D., ... & Ni, B. J. (2024). Persistent free radicals on biochar for its catalytic capability: A review. Water Research, 250, 120999. https://doi.org/10.1016/j.watres.2023.120999

Mei, Y., Zhuang, S., & Wang, J. (2025). Adsorption of heavy metals by biochar in aqueous solution: A review. *Science of The Total Environment*, 968, 178898. https://doi.org/10.1016/j.scitotenv.2025.178898

Mensah, A. K., & Frimpong, K. A. (2018). Biochar and/or compost applications improve soil properties, growth, and yield of maize grown in acidic rainforest and coastal savannah soils in Ghana. *International journal of agronomy*, 2018(1), 6837404. https://doi.org/10.1155/2018/6837404

Muthusamy, M., Uma, S., Suthanthiram, B., Saraswathi, M. S., & Chandrasekar, A. (2019). Genome-wide identification of novel, long non-coding RNAs responsive to Mycosphaerella eumusae and Pratylenchus coffeae infections and their differential expression patterns in disease-resistant and sensitive banana cultivars. *Plant Biotechnology Reports*, 13, 73-83. https://doi.org/10.1007/s11816-018-00514-z

Neder, D.G., Costa, F.R., Edvan, R. L., & Souto Filho, L. T. (2013). Correlações e análise de trilha de características morfológicas e de produção de acessos de palma forrageira. *Biotecnologia Aplicada ao Melhoramento Agrícola*. 13: 203-207.https://doi.org/10.1590/S198470332013000300009.2013

Nie, W., He, S., Lin, Y., Cheng, J. J., & Yang, C. (2024). Functional biochar in enhanced anaerobic digestion: synthesis, performances, and mechanisms. *Science of the Total*

Environment, 906, 167681. https://doi.org/10.1016/j.scitotenv.2023.167681

Oni, B. A., Oziegbe, O., & Olawole, O. O. (2019). Significance of biochar application to the environment and economy. *Annals of Agricultural Sciences*, 64(2), 222-236. https://doi.org/10.1016/j.aoas.2019.12.006

Ortiz, L. R., Torres, E., Zalazar, D., Zhang, H., Rodriguez, R., & Mazza, G. (2020). Influence of pyrolysis temperature and bio-waste composition on biochar characteristics. *Renewable Energy*, 155, 837-847. https://doi.org/10.1016/j.renene.2020.03.181

Palansooriya, K. N., Ok, Y. S., Awad, Y. M., Lee, S. S., Sung, J. K., Koutsospyros, A., & Moon, D. H. (2019). Impacts of biochar application on upland agriculture: A review. *Journal of environmental management*, 234, 52-64. https://doi.org/10.1016/j.jenvman.2018.12.085

Petersen, N.S., Kolen, M.J., & Hoover, H.D. (1989). *Scaling, norming, and equating*. In: Linn RL. (Ed.). Educational measurement. American Council on Education: New York.

Ponnusamy, V. K., Nagappan, S., Bhosale, R. R., Lay, C. H., Nguyen, D. D., Pugazhendhi, A., ... & Kumar, G. (2020). Review on sustainable production of biochar through hydrothermal liquefaction: Physico-chemical properties and applications. Bioresource technology, 310, 123414. https://doi.org/10.1016/j.biortech.2020.123414

Qi, L., Pokharel, P., Ni, C., Gong, X., Zhou, P., Niu, H., ... & Gao, M. (2020). Biochar changes thermal activation of greenhouse gas emissions in a rice–lettuce rotation microcosm experiment. *Journal of Cleaner Production*, 247, 119148. https://doi.org/10.1016/j.jclepro.2019.119148

Qian, K., Kumar, A., Zhang, H., Bellmer, D., & Huhnke, R. (2015). Recent advances in utilization of biochar. Renewable and sustainable energy reviews, 42, 1055-1064. https://doi.org/10.1016/j.rser.2014.10.074

Quintana-Najera, J., Blacker, A. J., Fletcher, L. A., & Ross, A. B. (2023). Understanding the Influence of Biochar Augmentation in Anaerobic Digestion by Principal Component Analysis. Energies, 16(6), 2523. https://doi.org/10.3390/en16062523

Rambhatla, N., Panicker, T. F., Mishra, R. K., Manjeshwar, S. K., & Sharma, A. (2025). Biomass pyrolysis for biochar production: Study of kinetics parameters and effect of temperature on biochar yield and its physicochemical properties. Results in Engineering, 25, 103679. https://doi.org/10.1016/j.rineng.2024.103679

Razzaghi, F., Obour, P. B., & Arthur, E. (2020). Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma*, 361, 114055. https://doi.org/10.1016/j.geoderma.2019.114055

Regazzi AJ. (2000). Análise multivariada, notas de aula INF 766. Departamento de Informática da Universidade Federal de Viçosa.

Sadegh, F., Sadegh, N., Wongniramaikul, W., Apiratikul, R., & Choodum, A. (2024). Adsorption of volatile organic compounds on biochar: A review. *Process Safety and Environmental Protection*, 182, 559-578. https://doi.org/10.1016/j.psep.2023.11.071

Sadeghi, S. H., Panah, M. H. G., Younesi, H., & Kheirfam, H. (2018). Ameliorating some quality properties of an erosion-prone soil using biochar produced from dairy wastewater sludge. *Catena*, 171, 193-198.

Sakhiya, A. K., Anand, A., & Kaushal, P. (2020). Production, activation, and applications of biochar in recent times. *Biochar*, 2, 253-285.https://doi.org/10.1007/s42773-020-00047-1

Santos, D. C., Evaristo, R. B., Dutra, R. C., Suarez, P. A., Silveira, E. A., & Ghesti, G. F. (2025). Advancing Biochar Applications: A Review of Production Processes, Analytical Methods, Decision Criteria, and Pathways for Scalability and Certification. Sustainability, 17(6), 2685. https://doi.org/10.3390/su17062685

Sheikh, L., Naz, N., Oranab, S., Younis, U., Alarfaj, A. A., Alharbi, S. A., & Ansari, M. J. (2025). Minimization of cadmium toxicity and improvement in growth and biochemical attributes of spinach by using acidified biochar. *Scientific Reports*, 15(1), 5880. https://doi.org/10.1038/s41598-025-90746-1

Silva, S. C. D., & Sbrissia, A. F. (2010). Análise de componentes principais entre características morfogênicas e estruturais em capim-marandu sob lotação contínua. *Ciência Rural*, 40, 690-693. https://doi.org/10.1590/S0103-84782010000300034

Singh, J. K., Chaurasia, B., Dubey, A., Faneite Noguera, A. M., Gupta, A., Kothari, R., ... & Abd Allah, E. F. (2020). Biological characterization and instrumental analytical comparison of two biorefining pretreatments for water hyacinth (Eichhornia crassipes) biomass hydrolysis. *Sustainability*, 13(1), 245. https://doi.org/10.3390/su13010245

Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2010). A review of biochar and its use and function in soil. Advances in agronomy, 105, 47-82. https://doi.org/10.1016/S0065-2113(10)05002-9

Song, W., & Guo, M. (2012). Quality variations of poultry litter biochar generated at different pyrolysis temperatures. *Journal of analytical and applied pyrolysis*, 94, 138-145. https://doi.org/10.1016/j.jaap.2011.11.018

Teixeira, P. C., Campos, D.V.B., Bianchi, S.R., Pérez, D.V., Saldanha, M.F.C. (2017b). Cátions trocáveis. In: Teixeira PC, Donagemma GK, Fontana A, Teixeira WG. (eds). Manual de métodos de análises de solo. Embrapa: Brasília (DF); 224-232.

Teixeira, P. C., Campos, D.V.B., Saldanha, M.F.C. (2017a). Fósforo disponível. In: Teixeira PC, Donagemma, GK, Fontana A, Teixeira WG. (eds). Manual de métodos de análises de solo. Embrapa: Brasília (DF); 203-208.

Teixeira, P.C., Campos, D.V.B., Bianchi, S.R., Pérez, D.V., Saldanha, M.F.C. (2017c). Cátions trocáveis. In: Teixeira PC, Donagemma GK, Fontana A, Teixeira WG. (eds). Manual de métodos de análises de solo. Embrapa: Brasília (DF); 221-224.

Teixeira, P.C., Campos, D.V.B., Saldanha, M.F.C. (2017d). pH do solo. In: Teixeira PC, Donagemma GK, Fontana A, Teixeira WG. (eds). Manual de métodos de análises de solo. Teixeira PC, Donagemma, GK, Fontana A, Teixeira WG. (eds). Manual de métodos de análises de solo. Embrapa: Brasília (DF); 199-202.

Vicente, L., Peña, D., Fernández, D., Albarrán, Á., Rato-Nunes, J. M., & López-Piñeiro, A. (2025). Alternate wetting and drying irrigation with field aged biochar may enhance water and rice productivity. *Agronomy for Sustainable Development*, 45(1), 1-17. https://doi.org/10.1007/s13593-024-01000-3

Waheed, A., Xu, H., Qiao, X., Aili, A., Yiremaikebayi, Y., Haitao, D., & Muhammad, M. (2025). Biochar in sustainable agriculture and Climate Mitigation: Mechanisms, challenges, and applications in the circular bioeconomy. *Biomass and Bioenergy*, 193, 107531. https://doi.org/10.1016/j.biombioe.2024.107531

Wang, J., & Wang, S. (2019). Preparação, modificação e aplicação ambiental de biochar: Uma revisão. Journal of Cleaner Production , 227 , 1002-1022. https://doi.org/10.1016/j.jclepro.2019.04.282

Wang, L., Ok, Y. S., Tsang, D. C., Alessi, D. S., Rinklebe, J., Wang, H., ... & Hou, D. (2020). New trends in biochar pyrolysis and modification strategies: feedstock, pyrolysis conditions, sustainability concerns and implications for soil amendment. *Soil Use and Management*, 36(3), 358-386. https://doi.org/10.1111/sum.12592

Weber, K., & Quicker, P. (2018). Properties of biochar. Fuel, 217, 240-261. https://doi.org/10.1016/j.fuel.2017.12.054

Wijitkosum, S., & Jiwnok, P. (2019). Elemental composition of biochar obtained from agricultural waste for soil amendment and carbon sequestration. *Applied sciences*, 9(19), 3980. https://doi.org/10.3390/app9193980

Williams, C. H., & Steinbergs, A. (1959). Soil sulphur fractions as chemical indices of available sulphur in some Australian soils. *Australian Journal of Agricultural Research*, 10(3), 340-352. https://doi.org/10.1071/AR9590340

Wu, B., Yang, H., Li, S., & Tao, J. (2024). The effect of biochar on crop productivity and soil salinity and its dependence on experimental conditions in salt-affected soils: a meta-analysis. *Carbon Research*, 3(1), 56. https://doi.org/10.1007/s44246-024-00138-9

Xie, Y., Wang, L., Li, H., Westholm, L. J., Carvalho, L., Thorin, E., ... & Skreiberg, Ø. (2022). A critical review on production, modification and utilization of biochar. *Journal of Analytical and Applied Pyrolysis*, 161, 105405. https://doi.org/10.1016/j.jaap.2021.105405

Yadav, S. P. S., Bhandari, S., Bhatta, D., Poudel, A., Bhattarai, S., Yadav, P., ... & Oli, B. (2023). Biochar application: A sustainable approach to improve soil health. *Journal of Agriculture and Food Research*, 11, 100498. https://doi.org/10.1016/j.jafr.2023.100498

Yang, L., Zhang, K., Chen, Z., & Liang, Y. (2023). Fault diagnosis of WOA-SVM high voltage circuit breaker based on PCA Principal Component Analysis. *Energy Reports*, 9, 628-634. https://doi.org/10.1016/j.egyr.2023.04.341

Yuan, J., Liang, X., & Yang, X. (2025). Impact of biochar on the flowering and growth of strawberry varied with different pyrolysis temperatures. *Journal of Plant Growth Regulation*, 1-10. https://doi.org/10.1007/s00344-025-11686-8

Zhang, J., Amonette, J. E., & Flury, M. (2021b). Effect of biochar and biochar particle size on plant-available water of sand, silt loam, and clay soil. Soil and Tillage Research, 212, 104992.https://doi.org/10.1016/j.still.2021.104992

Zhang, J., Liu, J., & Liu, R. (2015). Effects of pyrolysis temperature and heating time on biochar obtained from the pyrolysis of straw and lignosulfonate. *Bioresource Technology*, 176, 288-291. https://doi.org/10.1016/j.biortech.2014.11.011

Zhang, X., Zhao, B., Liu, H., Zhao, Y., & Li, L. (2022). Effects of pyrolysis temperature on biochar's characteristics and speciation and environmental risks of heavy metals in sewage sludge biochars. *Environmental Technology & Innovation*, 26, 102288. https://doi.org/10.1016/j.eti.2022.102288

Zhang, Y., Wang, J., & Feng, Y. (2021). The effects of biochar addition on soil physicochemical properties: A review. *Catena*, 202, 105284. https://doi.org/10.1016/j.catena.2021.10528

Zhao, Q., Meng, D., & Xu, Z. (2014). Robust sparse principal component analysis. *Science China Information Sciences*, 57, 1-14. https://doi.org/10.1007/s11432-013-4970-y

Zhou, X., Zhu, Y., Niu, Q., Zeng, G., Lai, C., Liu, S., ... & Liu, J. (2021). New notion of biochar: A review on the mechanism of biochar applications in advannced oxidation processes. *Chemical Engineering Journal*, 416, 129027. https://doi.org/10.1016/j.cej.2021.129027

Zou, X., Debiagi, P., Amjed, M. A., Zhai, M., & Faravelli, T. (2024). Impact of high-temperature biomass pyrolysis on biochar formation and composition. *Journal of Analytical and Applied Pyrolysis*, 179, 106463. https://doi.org/10.1016/j.jaap.2024.106463