agronomy

MDPI

Article

Açaí Waste Biochar Combined with Phosphorus Fertiliser and Phosphorus Use Efficiency in Cowpea (*Vigna unguiculata* (L.) Walp)

Ana Rita de Oliveira Braga [1,2,*], Vinicius John [1,2], Criscian Kellen Amaro de Oliveira Danielli [1,2], Heiriane Martins Sousa [2], Filipe Eduardo Danielli [1,3], Cláudia Saramago de Carvalho Marques-dos-Santos [1], Danielle Monteiro de Oliveira [4] and Newton Paulo de Souza Falcão [4]

[1] Forest Research Centre CEF, Associate Laboratory TERRA, School of Agriculture, University of Lisbon, Tapada da Ajuda, 1349-017 Lisboa, Portugal; vinicius.john@ifam.edu.br (V.J.); criscian.oliveira@ifam.edu.br (C.K.A.d.O.D.); filipe.danielli@suframa.gov.br (F.E.D.); cms@isa.ulisboa.pt (C.S.d.C.M.-d.-S.)

[2] Federal Institute of Education, Science, and Technology of Amazonas—IFAM, Manaus 69025-010, AM, Brazil; heiriane.sousa@ifam.edu.br

[3] Superintendency of the Manaus Free Trade Zone—SUFRAMA, Manaus 69075-830, AM, Brazil

[4] National Institute for Amazonian Research—INPA, Manaus 69060-001, AM, Brazil; danielle.monteiro@inpa.gov.br (D.M.d.O.); nfalcao@inpa.gov.br (N.P.d.S.F.)

* Correspondence: ana.braga@ifam.edu.br

Abstract: Biochar is a multifunctional tool that enhances soil quality, with particularly positive effects on acidic soils with low nutrient content, common in tropical regions worldwide, such as in the Amazon region in Brazil. This study investigates the effects of açaí fruit waste biochar (*Euterpe oleracea* Mart.) amendment and phosphate fertilisation on the chemical characteristics of a Ferralsol and on the biological components of cowpea (*Vigna unguiculata* (L.) Walp). In a greenhouse setting, a randomised block design was employed, testing five doses of biochar (0, 7.5, 15, 30, and 60 t ha^{-1}) combined with four doses of phosphorus (P) (0, 40, 80, and 120 kg ha^{-1}), resulting in 20 treatments with three replicates and 60 experimental units. Cowpea responded to inorganic fertilisation, with lower doses of P limiting the biological components (height, leaves, leaf area, dry biomass, and dry root mass). Higher doses of biochar and P increased the soil's available P content by up to 2.3 times, reflected in the P content of cowpea dry biomass. However, this increase in biochar and P levels led to a maximum increase of 7.7% in agronomic phosphorus efficiency (APE) in cowpea in the short term. The higher doses of biochar promoted increases in pH value, cation exchange capacity (CEC), and the contents of potassium (K), calcium (Ca), and total nitrogen (N). In contrast, a decrease in magnesium (Mg) and aluminium (Al) levels was observed, while the concentration of easily extractable glomalin (EE-GRSP) was not significantly affected during the evaluated period. We conclude that biochar altered the soil environment, promoting the increased solubility and availability of phosphorus.

Keywords: acidic soils; biochar co-application; phosphate fertilisation; available P; plant growth; açaí waste

check for updates

Academic Editor: Guang-Wei Ding

Received: 27 December 2024
Revised: 16 January 2025
Accepted: 21 January 2025
Published: 31 January 2025

Citation: Braga, A.R.d.O.; John, V.; Danielli, C.K.A.d.O.; Sousa, H.M.; Danielli, F.E.; Marques-dos-Santos, C.S.d.C.; Oliveira, D.M.d.; Falcão, N.P.d.S. Açaí Waste Biochar Combined with Phosphorus Fertiliser and Phosphorus Use Efficiency in Cowpea (*Vigna unguiculata* (L.) Walp). *Agronomy* **2025**, *15*, 393. https://doi.org/10.3390/agronomy15020393

1. Introduction

In tropical regions in general, such as the Amazon, there is a marked contrast between the lushness of the forest and the low natural fertility of most of its soils. Acrisols and Ferralsols dominate approximately 75% of the landscape and are characterised by high weathering, significant acidity, and a continuous renewal of organic matter [1,2]. Additionally, these soils possess a high P-fixation capacity, with an elevated adsorption energy and P capacity factor, especially in Ferralsols [3].

Unlike these soils, Amazonian Dark Earths (ADE), often formed over Acrisols and Ferralsols, exhibit high nutrient availability, high organic matter content, and substantial charcoal content (>1% by volume) [4,5]. This charcoal contributes to reducing organic matter degradation [6], helping to maintain soil fertility over the long term. The properties of ADE have inspired research into biochar utilisation, combining its agronomic potential with climate change mitigation, as evidenced by the growing body of scientific studies in recent years [7,8].

Biochar is a solid material obtained through thermochemical conversion of biomass at temperatures above 250 °C under oxygen-limited or oxygen-free conditions [9,10]. This process alters the physical and chemical properties of biomass, resulting in a carbon-rich material (mainly aromatic compounds) with high alkalinity, a large surface area, porosity, variable charge, and nutrient presence [11]. Biochar from different biomass sources and with varying particle sizes interacts with soil in diverse ways, leading to distinct crop yield responses [12], and determines its potential to be used as soil amendment.

In acidic soils, the agricultural application of biochar raises pH, influences nutrient dynamics, and increases carbon stocks, both due to its stable fraction and by reducing the decomposition rate of organic matter, prompted by a “negative priming” effect, especially in clayey soils [13]. These effects provide benefits such as enhanced soil fertility, increased agricultural productivity, and efficient long-term carbon sequestration [11,14]. Moreover, biochar improves fertiliser retention and reduces nutrient loss, facilitating nutrient uptake and utilisation by plants [15].

Biochar has also shown a potential to increase P availability across various soil types (pH, texture), whether applied alone or in combination with fertilisers, regardless of feedstock type, pyrolysis conditions, or C:N ratios [16]. Biochar has been reported to influence soil P availability through several mechanisms: (i) acting as a direct source of P; (ii) modifying P solubility by altering soil pH; (iii) changing adsorption and desorption processes of specific chelates; and (iv) promoting the growth of P-solubilising bacteria [17]. The combined application of biochar with mineral fertilisers enhances soil chemistry and enzymatic activities, enabling reductions in fertiliser use and food production costs [18], which is particularly relevant in developing economies and remote regions, such as Central Amazonia in Brazil.

Açaí (*Euterpe oleracea* Mart.), widely cultivated in the Amazon, presents substantial potential for biochar production, as approximately 83% of the fruit’s residues, primarily in the form of seeds and fibres, are discarded after processing [19], often causing environmental pollution [20,21]. Açaí production is concentrated mainly in the states of Pará (~90%) and Amazonas, the second-largest producer [22]. In 2022, Brazilian production reached approximately 1.7 million tonnes of fruit, with revenues around USD 1.2 billion [22]. Growing national and international demand has led to an expansion in cultivation areas, doubling revenues compared to 2018. Increased açaí production results in greater waste generation and presents an opportunity to add value by using it as a feedstock for biochar production.

Scientific studies on biochar produced from açaí waste are in the developmental stage, with a focus on the physicochemical characterisation of this material [23,24]. Results from laboratory experiments have demonstrated the potential of biochar to increase P, K, and Mg levels while reducing Al concentrations in the soil [25]. The findings from these studies suggest that biochar derived from this biomass holds significant potential for improving soil fertility and contributing to carbon sequestration [23,24].

The hypothesis of this study is that the application of biochar derived from açaí waste significantly influences soil properties by reducing the adsorption of inorganic P, increasing its availability to plants, and thereby enhancing cowpea yields as the selected experimental crop. This hypothesis is based on the behaviour of available P in tropical soils, where its availability is mainly limited by precipitation with aluminium (Al) and iron (Fe) ions. The aim of this study was to evaluate the effects of adding açaí waste biochar in combination with inorganic phosphorus fertiliser on the following: (i) the chemical and biological properties of a clayey Ferralsol; (ii) P uptake by cowpea (*Vigna unguiculata* (L.) Walp); and (iii) the biological components of cowpea.

2. Materials and Methods

2.1. Soil Collection and Biochar Production

Soil from the 0–20 cm layer was collected in a fallow agricultural area covered with approximately 30-year-old secondary vegetation. The collection took place at the experimental area of the Tropical Fruit Station of the National Institute of Amazonian Research (INPA), located at coordinates 2°37′11.8″ S and 60°02′28.8″ W at kilometre 41 of the BR 174 highway, Manaus, Am, Brazil. Soil samples were air-dried, sieved to 2 mm, and subjected to chemical analysis at the Thematic Laboratory of Soils and Plants at INPA. The soil was classified as a Ferralsol (WRB/FAO) [26] (Table 1).

Table 1. Chemical and physical properties of the 0–20 cm layer of a Ferralsol used in the pot experiments ($n = 6$).

Soil Properties	Unit	Low	Medium	High
pH (H_2O)	-	3.99	4.10	4.43
Available P	mg kg^{-1}	0.67	1.97	2.90
Total N	g kg^{-1}	0.52	0.88	1.27
Soil organic carbon (SOC)	g kg^{-1}	15.16	16.00	16.17
K	$cmol_c$ kg^{-1}	0.03	0.05	0.07
Ca	$cmol_c$ kg^{-1}	0.10	0.15	0.16
Mg	$cmol_c$ kg^{-1}	0.03	0.04	0.05
Na	$cmol_c$ kg^{-1}	0.01	0.01	0.01
Al	$cmol_c$ kg^{-1}	0.91	1.10	2.45
Potential Acidity (H + Al)	$cmol_c$ kg^{-1}	4.47	4.69	5.81
CEC	$cmol_c$ kg^{-1}	1.08	1.35	2.72
Clay	%	-	53.0	-
Silt	%	-	17.7	-
Sand	%	-	29.3	-

Biochar was produced through the pyrolysis of açaí agro-industrial waste in a low-cost mobile pyrolysis furnace with an average temperature of 431.7 °C and a residence time of 145 min [24]. Figure 1 presents the steps involved in the production of biochar from açaí waste, and Table 2 provides the characterisation of açaí waste biochar, as described by [27].

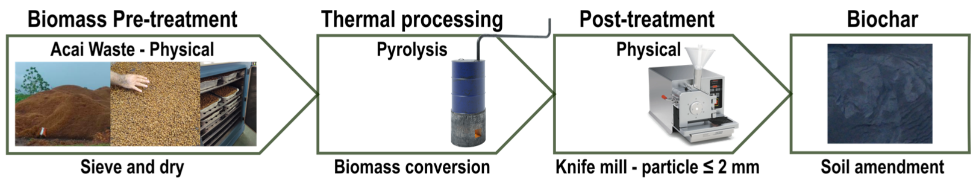

Figure 1. Açaí waste biochar production process phases [24].

Table 2. Characteristic of açaí waste biochar (*n* = 4) produced by pyrolyse at a temperature of 431.7 °C.

Element	Unit	Mean	Standard Deviation
Carbon (C)	g $100g^{-1}$	76.96	3.19
N	g $100g^{-1}$	0.41	0.12
Oxygen (O)	g $100g^{-1}$	16.04	3.04
Hydrogen (H)	g $100g^{-1}$	1.47	0.13
H/C	-	0.23	0.03
O/C	-	0.16	0.04
C/N	-	232.85	58.45
pH (H_2O)	-	8.86	0.73
Electrical conductivity	µS m^{-1}	273	72.76
CEC	$mmol_c$ kg^{-1}	41.25	18.87
Ashes	g $100g^{-1}$	5.20	1.00
$CaCO_{3\ equivalent}$	g $100g^{-1}$	4.20	0.95
Organic C	g $100g^{-1}$	23.69	3.81
Total N	g $100g^{-1}$	0.51	0.60
P_2O_5	g $100g^{-1}$	0.59	0.17
K_2O	g $100g^{-1}$	1.44	0.43
Mg	g $100g^{-1}$	0.12	0.02
Ca	g $100g^{-1}$	0.15	0.02
Sulphur (S)	%	0.12	0.10

2.2. Experimental Design

The experiment was conducted in a greenhouse at INPA, Campus V8. This study tested the combination of increasing doses of biochar (0, 7.5, 15, 30, and 60 t ha^{-1}) and inorganic phosphate fertiliser (0, 40, 80, and 120 kg ha^{-1} of P_2O_5) using cowpea (*Vigna unguiculata* (L.) Walp), cultivar BR3 Tracuateua (purified, with a typical 70-day growth cycle), as the test crop. The treatment with 80 kg ha^{-1} of P without biochar addition was considered to be the reference treatment for comparison with other treatments, according to the technical recommendations from Embrapa Amazônia Ocidental [28]. The experimental design was a randomised block design with 20 treatments and 3 replications, totalling 60 experimental units. The overview of the methodology is presented in Figure 2.

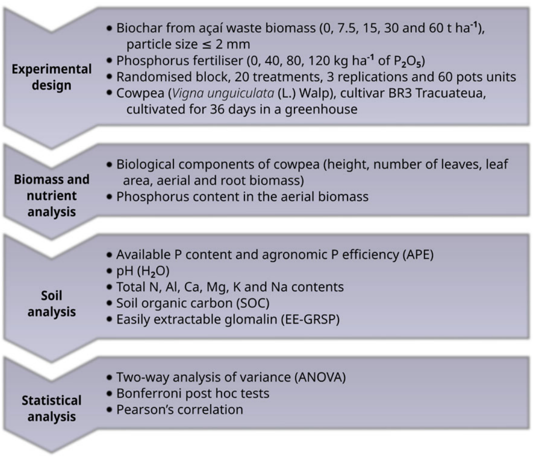

Figure 2. Overview of the methodology.

Each experimental unit consisted of a 7 L pot with a drainage hole at the bottom, lined with non-woven fabric (TNT). The pots were filled with 4 kg of sieved soil (<2 mm). Biochar (<2 mm) was added at doses of 0 g, 21.43 g, 42.86 g, 85.71 g, and 171.43 g, corresponding to treatments of 0, 7.5, 15, 30, and 60 t ha^{-1}, respectively. Concurrently, all pots underwent soil acidity correction with dolomitic lime to raise the base saturation (V%) to 60% (Figure 3A). The substrate was manually mixed and maintained at 60% field capacity for 30 days. Cowpea seeds were sown with four seeds per experimental unit, sourced from farmers in the southern region of Amazonas, Brazil.

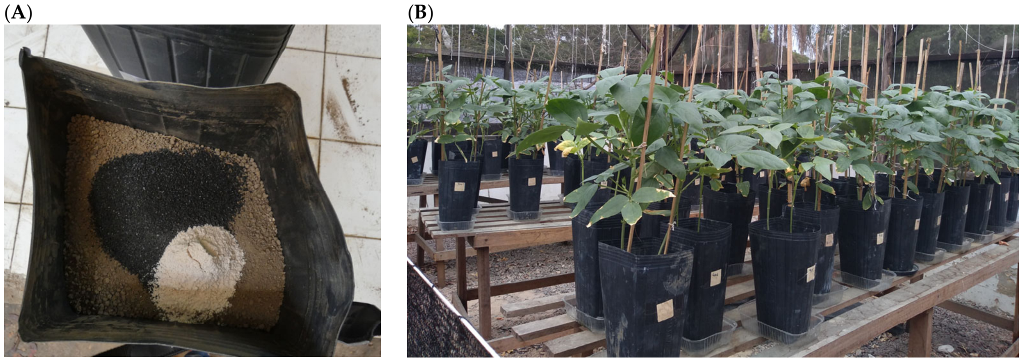

Figure 3. (**A**) Ferralsol with biochar and dolomitic lime. (**B**) Cowpea at 36 days of cultivation in a greenhouse.

Thinning was carried out on the eighth day after germination, leaving two plants per pot. During cowpea sowing, 40 kg ha^{-1} of K_2O and 25 kg ha^{-1} of micronutrients (FTE BR 12), containing S (3%), B (1.8%), Mn (2%), and Zn (9%), were applied for a plant population of up to 187,000 plants ha^{-1} [28]. Fertilisers were dosed in each pot to meet the nutritional requirements of two plants: 1.33 g of potassium salt (60% KCl) and 0.5 g of FTE BR 12 micronutrients. Triple superphosphate (45% P_2O_5) was added in proportions of 0, 1.78 g, 3.56 g, and 5.34 g per pot. Urea was applied 15 days after leaf emergence, with 1.34 g of urea (46% N) diluted in 100 mL of water. The pots were maintained at 60% field water capacity. The volumetric water content was directly measured in each pot using a moisture sensor, calculating the volume of water needed to restore moisture to field capacity. The experiment continued until the 50% flowering phase, which occurred 36 days after seedling emergence (Figure 3B).

2.3. Biomass and Nutrient Analysis in Cowpea

Plants from each experimental pot were collected, with the aerial part cut at soil level and fresh weight measured using a precision balance. Roots were then removed using a 1 mm sieve, washed under running water, and weighed. Biological components (height, number of leaves, leaf area, and aerial and root biomass) were evaluated. Plant height was measured using a measuring tape, and the number of leaves on each plant was determined by manual counting. Leaf area was determined by selecting one plant from each experimental unit; four representative leaves were decomposed, scanned, and digitally analysed using the ImageJ® software (version 1.54g, National Institutes of Health, Bethesda, MD, USA).

The aerial and root biomass of the two plants were placed in paper bags and dried in an oven at 65 °C until a constant weight was reached (~72 h), and dry mass was determined using a precision balance. The aerial biomass samples were ground, homogenised, and stored in plastic bags. Phosphorus content in the aerial biomass was analysed through digestion with nitric and hydrochloric acids in a digestion block at 105 °C for 60 min, followed by determination using inductively coupled plasma optical emission spectrometry (ICP-OES).

2.4. Soil Analysis

At the end of the experiment, a soil sample from each experimental pot was collected, air-dried, sieved to 2 mm, and stored in plastic bags. Available P content was extracted using the Mehlich I extractor (HCl 0.05 mol L^{-1} and H_2SO_4 0.0125 mol L^{-1}) and determined using the molybdate blue method by spectrophotometry set at 660 nm [26]. APE was calculated by comparing treatments with combined biochar and P application to those with only P application at the same dosage [29], following Equation (1).

$$APE = \frac{Y_{B+P} - Y_P}{F_P} \quad (1)$$

where Y_{B+P} is the biomass yield from the experimental pots that received the biochar and P treatments; Y_P is the biomass yield from the pots that received only P; and F_P is the P application rate (in kg P ha^{-1}).

The chemical characteristics of other soil nutrients were performed according to the procedures established in the Manual of Soil Analysis Methods by EMBRAPA [26]: pH was measured using a combined electrode immersed in a soil-to-water suspension in a ratio of 1:2.5, and total N was determined using the semi-micro Kjeldahl method after sulphuric acid digestion. Al, Ca, and Mg contents were extracted using a potassium chloride (KCl 1 mol L^{-1}) extracting solution. Al was determined by titration with NaOH, while Ca and Mg were determined by atomic absorption spectrophotometry. K and sodium (Na) were extracted using the Mehlich I extractor and determined by flame spectrophotometry.

Total content of organic carbon was determined by the oxidation method for organic compounds [30] and was used to estimate SOC. For the extraction of easily extractable glomalin (EE-GRSP), a 20 mM sodium citrate solution was added to fresh soil samples. The samples were autoclaved for 30 min at 121 °C and centrifuged at 10,000 RPM for 5 min. The assessment was performed in triplicate, totalling 180 samples [31]. Finally, EE-GRSP levels were determined using the Bradford method [32] with a spectrophotometer set at 595 nm; the results were fitted to a calibration curve, yielding the concentrations for each treatment.

2.5. Statistical Analysis

Statistical analysis was performed using R software (version 4.3.3, R Foundation for Statistical Computing, Vienna, Austria). Experimental data were initially tested for normality using the Shapiro–Wilk test and for homogeneity of variances with Levene's test. Subsequently, a two-way analysis of variance (ANOVA) was conducted to investigate the relationships among the variables of interest. This procedure evaluated potential significant differences between the means of dependent variables concerning the independent variables using Bonferroni post hoc tests with a significance level of $p < 0.05$. Pearson's correlation was employed to examine the relationship between the measured parameters.

3. Results

3.1. Biological Components of Cowpea

All biometric parameters of cowpea were significantly influenced by the addition of P ($p < 0.001$), as shown in Table 3. Leaf area was significantly affected by the addition of biochar ($p < 0.01$). Leaf area increased with the application of 60 t ha^{-1} of biochar and 80 kg ha^{-1} of P, reaching an average of 323.58 cm^2, which was statistically similar to the reference treatment (268.65 cm^2). Treatments that received only biochar exhibited a greater leaf area compared to the control treatment (68.58 cm^2). However, the results were lower than those observed in treatments that included P application either alone or in combination with biochar.

Table 3. Effects of increasing doses of biochar and P on the biological components of cowpea after 36 days of greenhouse cultivation.

Biochar ($t\ ha^{-1}$)	P ($kg\ ha^{-1}$)	Height (cm)	Number of Leaves	Leaf Area (cm^2)	Aerial Biomass (g)	Root Biomass (g)
0	0	34.33 ± 4.93 Bb	4.17 ± 1.04 Ab	68.58 ± 10.32 Cb	9.27 ± 0.34 Bb	0.48 ± 0.2 Ab
	40	101.00 ± 15.62 Aa	14.83 ± 1.53 Aa	230.22 ± 7.43 Aa	28.4 ± 0.66 Aa	3.06 ± 0.6 Aa
	80	101.83 ± 15.18 Aa	14.17 ± 0.29 Aa	268.65 ± 3.22 Aa	28.94 ± 0.66 Aa	2.71 ± 0.13 Aa
	120	83.33 ± 2.89 Aa	17.33 ± 3.62 Aa	265.84 ± 78.54 Aa	28.49 ± 2.66 Aa	3.05 ± 1.22 Aa
7.5	0	33.92 ± 10.52 Bb	3.17 ± 1.26 Ab	114.28 ± 12.1 BCb	9.69 ± 1.6 Bb	0.71 ± 1.12 Ab
	40	91.83 ± 8.95 Aa	13.33 ± 1.44 Aa	242.4 ± 17.91 Aa	28.5 ± 0.65 Aa	2.2 ± 0.88 Aab
	80	86.67 ± 13.16 Aa	14.0 ± 1.8 Aa	240.31 ± 55.64 Aa	29.06 ± 1.92 Aa	2.49 ± 0.28 Aab
	120	93.33 ± 15.97 Aa	13.67 ± 4.31 Aa	256.59 ± 65.46 Aa	28.78 ± 1.64 Aa	2.94 ± 0.21 Aa
15	0	32.83 ± 4.04 Bb	5.0 ± 1 Ab	142.47 ± 27.27 ABCb	10.27 ± 0.49 Bb	0.32 ± 0.04 Aa
	40	118.17 ± 24.76 Aa	13.17 ± 1.26 Aa	258.67 ± 49.71 Aa	28.27 ± 0.55 Aa	2.2 ± 0.83 Aa
	80	96.00 ± 12.12 Aa	15.67 ± 2.25 Aa	269.82 ± 31.94 Aa	28.98 ± 3.18 Aa	2.25 ± 0.34 Aa
	120	110.67 ± 29.62 Aa	16.0 ± 1.5 Aa	272.79 ± 69.31 Aa	27.93 ± 1.73 Aa	2.09 ± 0.82 Aa
30	0	55.58 ± 7.8 ABb	6.33 ± 0.58 Ab	168.00 ± 32.39 ABb	12.44 ± 0.79 ABb	1.37 ± 1.13 Ab
	40	85.63 ± 16.87 Aab	14.17 ± 1.89 Aa	252.31 ± 38.96 Aab	29.74 ± 1.09 Aa	3.57 ± 1.64 Aa
	80	88.00 ± 9.99 Aab	14.83 ± 0.76 Aa	231.59 ± 15.15 Aab	28.39 ± 0.72 Aa	2.25 ± 0.73 Aab
	120	94.17 ± 13.61 Aa	15.33 ± 0.76 Aa	273.36 ± 39.93 Aa	29.62 ± 1.54 Aa	2.24 ± 0.28 Aab
60	0	79.00 ± 21.66 Aa	7.5 ± 2.18 Ab	224.79 ± 18.47 Ab	14.45 ± 2.42 Ab	0.86 ± 0.3 Ab
	40	91.33 ± 9.36 Aa	13.67 ± 2.31 Aa	253.54 ± 29.6 Aab	27.96 ± 1.73 Aa	3.68 ± 1.42 Aa
	80	86.5 ± 9.12 Aa	14.5 ± 0.5 Aa	323.58 ± 26.83 Aa	29.15 ± 1.91 Aa	3.6 ± 2.04 Aa
	120	96.08 ± 22.74 Aa	13.0 ± 0.87 Aa	264.49 ± 22.83 Aab	28.89 ± 1.38 Aa	3.06 ± 1.03 Aa
	B	NS	NS	**	NS	NS
Anova	P	***	***	***	***	***
	B × P	*	NS	NS	NS	NS

Mean ± standard deviation ($n = 3$). P indicates phosphorus doses. *, **, ***, Significant at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively. NS = not significant ($p > 0.05$). Uppercase letters compare different doses of biochar for each phosphorus dose, while lowercase letters compare different phosphorus doses for each biochar dose according to the F-test from ANOVA and Bonferroni's multiple mean comparison test at the 95% significance level.

Plant height was the only biometric variable that showed a significant interaction between the factors studied ($p < 0.05$). The greatest plant height was observed with the combined application of 15 $t\ ha^{-1}$ of biochar and 40 $kg\ ha^{-1}$ of P, averaging 118.17 cm. This represents an increase of approximately 16 cm in plant height compared to the reference treatment (101.83 cm), although they were statistically similar. The absence of P resulted in the shortest cowpea plant heights, especially at the lowest biochar doses (0, 7.5, and 15 $t\ ha^{-1}$).

The addition of P significantly affected ($p < 0.001$) cowpea leaf production, with no significant effects from biochar or the interactions between factors. In the treatment with 15 $t\ ha^{-1}$ of biochar and 80 $kg\ ha^{-1}$ of P, plants showed the highest number of leaves, averaging 15.67 leaves per plant, which was statistically similar to the reference treatment that recorded 14.17 leaves per plant. Overall, the lowest leaf production was observed in treatments without P addition, which differed statistically ($p < 0.05$) from the other groups.

The treatments with P significantly affected cowpea biomass production ($p < 0.001$). The addition of 30 $t\ ha^{-1}$ of biochar and 40 $kg\ ha^{-1}$ of P resulted in the highest biomass production, with an average of 29.74 g. However, this was not statistically different from the reference treatment, which produced 28.94 g of dry weight. The absence of P led to the lowest biomass yields, differing statistically from treatments that included this nutrient. Phosphorus application also significantly affected ($p < 0.001$) the dry weight of roots, with no significant effects observed from biochar or the interactions between factors. The highest root dry weight was observed after addition of 60 $t\ ha^{-1}$ of biochar and 40 $kg\ ha^{-1}$ of P (3.68 g), which did not differ statistically from the reference treatment (2.71 g). Treatments without P addition had the lowest root dry weight.

3.2. Soil Available P Content, P Content in Biomass, and Agronomic Efficiency in Cowpea

The treatments significantly influenced ($p < 0.001$) available soil P levels (Table 4), showing an interaction between biochar and P. Biochar demonstrated greater efficacy in increasing the soil's available P content at higher doses of P (120 kg ha^{-1}), with significant effects observed with the addition of 7.5 t ha^{-1} of biochar. The application of 60 t ha^{-1} of biochar combined with 80 kg ha^{-1} of P raised available P levels to 146.43 mg kg^{-1}, representing a 1.6-fold increase compared to the reference treatment (88.99 mg kg^{-1}). When combined with 120 kg of P, the addition of 60 t ha^{-1} of biochar increased available P levels by 2.3 times compared to the reference treatment. Treatments without P or with reduced doses (40 kg ha^{-1}) recorded the lowest P levels, differing statistically from treatments with higher P doses.

Table 4. Effects of increasing doses of açaí residue biochar and P on soil available P content and P content in cowpea biomass after 36 days of cultivation in a greenhouse.

Biochar (t ha^{-1})	P (kg ha^{-1})	Soil Available P (mg kg^{-1})	P Plant Content (g kg^{-1})	APE (%)
0	0	11.12 ± 4.23 Ac	1.64 ± 0.18 Ad	-
	40	49.60 ± 9.98 Ab	4.01 ± 0.39 Bc	109.69 ± 3.77 a
	80	88.99 ± 9.85 Ba	6.49 ± 0.38 Ab	56.38 ± 1.89 b
	120	96.37 ± 9.03 Ca	8.29 ± 1.03 Aa	36.74 ± 5.08 c
7.5	0	9.15 ± 0.54 Ad	2.28 ± 0.69 Ac	-
	40	43.58 ± 5.28 Ac	4.31 ± 0.49 ABb	110.26 ± 3.70 a
	80	90.63 ± 16.41 Bb	6.88 ± 0.43 Aa	56.75 ± 5.50 b
	120	166.67 ± 25.65 Ba	7.99 ± 0.23 Aa	37.30 ± 3.14 c
15	0	12.57 ± 0.52 Ac	2.22 ± 0.33 Ad	-
	40	49.60 ± 7.52 Ab	4.47 ± 0.24 ABc	108.96 ± 3.18 a
	80	62.18 ± 13.96 Bb	6.72 ± 0.35 Ab	56.52 ± 9.11 b
	120	174.32 ± 3.28 Ba	8.9 ± 0.57 Aa	35.66 ± 3.30 Ac
30	0	15.86 ± 2.41 Ad	2.2 ± 0.48 Ad	-
	40	52.34 ± 8.10 Ac	5.05 ± 0.18 ABc	117.37 ± 6.25 Aa
	80	92.27 ± 13.03 Bb	6.55 ± 0.83 Ab	54.83 ± 2.05 Ab
	120	170.22 ± 22.15 Ba	8.77 ± 0.64 Aa	38.89 ± 2.94 Ac
60	0	23.47 ± 1.43 Ad	2.8 ± 0.74 Ad	-
	40	56.71 ± 7.76 Ac	5.45 ± 0.1 Ac	107.17 ± 9.93 Aa
	80	146.43 ± 29.68 Ab	6.88 ± 0.75 Ab	56.98 ± 5.47 Ab
	120	208.79 ± 11.83 Aa	8.83 ± 0.82 Aa	37.51 ± 2.65 Ac
Anova	B	***	**	NS
	P	***	***	***
	B × P	***	NS	NS

Mean ± standard deviation ($n = 3$). APE = agronomic P efficiency. P = indicates phosphorus doses. **, ***, Significant at $p < 0.01$ and $p < 0.001$, respectively. NS = not significant ($p > 0.05$). Uppercase letters compare different doses of biochar for each phosphorus dose, while lowercase letters compare different phosphorus doses for each biochar dose according to the F-test from ANOVA and Bonferroni's multiple mean comparison test at the 95% significance level.

Regarding P content in cowpea dry weight, the treatments showed significant differences for both biochar addition ($p < 0.01$) and P ($p < 0.001$), as shown in Table 4. The P content in biomass directly reflected the effects of the treatments, with increases proportional to higher P doses, and statistically different from treatments using lower P dosages. The highest P content (8.83 g kg^{-1}) was observed in the treatment with 60 t ha^{-1} of biochar and 120 kg ha^{-1} of P, statistically differing from the reference treatment, which presented 6.49 g kg^{-1} of P. The increase in plant biomass P content showed signs of stabilisation from the application of 15 t ha^{-1} of biochar combined with 120 kg ha^{-1} of P.

APE was higher at the lower doses of P applied alone. The application of 40 kg ha^{-1} of P achieved an efficiency of 109.69%, while higher doses reduced efficiency to 36.74% with the application of 120 kg ha^{-1} of P. The greatest increase in APE was observed in the treatment that combined 30 t ha^{-1} of biochar with 40 kg ha^{-1} of P, resulting in an efficiency of 117.37%.

3.3. Soil Properties

The addition of biochar and P significantly affected soil pH value ($p < 0.01$), showing an interaction between the evaluated factors (Table 5). In the control treatment, without biochar or P addition, the recorded pH value was 4.86. The isolated addition of biochar at doses of 30 and 60 t ha^{-1} significantly raised the pH ($p < 0.05$) to 5.76 and 5.97, respectively, demonstrating that biochar had a predominant effect in raising pH, especially when compared to treatments without biochar.

Total soil N levels were also significantly affected by the treatments ($p < 0.05$), with an interaction observed between and actions of biochar and P (Table 5). The addition of 60 t ha^{-1} of biochar combined with 40, 80, or 120 kg ha^{-1} of P resulted in the highest total N levels, reaching 2.59, 2.51, and 2.45 g kg^{-1}, respectively, representing an increase of up to 54% compared to the soil reference treatment, which contained 1.68 g kg^{-1} of N.

For exchangeable cations, increasing doses of biochar and P showed a significant interaction between the factors studied for Ca, Al ($p < 0.001$), and Mg ($p < 0.05$). On the other hand, K and Na contents showed significant effects ($p < 0.001$) for both biochar and P, with the availability of both increasing proportionally with biochar doses. Effective CEC also showed a significant interaction ($p < 0.01$) between the factors (Table 5).

Regarding exchangeable Ca, the highest content was observed in the control treatment, without the addition of biochar or P, with a content of 2.45 $cmol_c$ kg^{-1}. In contrast, significant changes in Ca availability were noted in treatments that combined different biochar doses with the highest dose of P (120 kg ha^{-1}), differing statistically from those without P addition.

Exchangeable Mg content significantly decreased with increasing biochar doses, particularly from doses of 15 t ha^{-1}. The highest Mg content was observed in the control treatment, at 1.89 $cmol_c$ kg^{-1}, while the lowest content (1.13 $cmol_c$ kg^{-1}) was found in the combination of 30 t ha^{-1} of biochar and 40 kg ha^{-1} of P.

The highest K levels in the soil were recorded in combinations of biochar (7.5, 30, and 60 t ha^{-1}) with 120 kg ha^{-1} of P reaching 0.11 $cmol_c$ kg^{-1}, an increase of 37.5% compared to the reference treatment (0.08 $cmol_c$ kg^{-1}). Na levels increased significantly with the addition of 60 t ha^{-1} of biochar without P, reaching 1.07 $cmol_c$ kg^{-1}, approximately eight times higher than the reference treatment (0.13 $cmol_c$ kg^{-1}).

The decrease in Al levels was proportional to the increase in biochar doses, dropping from 0.15 $cmol_c$ kg^{-1} in the control treatment to 0.01 $cmol_c$ kg^{-1}. Consequently, soil CEC was highest in the control treatment, with a value of 4.99 $cmol_c$ kg^{-1}. The addition of 60 t ha^{-1} of biochar, in combination with different doses of P, resulted in a reduction of approximately 12% in CEC, a value lower than that observed in the other treatments.

Table 5. Effects of increasing doses of biochar and P on soil chemical properties after 36 days of cowpea cultivation in a greenhouse.

Biochar ($t\ ha^{-1}$)	P ($kg\ ha^{-1}$)	pH	N ($g\ kg^{-1}$)	Ca	Mg	K	Na	Al	CEC
				($cmol_c\ kg^{-1}$)					
0	0	4.86 ± 0.08 Cb	1.78 ± 0.05 Ba	2.45 ± 0.04 Aa	1.89 ± 0.04 Aa	0.07 ± 0.01 Aa	0.44 ± 0.05 Ca	0.15 ± 0.01 Aa	4.99 ± 0.1 Aa
	40	5.33 ± 0.01 Ca	1.81 ± 0.08 BCa	1.97 ± 0.08 Ab	1.52 ± 0.09 ABb	0.08 ± 0 Aa	0.14 ± 0.03 Cb	0.14 ± 0.01 Aab	3.84 ± 0.13 ABb
	80	5.37 ± 0.01 Ba	1.68 ± 0.08 Ca	2.14 ± 0.04 Ab	1.57 ± 0.08 Ab	0.08 ± 0.01 Aa	0.13 ± 0.02 Cb	0.11 ± 0.02 Abc	4.03 ± 0.05 ABb
	120	5.32 ± 0.03 Ba	1.56 ± 0.07 Ca	2.15 ± 0.11 Ab	1.66 ± 0.1 Ab	0.08 ± 0.02 Ba	0.11 ± 0.01 Cb	0.09 ± 0.01 Ac	4.09 ± 0.22 ABb
7.5	0	5.11 ± 0.29 BCb	1.76 ± 0.06 Ba	1.95 ± 0.11 Cbc	1.67 ± 0.09 Aa	0.06 ± 0.02 Ab	0.46 ± 0.09 Ca	0.07 ± 0.02 Ba	4.22 ± 0.25 Ba
	40	5.42 ± 0.03 BCab	1.61 ± 0.16 Ca	1.88 ± 0.05 Ac	1.54 ± 0.05 Aab	0.08 ± 0 Aab	0.16 ± 0.02 Cb	0.07 ± 0.01 Ba	3.73 ± 0.07 Bb
	80	5.44 ± 0.06 Ba	1.74 ± 0.01 Ca	2.15 ± 0.12 Ab	1.65 ± 0.09 Aa	0.09 ± 0 Aa	0.17 ± 0.01 Cb	0.06 ± 0.02 Ba	4.12 ± 0.18 Aab
	120	5.41 ± 0.06 Bab	1.85 ± 0.16 BCa	2.37 ± 0.07 Aa	1.35 ± 0.26 Bb	0.11 ± 0.01 ABa	0.21 ± 0.04 Cb	0.06 ± 0 ABa	4.08 ± 0.34 Bab
15	0	5.31 ± 0.18 Ba	1.94 ± 0.08 Ba	2.28 ± 0.11 ABa	1.35 ± 0.09 Ba	0.06 ± 0.02 Ab	0.48 ± 0.11 Ca	0.06 ± 0.02 Ba	4.23 ± 0.33 Ba
	40	5.45 ± 0.05 BCa	1.93 ± 0.15 Ba	2.02 ± 0.01 Ab	1.21 ± 0.04 Ca	0.09 ± 0.01 Aa	0.25 ± 0.01 Cb	0.07 ± 0.01 Ba	3.64 ± 0.05 Bb
	80	5.42 ± 0.13 Ba	1.80 ± 0.09 Ca	2.04 ± 0.18 Ab	1.22 ± 0.04 Ba	0.09 ± 0.01 Aa	0.21 ± 0.01 Cb	0.07 ± 0.02 Ba	3.63 ± 0.23 Bb
	120	5.49 ± 0.03 ABa	1.94 ± 0.02 Ba	2.27 ± 0.02 Aa	1.22 ± 0.05 Ba	0.09 ± 0.01 ABa	0.22 ± 0.03 Cb	0.07 ± 0.01 ABa	3.88 ± 0.06 Bab
30	0	5.76 ± 0.43 Aa	2.00 ± 0.21 ABa	2.07 ± 0.18 BCab	1.3 ± 0.08 Ba	0.07 ± 0.01 Ab	0.7 ± 0.05 Ba	0.05 ± 0 Ba	4.19 ± 0.3 Ba
	40	5.7 ± 0.07 ABa	1.94 ± 0.20 Ba	1.92 ± 0.07 Ab	1.13 ± 0.17 Ca	0.1 ± 0.01 Aa	0.44 ± 0.02 Bb	0.04 ± 0.01 BCa	3.62 ± 0.24 Bb
	80	5.49 ± 0.05 Ba	2.14 ± 0.08 Ba	2.09 ± 0 Aab	1.26 ± 0.02 Ba	0.1 ± 0.01 Aa	0.46 ± 0.03 Bb	0.04 ± 0.01 BCa	3.96 ± 0.05 ABab
	120	5.58 ± 0.13 ABa	2.11 ± 0.16 Ba	2.27 ± 0.08 Aa	1.3 ± 0.05 Ba	0.11 ± 0.01 Aa	0.45 ± 0.02 Bb	0.06 ± 0.02 ABa	4.19 ± 0.1 ABa
60	0	5.97 ± 0.13 Aa	2.31 ± 0.18 Aa	2.05 ± 0.05 Cab	1.41 ± 0.1 Ba	0.08 ± 0.01 Ab	1.07 ± 0.11 Aa	0.01 ± 0.01 Cb	4.62 ± 0.26 ABa
	40	5.95 ± 0.08 Aa	2.59 ± 0.18 Aa	1.93 ± 0.04 Ab	1.29 ± 0.02 BCa	0.1 ± 0.01 Aab	0.91 ± 0.04 Ab	0.02 ± 0.02 Cab	4.25 ± 0.01 Aa
	80	5.87 ± 0.04 Aa	2.51 ± 0.15 Aa	2.1 ± 0.11 Aab	1.31 ± 0.03 Ba	0.11 ± 0.01 Aa	0.83 ± 0.09 Ab	0.02 ± 0.01 Cab	4.36 ± 0.04 Aa
	120	5.82 ± 0.08 Aa	2.45 ± 0.08 Aa	2.16 ± 0.13 Aa	1.34 ± 0.08 Ba	0.11 ± 0.01 Aa	0.90 ± 0.06 Ab	0.04 ± 0.01 Ba	4.55 ± 0.19 Aa
Anova	B	***	***	*	***	***	***	***	***
	P	*	NS	***	***	***	***	NS	***
	B × P	**	*	***	*	NS	NS	***	**

Mean ± standard deviation (n = 3). P indicates phosphorus doses. *, **, ***, Significant at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively. NS = not significant ($p > 0.05$). Uppercase letters compare different doses of biochar for each phosphorus dose, while lowercase letters compare different phosphorus doses for each biochar dose according to the F-test from ANOVA and Bonferroni's multiple mean comparison test at the 95% significance level.

3.4. Soil Organic Carbon (SOC) and Easily Extractable Glomalin (EE-GRSP)

The treatments significantly influenced SOC content ($p < 0.05$), showing an interaction between biochar and P action (Table 6). The highest SOC content was observed in the treatment with 30 t ha^{-1} of biochar without P addition, reaching 39.37 g kg^{-1}, representing a 6% increase compared to the reference treatment (37.01 g kg^{-1}). In general, the addition of biochar at doses starting from 15 t ha^{-1}, combined with higher doses of P (between 80 and 120 kg ha^{-1}), resulted in SOC levels that did not differ statistically from the reference treatment. Additionally, the treatments showed no significant effects ($p > 0.05$) from the study factors on EE-GRSP levels (Table 6).

Table 6. Effects of increasing doses of biochar and P on SOC and EE-GRSP after 36 days of cowpea cultivation in a greenhouse.

Biochar (t ha^{-1})	**P (kg ha^{-1})**	**SOC (g kg^{-1})**	**EE-GRSP (mg g^{-1})**
0	0	37.35 ± 2.13 ABa	0.79 ± 0.14 ABb
	40	35.94 ± 3.83 ABa	1.05 ± 0.09 Aab
	80	37.01 ± 0.78 Aa	1.14 ± 0.14 Aa
	120	31.52 ± 0.52 Aa	0.94 ± 0.12 Aab
7.5	0	31.71 ± 2.13 Bb	0.73 ± 0.06 Bb
	40	31.29 ± 3.80 Bb	1.05 ± 0.1 Aa
	80	38.34 ± 2.21 Aa	0.84 ± 0.16 ABab
	120	36.32 ± 3.59 Aab	0.92 ± 0.03 Aab
15	0	37.44 ± 2.43 ABa	0.93 ± 0.04 Aba
	40	38.22 ± 1.25 Aa	1.01 ± 0.08 Aa
	80	35.65 ± 4.50 Aa	0.79 ± 0.11 Ba
	120	35.21 ± 3.19 Aa	0.88 ± 0.15 Aa
30	0	39.37 ± 4.28 Aa	1.05 ± 0.27 ABa
	40	34.24 ± 0.87 ABa	0.98 ± 0.24 Aa
	80	36.96 ± 1.85 Aa	0.97 ± 0.09 ABa
	120	37.25 ± 1.97 Aa	1.01 ± 0.06 Aa
60	0	37.62 ± 1.04 ABa	1.06 ± 0.03 Aa
	40	35.19 ± 0.42 ABa	1.02 ± 0.18 Aa
	80	36.58 ± 2.89 Aa	0.89 ± 0.18 ABa
	120	36.95 ± 1.58 Aa	1.03 ± 0.03 Aa
	B	NS	NS
Anova	P	NS	NS
	B × P	*	NS

Mean ± standard deviation ($n = 3$). SOC = Soil organic carbon. EE-GRSP = easily extractable glomalin. P indicates phosphorus doses. *, Significant at $p < 0.05$, NS = not significant ($p > 0.05$). Uppercase letters compare different doses of biochar for each phosphorus dose, while lowercase letters compare different phosphorus doses for each biochar dose according to the F-test from analysis of variance (ANOVA) and Bonferroni's multiple mean comparison test at the 95% significance level.

3.5. Correlation Between Soil Factors and Biological Components of Cowpea

Pearson's correlation analysis showed a very strong positive correlation between cowpea biomass and leaf number (r = 0.91, $p < 0.01$), a strong positive correlation with leaf area (r = 0.80, $p < 0.01$), P content in plant dry weight (r = 0.78, $p < 0.01$), cowpea height (r = 0.78, $p < 0.01$), and root dry weight (r = 0.71, $p < 0.01$). Additionally, a moderate positive correlation was observed between biomass and exchangeable soil K content (r = 0.66, $p < 0.01$) and available P (r = 0.62, $p < 0.01$), as shown in Table 7.

Table 7. Pearson correlation matrix between soil factors and biological components of cowpea after a greenhouse experiment with 36 days of cultivation.

Variables	Height	Leaves	Leaf Area	Biomass	Root	pH	E. Al	SOC	Total N	Soil AP	E. Na	E. K	E. Ca	E. Mg	CEC	PPC	EE-GRSP
Height	1																
Leaves	0.73 **	1															
Leaf area	0.63 **	0.70 **	1														
Biomass	0.78 **	0.91 **	0.80 **	1													
Root	0.45 **	0.62 **	0.65 **	0.71 **	1												
pH	0.37 **	0.26 *	0.51 **	0.29 *	0.39 **	1											
E. Al	−0.12	−0.06	−0.34	−0.12	−0.18	−0.76	1										
SOC	0.03	−0.15	0.04	−0.07	−0.06	0.19	−0.02	1									
Total N	0.11	0.03	0.22	0.07	0.17	0.71 **	−0.63	0.26 *	1								
Soil AP	0.50 **	0.60 **	0.58 **	0.62 **	0.41 **	0.28 *	−0.20	0.02	0.28 *	1							
E. Na	−0.23	−0.36	−0.06	−0.33	−0.04	0.61 **	−0.62	0.21	0.81 **	−0.02	1						
E. K	0.49 **	0.52 **	0.52 **	0.66 **	0.48 **	0.35 **	−0.34	0.08	0.41 **	0.66 **	0.17	1					
E. Ca	−0.15	−0.14	−0.18	−0.16	−0.20	−0.26	0.20	0.33 *	−0.03	0.34 **	−0.09	0.10	1				
E. Mg	−0.36	−0.40	−0.46	−0.36	−0.24	−0.55	0.53 **	−0.07	−0.41	−0.29	−0.21	−0.36	0.30 *	1			
CEC	−0.44	−0.55	−0.39	−0.51	−0.25	0.00	−0.02	0.28 *	0.36 **	−0.01	0.57 **	−0.01	0.57 **	0.56 **	1		
PPC	0.61 **	0.77 **	0.67 **	0.78 **	0.47 **	0.23	−0.16	−0.04	0.12	0.89 **	−0.21	0.68 **	0.18	−0.29	−0.22	1	
EE-GRSP	0.20	0.20	0.26 *	0.22	0.25	0.40 **	−0.12	0.18	0.17	0.06	0.10	0.01	−0.10	−0.15	−0.07	0.07	1

**, Correlation is significant at the 0.01 level. *, Correlation is significant at the 0.05 level. E. = exchangeable cations. Soil AP = Soil available P. PPC = Plant P content.

Available P content also showed a strong positive correlation with P content in cowpea dry weight (r = 0.89, $p < 0.01$) and a moderate positive correlation with exchangeable soil K (r = 0.66, $p < 0.01$), leaf number (r = 0.60, $p < 0.01$), leaf area (r = 0.58, $p < 0.01$), and cowpea height (r = 0.50, $p < 0.01$). In turn, P content in cowpea dry weight also demonstrated a strong positive correlation with leaf number (r = 0.77, $p < 0.01$) and a moderate positive relationship with leaf area (r = 0.67, $p < 0.01$) and plant height (r = 0.61, $p < 0.01$).

For soil pH, a strong positive correlation was observed with total N content (r = 0.71, $p < 0.01$) and a moderate positive correlation with exchangeable Na content (r = 0.61, $p < 0.01$) and leaf area (r = 0.51, $p < 0.01$). Total N content also showed a strong positive relationship with exchangeable Na content (r = 0.81, $p < 0.01$). Finally, CEC demonstrated a moderate positive relationship with exchangeable Na and Ca contents (r = 0.57, $p < 0.01$) and with exchangeable Mg content (r = 0.56, $p < 0.01$).

4. Discussion

The P content in cowpea dry biomass increased with rising doses of P, especially when combined with biochar, suggesting that biochar enhanced P availability to the plants [33,34]. The high positive correlation (r = 0.89, $p < 0.01$) between available soil P and P content in cowpea dry weight indicates a strong association between soil available P content and its accumulation in cowpea tissue (Table 7). These correlations suggest that overall plant growth is closely related to P uptake [35], highlighting the essential role of inorganic fertiliser in promoting cowpea height, leaf number, leaf area, biomass, and root growth. The linear fit ($R^2 = 0.791$) indicates that 79.1% of the variation in P accumulation in biomass can be explained by soil available P content, with an increase of 0.04 g kg^{-1} in P in plant dry biomass for each increment in available soil P content (Figure 4).

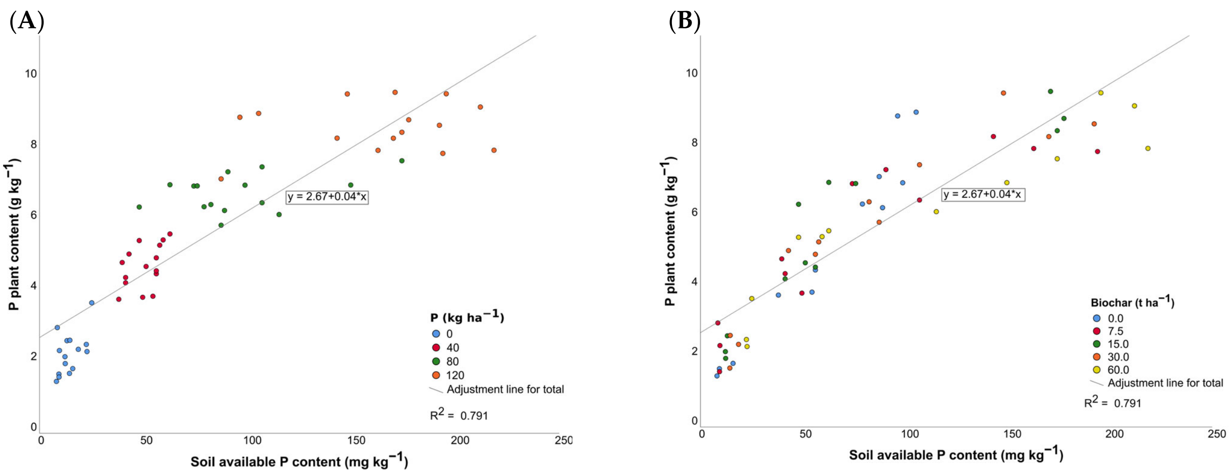

Figure 4. Scatterplot of available soil P content (mg kg^{-1}) in relation to P content in cowpea dry biomass (g kg^{-1}) following the application of açaí waste biochar and inorganic P. (**A**) Variables as a function of different inorganic P doses (0, 40, 80, and 120 kg ha^{-1}). (**B**) Variables as a function of different biochar doses (0, 7.5, 15, 30, and 60 t ha^{-1}). Means (n = 3) obtained after 36 days of greenhouse cultivation.

Although the combination of biochar and P increased pH, total N, exchangeable cations, and available P content, no significant interaction between the study factors was observed for the biological components of cowpea, except for height (Table 3). This effect may be attributed to biochar, which temporarily immobilises P and releases it gradually [36]. However, this slower release may not have sufficed to meet the demands of cowpea, a short-cycle plant requiring rapid nutrient availability [28], particularly in tropical ecosystems, where P is often the primary limiting factor for primary production [36].

The increase in biochar and P levels had a limited impact on APE in cowpea in the short term. The addition of 60 t ha^{-1} of biochar and 80 kg ha^{-1} of P resulted in only a 0.60% increase in APE compared to the reference treatment, which showed 56.38%. The most significant increase in APE was observed in the treatment with the addition of 30 t ha^{-1} of biochar and 40 kg ha^{-1} of P, which enhanced phosphorus efficiency by 7.7% compared to the treatment using only P, which achieved an APE of 109.69%.

The application of P in reduced doses (40 kg ha^{-1}), combined with different doses of biochar, did not represent an increase in P availability. P availability at low concentrations in soil solution is reduced due to the formation of bidentate complexes by P anions at high-energy sorption sites on the sorbent surface, making P less accessible to plants [37]. In contrast, the authors argue that high P concentrations in the solution, in addition to forming bidentate complexes, promote the formation of exchangeable monodentate complexes, which are more readily available to plants.

The increase in available P content was particularly observed with biochar application starting from 7.5 t ha^{-1} combined with 120 kg ha^{-1} of P. The application of 60 t ha^{-1} of biochar combined with 80 kg ha^{-1} of P showed potential to substantially enhance phosphate fertilisation efficiency. This effect may be attributed to the high P adsorption capacity in clayey Ferralsol, which required high doses of biochar or P to increase P availability for plants, possibly due to the presence of free oxides of Fe, Al, and Mn [33,34].

Furthermore, P adsorption by the soil may also have been favoured by its pH, which, even at higher biochar doses (from 30 to 60 t ha^{-1}), remained below the optimal range for P availability (between 6.0 and 6.5), making P more susceptible to immobilisation by Fe and Al [35]. Even so, in this pH range, the dominant form of P is the $H_2PO_4^-$ ion, which has lower adsorption free energy, facilitating its adsorption by biochar [15].

Biochar characteristics, such as the C:N ratio, mainly influenced by feedstock type and pyrolysis temperature, explain 59% of the variability in available soil P response [16]. In this regard, the high C:N ratio of açaí waste biochar (232.85), derived from lignin-rich biomass with low P content, appears to enhance its efficacy in promoting P availability, particularly at high biochar doses [16].

The addition of açaí waste biochar at doses of 7.5 t ha^{-1}, 15 t ha^{-1}, 30 t ha^{-1}, and 60 t ha^{-1} resulted in the application of approximately 44.25 kg, 88.5 kg, 177 kg, and 354 kg of P to the soil, respectively. Starting from 15 t ha^{-1}, biochar could potentially supply the required amount of P for cowpea development [28]. Between 5 and 20% of the P in biochar may be considered available [36]. Pyrolysis conditions influence retained and lost nutrients, making nutrient availability to plants highly variable [38].

P release from biochar is regulated by the same factors that determine P availability in the soil [39]. According to these authors, the water and soil environment, such as pH and the composition and concentration of cations, determines whether P derived from biochar will be used by plants, leached, or immobilised. Açaí waste biochar had a $CaCO_3$ equivalent content of 4.2%, with liming power classified as class 1 on a scale from 0 to 3, according to the International Biochar Initiative (IBI) [27].

In acidic soils, small pH changes can result in a substantial reduction in P precipitation with Al and Fe [36]. The increase in soil pH favoured cowpea growth by reducing the negative effects of acidic soils, making nutrients more available and plants less susceptible to pests and diseases [40]. This effect was particularly observed with total N (r = 0.71, $p < 0.01$), a macronutrient related to plant growth.

The addition of 30 and 60 t ha^{-1} of açaí waste biochar, combined with different doses of P, significantly raised soil pH value, which ranged from 5.49 to 5.97, favouring cowpea development, which requires a pH around 5.5 [41]. Compared to the control soil, these same treatments increased pH by up to 1.1 units, indicating a significant effect in reducing soil acidity with biochar application [42].

Soil pH neutralisation primarily occurred through the neutralisation of exchangeable Al in the soil, which was initially at 0.15 $cmol_c\ kg^{-1}$ in the control soil and reduced to 0.01 $cmol_c\ kg^{-1}$ with the addition of 60 t ha^{-1} of biochar. This reduction can be attributed to the increased precipitation of Al as hydroxides, as well as the formation of organometallic complexes with organic ligands released by the biochar [33].

Additionally, the chemical and physical properties of açaí biochar can directly influence the acid–base balance in the soil. In this study, factors inherent to açaí waste biochar, such as its alkalinity (pH of 8.86 in H_2O), high CEC (41.25 $mmol_c\ kg^{-1}$), and the presence of functional groups on its surface, such as carboxyls (COO^-), carbonates ($CaCO_3$), phosphates ($PO_4{}^{3-}$), and other alkaline substances [43], likely acted together to neutralise soil pH. Alkaline biochars release basic ions, such as hydroxyls (OH^-) and carbonates ($CO_3{}^{2-}$), which help neutralise soil acidity [43].

The alkaline substances present in biochar, derived from equivalent base cations, interact with soil minerals, raising the pH value. This interaction is considered more relevant to soil pH elevation than the biochar's inherent pH [44]. Soil solution pH influences both nutrient mobility and nutrient release from biochar itself, affecting nutrient availability in the soil solution, especially P [38].

The basic cations present in biochar can impart a high positive charge potential to its surface, facilitating the formation of divalent cation bridges, which favour the sorption of negatively charged P ions [33]. The Ca content in açaí biochar contributed to greater P availability in the soil, considering that maximum P release in soil is favoured by low Ca concentrations in the biochar (<1%) and soil solution, as well as a Ph value below 7.5 at the soil–biochar interface [39]. The high K concentration in biochar may have intensified competition for cation exchange sites, disadvantaging Mg absorption, although CEC selectivity is often reported as preferential for the following cations: $Al^{3+} > Ca^{2+} > Mg^{2+} > K^+ \approx NH_4{}^+ > Na^+$ [45].

Açaí biochar also significantly impacted available N content in the soil, suggesting that this material positively influences soil N availability. These findings are supported by observations indicating that the combined application of biochar and phosphate fertiliser increases total soil nitrogen (N) levels with increasing doses of biochar [42]. An increase in total nitrogen (N) content in maize and wheat crops promoted by forest waste biochar was also reported [46].

In this study, although effects on SOC levels were observed due to the interaction between biochar and P, which can positively affect soil health and fertility [47] and provide a potential source of bioavailable C for soil microorganisms [48], no significant impacts of these factors were found on EE-GRSP concentrations. In the reference treatment, the EE-GRSP concentration (1.14 mg g^{-1}) was lower than the values reported in another study, which ranged from 2.41 to 3.5 mg g^{-1} of EE-GRSP in the Brazilian Amazon forest [49]. EE-GRSP produced by arbuscular mycorrhizal fungi contributed 8.67% to SOC storage, within a total of 23.26% of total glomalin, acting as a potent carbon sink [48].

The observed results for EE-GRSP can be attributed to the high recalcitrance of the biochar used in this study, characterised by a low content of labile carbon fraction and a higher proportion of stable organic carbon, as indicated by the H/C ratio of 0.23. It is estimated that 538 g kg^{-1} of this C will remain in the soil for at least 100 years, corresponding to class 4 of the IBI carbon storage classification [24]. This characteristic favours a gradual increase in SOC due to the stabilisation of labile carbon by biochar [50]. The low labile carbon content of açaí biochar, combined with the short interaction period with the soil, may have been insufficient to induce significant changes in the mycorrhizal fungal community and, consequently, EE-GRSP production. The addition of biochar and P improved key soil properties related to mycorrhizal response, such as pH, SOC, and CEC [49]. In the short term, this improvement may not have been sufficient to influence EE-GRSP production.

Therefore, based on the evaluated parameters, the increase in the soil's available P content can be attributed to enhanced P solubility, promoted by reduced soil acidity and increased exchangeable cations [17]. In acidic soils, the addition of alkaline metals (Ca, Mg, the K), either as soluble salts or through biochar exchange sites, likely represents the most significant effect of biochar on short-term P solubility [36]. The authors further suggest that biochar may influence long-term P bioavailability through several mechanisms associated with P precipitation, such as the adsorption of biochar-induced chelating organic molecules.

5. Conclusions

The application of P had a significant effect on the biological components evaluated for cowpea (length, number of leaves, leaf area, aerial dry biomass, and root dry mass), while reduced P doses negatively impacted plant growth and biomass production. Açaí residue biochar exhibited significant effects only on leaf area. The increase in biochar and P levels resulted in a maximum short-term enhancement of 7.7% in APE for cowpea, possibly due to the high recalcitrance of açaí residue biochar and the strong adsorption energy of Ferralsol.

The application of açaí residue biochar in combination with P improved the chemical properties of Ferralsol. Compared to the control treatment, the available P content in the soil increased by 2.3 times with the application of 60 t ha^{-1} of biochar and by 1.87 times with 7.5 t ha^{-1} of biochar, both combined with 120 kg ha^{-1} of P.

The application of 60 t ha^{-1} of biochar yielded the most notable results in increasing soil pH value (without the addition of P). It also promoted a 54% increase in total N content (with 40 kg of P) and a 37.5% increase in K content (with 80 kg of P). The co-application of increasing rates of biochar and P also enhanced the levels of Ca, Na (eight-fold), effective CEC, and SOC (6%), while significantly reducing the exchangeable Mg and Al contents. In contrast, the EE-GRSP levels were not influenced by the studied factors.

In the short term, biochar did not demonstrate a significant effect as a P source, as observed in treatments with reduced P doses. Instead, biochar modified the soil environment, promoting increased P solubility and availability. The tested hypothesis was partially confirmed by the improvement in soil chemical properties and increased P availability; however, no significant interaction between action of different doses of biochar and P on cowpea biological components was observed.

The agronomic utilisation of this biochar can be implemented gradually through annual fractional applications, as it accumulates over time, similar to the practises developed by the Indigenous peoples of the Amazon for the formation of Amazonian Dark Earth. This management approach enables the achievement of multiple benefits, including improvements in soil fertility and the sustainability of agricultural systems.

Açaí waste biochar has the potential to generate more significant effects in future cultivation cycles, due to its slow nutrient release. It is therefore recommended that future studies explore its long-term impacts under field conditions. The use of this biochar emerges as a promising approach, particularly in remote regions like the Amazon, where agricultural inputs are costly. In addition to enhancing soil properties, biochar can contribute to carbon emission reduction, aligning with Sustainable Development Goal 13.

Author Contributions: A.R.d.O.B.: Conceptualization, Methodology, Investigation, Writing, Funding acquisition; V.J.: Reviewing, Funding acquisition; C.K.A.d.O.D.: Project administration; H.M.S.: Investigation, Methodology, Reviewing; F.E.D.: Investigation; C.S.d.C.M.-d.-S.: Supervision, Reviewing;

D.M.d.O.: Methodology, Reviewing; N.P.d.S.F.: Supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Amazonas State Research Foundation (Fundação de Amparo à Pesquisa do Estado do Amazonas—FAPEAM) through Notice Number 001/2021—Women in Science, Process Number 01.02.016301.01742/2021.

Data Availability Statement: All data are available and can be provided upon request.

Acknowledgments: The authors express deep gratitude for the support received at all stages of this research from the Federal Institute of Education of Amazonas (IFAM—Brazil), the National Institute of Amazonian Research (INPA—Brazil) and the Terra Preta Nova da Amazônia Central Research Group. We express our gratitude to the Doctoral Program in Climate Change and Sustainable Development Policies, the Institute of Social Sciences of the University of Lisbon (ICS-UL), and the School of Agriculture (ISA-UL). This work was supported by FCT—Fundação para a Ciência e Tecnologia, I.P. through project references UIDB/00239/2020 (DOI 10.54499/UIDB/00239/2020) and UIDP/00239/2020 (DOI 10.54499/UIDP/00239/2020).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Lehmann, D.C.; Glaser, B.; Woods, W.I. *Dark Earths: Origin, Properties, Management*; Springer: Dordrecht, The Netherlands, 2003; 505p.
2. Teixeira, W.G.; Kern, D.C.; Madari, B.E.; Lima, H.N.; Woods, W. *As Terras Pretas de Índio da Amazônia: Sua Caracterização e Uso Deste Conhecimento na Criação de Novas Áreas*; Embrapa Amazônia Ocidental: Manaus, Brazil, 2009; ISBN 85-89111-06-7.
3. Falcão, N.P.d.S.; Silva, J.R.A.d. Características de adsorção de fósforo em alguns solos da Amazônia Central. *Acta Amaz.* **2004**, *34*, 337–342. [CrossRef]
4. Lehmann, J. Terra Preta Nova—Where to from Here? In *Amazonian Dark Earths: Wim Sombroek's Vision*; Woods, W.I., Teixeira, W.G., Steiner, C., WinklerPrins, A., Rebellato, L., Eds.; Springer: Dordrecht, The Netherlands, 2009; pp. 473–486. ISBN 978-1-4020-9031-8.
5. Sombroek, W.I.M.; Ruivo, M.D.L.; Fearnside, P.M.; Glaser, B.; Lehmann, J. Amazonian Dark Earths as Carbon Stores and Sinks. In *Amazonian Dark Earths: Origin Properties Management*; Springer: Dordrecht, the Netherlands, 2003; pp. 125–139.
6. Schellekens, J.; Santos, T.; Maceido, R.; Buurman, P.; Kuyper, T.; Vidal-Torrado, P. Molecular Composition of Several Soil Organic Matter Fractions from Anthropogenic Black Soils (Terra Preta de Índio) in Amazonia—A Pyrolysis-GC/MS Study. *Geoderma* **2017**, *288*, 154. [CrossRef]
7. Agyekum, E.B.; Nutakor, C. Recent Advancement in Biochar Production and Utilization—A Combination of Traditional and Bibliometric Review. *Int. J. Hydrogen Energy* **2024**, *54*, 1137–1153. [CrossRef]
8. Wang, J.; Wang, B.; Bian, R.; He, W.; Liu, Y.; Shen, G.; Xie, H.; Feng, Y. Bibliometric Analysis of Biochar-Based Organic Fertilizers in the Past 15 Years: Focus on Ammonia Volatilization and Greenhouse Gas Emissions during Composting. *Environ. Res.* **2024**, *243*, 117853. [CrossRef]
9. Leng, L.; Huang, H.; Li, H.; Li, J.; Zhou, W. Biochar Stability Assessment Methods: A Review. *Sci. Total Environ.* **2019**, *647*, 210–222. [CrossRef]
10. Wang, D.; Jiang, P.; Zhang, H.; Yuan, W. Biochar Production and Applications in Agro and Forestry Systems: A Review. *Sci. Total Environ.* **2020**, *723*, 137775. [CrossRef]
11. Lehmann, J.; Joseph, S. *Biochar for Environmental Management: Science, Technology and Implementation*, 2nd ed.; Routledge: London, UK, 2015; ISBN 978-0-415-70415-1.
12. Liu, Z.; Dugan, B.; Masiello, C.A.; Gonnermann, H.M. Biochar particle size, shape, and porosity act together to influence soil water properties. *PLoS ONE* **2017**, *12*, e0179079. [CrossRef]
13. Yang, Y.; Sun, K.; Han, L.; Chen, Y.; Liu, J.; Xing, B. Biochar Stability and Impact on Soil Organic Carbon Mineralization Depend on Biochar Processing, Aging and Soil Clay Content. *Soil Biol. Biochem.* **2022**, *169*, 108657. [CrossRef]
14. Semida, W.M.; Beheiry, H.R.; Sétamou, M.; Simpson, C.R.; Abd El-Mageed, T.A.; Rady, M.M.; Nelson, S.D. Biochar Implications for Sustainable Agriculture and Environment: A Review. *S. Afr. J. Bot.* **2019**, *127*, 333–347. [CrossRef]
15. Xue, P.; Hou, R.; Fu, Q.; Li, T.; Wang, J.; Zhou, W.; Shen, W.; Su, Z.; Wang, Y. Potentially Migrating and Residual Components of Biochar: Effects on Phosphorus Adsorption Performance and Storage Capacity of Black Soil. *Chemosphere* **2023**, *336*, 139250. [CrossRef]
16. Gao, S.; DeLuca, T.H.; Cleveland, C.C. Biochar Additions Alter Phosphorus and Nitrogen Availability in Agricultural Ecosystems: A Meta-Analysis. *Sci. Total Environ.* **2019**, *654*, 463–472. [CrossRef] [PubMed]

17. Gao, S.; DeLuca, T.H. Influence of Biochar on Soil Nutrient Transformations, Nutrient Leaching, and Crop Yield. *Adv. Plants Agric. Res* **2016**, *4*, 1–16.
18. Rafael, R.B.A.; Fernández-Marcos, M.L.; Cocco, S.; Ruello, M.L.; Fornasier, F.; Corti, G. Benefits of Biochars and NPK Fertilizers for Soil Quality and Growth of Cowpea (*Vigna unguiculata* L. Walp.) in an Acid Arenosol. *Pedosphere* **2019**, *29*, 311–333. [CrossRef]
19. Bentes, V.L.I. *Preparação e Caracterização de Compósitos a Base de Fosfatos de Ferro Suportados em Carvões Ativados de Resíduos de Caroços de Açaí e do Endocarpo de Tucumã para Aplicação Ambiental*; UFAM: Manaus, Brazil, 2017.
20. Miranda, L.d.V.A.; Mochiutti, S.; Cunha, A.C.d.; Cunha, H.F.A. Descarte e Destino Final de Caroços de Açaí na Amazônia Oriental-Brasil. *Ambiente Soc.* **2022**, *25*, e01382.
21. Neto, H.H.L.C.; Souza, I.V.d.; Façanha, A.C.M.; Santos, A.V.A.d.; Silva, A.G.d.; Pereira, C.E.d.R.; Silvestre, R.C.M.; Jean, R.N.P. A disposição final de caroço de açaí no distrito administrativo de Icoaraci, Pará. *Rev. Cient. Fac. Educ. Meio Ambiente* **2023**, *14*, 221–236. [CrossRef]
22. IBGE Produção de Açaí (Cultivo) No Brasil | IBGE. Available online: https://www.ibge.gov.br/explica/producao-agropecuaria/acai-cultivo/br (accessed on 26 March 2024).
23. Sato, M.K.; de Lima, H.V.; Costa, A.N.; Rodrigues, S.; Pedroso, A.J.S.; de Freitas Maia, C.M.B. Biochar from Acai Agroindustry Waste: Study of Pyrolysis Conditions. *Waste Manag.* **2019**, *96*, 158–167. [CrossRef]
24. John, V.; Braga, A.R.d.O.; Danielli, C.K.A.d.O.; Sousa, H.M.; Danielli, F.E.; de Araujo, R.O.; Marques-dos-Santos, C.; Falcão, N.P.d.S.; Guerra, J.F.C. Characterization of Biochar Produced in a Mobile Handmade Kiln from Small-Sized Waste Biomass for Agronomic and Climate Change Benefits. *Agronomy* **2024**, *14*, 1861. [CrossRef]
25. Sato, M.K.; de Lima, H.V.; Noronha Costa, A.; Rodrigues, S.; Mooney, S.J.; Clarke, M.; Silva Pedroso, A.J.; de Freitas Maia, C.M.B. Biochar as a Sustainable Alternative to Açaí Waste Disposal in Amazon, Brazil. *Process Saf. Environ. Prot.* **2020**, *139*, 36–46. [CrossRef]
26. Teixeira, P.C.; Donagemma, G.K.; Fontana, A.; Teixeira, W.G. *Manual de Métodos de Análise de Solo*; Embrapa: Rio de Janeiro, Brazil, 2017; 573p.
27. John, V.; Braga, A.R.d.O.B.; Oliveira Danielli, C.K.A.d.; Sousa, H.M.; Danielli, F.E.; Marques-dos-Santos, C.; Falcão, N.P.d.S.; Guerra, J.F.C. Economic Feasibility Analysis of Biochar as a Soil Amendment in Central Amazonia: A Case Study and Perspectives. 2025, *in press*.
28. Oliveira, I.J.; Fontes, J.R.A.; Dias, M.C.; Barreto, J.F. *Recomendações Técnicas para o Cultivo do Feijão-Caupi no Estado do Amazonas*; Embrapa Amazônia Ocidental: Manaus, Brazil, 2019; p. 30.
29. Yan, X.; Chen, X.; Ma, C.; Cai, Y.; Cui, Z.; Chen, X.; Wu, L.; Zhang, F. What Are the Key Factors Affecting Maize Yield Response to and Agronomic Efficiency of Phosphorus Fertilizer in China? *Field Crops Res.* **2021**, *270*, 108221. [CrossRef]
30. Walkley, A.; Black, I.A. An Examination of the Degtjareff Method for Determining Soil Organic Matter, and a Proposed Modification of the Chromic Acid Titration Method. *Soil Sci.* **1934**, *37*, 29–38. [CrossRef]
31. Wright, S.F.; Upadhyaya, A. Extraction of an Abundant and Unusual Protein from Soil and Comparison with Hyphal Protein of Arbuscular Mycorrhizal Fungi. *Soil Sci.* **1996**, *161*, 575–586. [CrossRef]
32. Bradford, M.M. A Rapid and Sensitive Method for the Quantitation of Microgram Quantities of Protein Utilizing the Principle of Protein-Dye Binding. *Anal. Biochem.* **1976**, *72*, 248–254. [CrossRef] [PubMed]
33. Chintala, R.; Schumacher, T.E.; McDonald, L.M.; Clay, D.E.; Malo, D.D.; Papiernik, S.K.; Clay, S.A.; Julson, J.L. Phosphorus Sorption and Availability from Biochars and Soil/Biochar Mixtures. *CLEAN—Soil Air Water* **2014**, *42*, 626–634. [CrossRef]
34. Sharma, S.; Sekhon, B.S.; Singh, P.; Siddiqui, M.H.; Kesawat, M.S. Response of Biochar Derives from Farm Waste on Phosphorus Sorption and Desorption in Texturally Different Soils. *Heliyon* **2023**, *9*, e19356. [CrossRef]
35. Blume, H.-P.; Brümmer, G.W.; Fleige, H.; Horn, R.; Kandeler, E.; Kögel-Knabner, I.; Kretzschmar, R.; Stahr, K.; Wilke, B.-M. Soil-Plant Relations. In *Scheffer/SchachtschabelSoil Science*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 409–484.
36. DeLuca, T.H.; Gundale, M.J.; MacKenzie, M.D.; Jones, D.L. Biochar Effects on Soil Nutrient Transformations. In *Biochar for Environmental Management*; Routledge: London, UK, 2015; pp. 421–454.
37. Sparks, D.L.; Singh, B.; Siebecker, M.G. *Environmental Soil Chemistry*; Academic Press: Amsterdam, The Netherlands, 2024.
38. Ippolito, J.A.; Spokas, K.A.; Novak, J.M.; Lentz, R.D.; Cantrell, K.B. Biochar Elemental Composition and Factors Influencing Nutrient Retention. In *Biochar for Environmental Management*; Routledge: London, UK, 2015; pp. 139–163.
39. Buss, W.; Assavavittayanon, K.; Shepherd, J.G.; Heal, K.V.; Sohi, S. Biochar Phosphorus Release Is Limited by High pH and Excess Calcium. *J. Environ. Qual.* **2018**, *47*, 1298–1303. [CrossRef]
40. El-Naggar, A.; Lee, S.S.; Awad, Y.M.; Yang, X.; Ryu, C.; Rizwan, M.; Rinklebe, J.; Tsang, D.C.W.; Ok, Y.S. Influence of Soil Properties and Feedstocks on Biochar Potential for Carbon Mineralization and Improvement of Infertile Soils. *Geoderma* **2018**, *332*, 100–108. [CrossRef]
41. Cardoso, M.J. *A Cultura do Feijão Caupi No Meio-Norte do Brasil*; Embrapa Meio-Norte: Teresina, Brazil, 2000.

42. Phares, C.A.; Atiah, K.; Frimpong, K.A.; Danquah, A.; Asare, A.T.; Aggor-Woananu, S. Application of Biochar and Inorganic Phosphorus Fertilizer Influenced Rhizosphere Soil Characteristics, Nodule Formation and Phytoconstituents of Cowpea Grown on Tropical Soil. *Heliyon* **2020**, *6*, e05255. [CrossRef]
43. Geng, N.; Kang, X.; Yan, X.; Yin, N.; Wang, H.; Pan, H.; Yang, Q.; Lou, Y.; Zhuge, Y. Biochar Mitigation of Soil Acidification and Carbon Sequestration Is Influenced by Materials and Temperature. *Ecotoxicol. Environ. Saf.* **2022**, *232*, 113241. [CrossRef]
44. Nkoh, J.N.; Baquy, M.A.-A.; Mia, S.; Shi, R.; Kamran, M.A.; Mehmood, K.; Xu, R. A Critical-Systematic Review of the Interactions of Biochar with Soils and the Observable Outcomes. *Sustainability* **2021**, *13*, 13726. [CrossRef]
45. Graver, E.R.; Singh, B.; Hanley, K.; Lehmann, J. Determination of Cation Exchange Capacity in Biochar. In *Biochar: A Guide to Analytical Methods*; CRC Press: Boca Raton, FL, USA, 2017.
46. Arif, M.; Ilyas, M.; Riaz, M.; Ali, K.; Shah, K.; Ul Haq, I.; Fahad, S. Biochar Improves Phosphorus Use Efficiency of Organic-Inorganic Fertilizers, Maize-Wheat Productivity and Soil Quality in a Low Fertility Alkaline Soil. *Field Crops Res.* **2017**, *214*, 25–37. [CrossRef]
47. Gross, A.; Bromm, T.; Glaser, B. Soil Organic Carbon Sequestration after Biochar Application: A Global Meta-Analysis. *Agronomy* **2021**, *11*, 2474. [CrossRef]
48. He, J.-D.; Chi, G.-G.; Zou, Y.-N.; Shu, B.; Wu, Q.-S.; Srivastava, A.K.; Kuča, K. Contribution of Glomalin-Related Soil Proteins to Soil Organic Carbon in Trifoliate Orange. *Appl. Soil Ecol.* **2020**, *154*, 103592. [CrossRef]
49. Rodríguez-Rodríguez, R.M.; Kemmelmeier, K.; Pedroso, D.d.F.; Pinto, F.A.; dos Santos, J.V.; Gastauer, M.; Caldeira, C.F.; Ramos, S.J.; Siqueira, J.O.; Carneiro, M.A.C. Native Arbuscular Mycorrhizal Fungi Respond to Rehabilitation in Iron Ore Mining Areas from the Eastern Brazilian Amazon. *Pedobiologia* **2021**, *89*, 150768. [CrossRef]
50. Li, S.; Tasnady, D. Biochar for Soil Carbon Sequestration: Current Knowledge, Mechanisms, and Future Perspectives. *C* **2023**, *9*, 67. [CrossRef]