agronomy

Article

Effects of Peanut Insertion on Soil Dynamics in Fallow Areas

Heytor Lemos Martins [1,*], Vanesca Korasaki [2], Arthur Nardi Campalle [1], João Francisco Damião Zanqueta [1], Andrey Batalhão de Oliveira [1], Mariana Casari Parreira [3] and Pedro Luís da Costa Aguiar Alves [1]

1 Department of Biology, School of Agricultural and Veterinary Sciences, São Paulo State University (UNESP), Jaboticabal 14884-900, Brazil; arthur.nardi@unesp.br (A.N.C.); jf.zanqueta@unesp.br (J.F.D.Z.); andrey-batalhao.oliveira@unesp.br (A.B.d.O.); pl.alves@unesp.br (P.L.d.C.A.A.)
2 Department of Agricultural and Biological Sciences, State University of Minas Gerais, Frutal 38202-436, Brazil; vanesca.korasaki@uemg.br
3 Instituto de Investigação e Tecnologias Agrárias e do Ambiente (IITAA), Faculty of Agricultural and Environmental Sciences, University of the Azores, 9700-042 Angra do Heroísmo, Portugal; mariana.c.parreira@uac.pt
* Correspondence: heytor.lemos18@gmail.com

Abstract: Fallow is a practice in which the soil is left uncultivated for a period of time and is used less due to the pressure on agricultural land, which impairs soil regeneration. The cultivation of legumes, such as peanuts, is a viable alternative that leads to an improvement in the soil chemistry and grain capacity. Despite their importance, there are gaps regarding the use of peanuts for land reclamation and their importance for enzymatic activity in the soil. Therefore, the aim of this study was to evaluate the effects of straw incorporation and peanut cultivation in fallow land on the soil's chemical and biological quality and to determine whether the introduction of these elements contributes to an improvement in the soil fertility parameters and enzymatic activity. To achieve these objectives, experimental plots were established in fallow soils with different amounts of straw (0; 5 and 10 t ha^{-1}), with and without herbicide application and with peanut incorporation. The soil chemistry and enzymatic activity, plant biometrics and productivity were evaluated. The results showed that the straw treatment resulted in better plant development and increased productivity by up to 80%. The pH, soil organic matter, soil organic carbon, P, K, sum of bases and cation exchange capacity variables increased significantly with the presence of the plant and the incorporation of straw compared to uncovered soil, by 10%, 86%, 80%, 68%, 42%, 38% and 27%, respectively. For the enzymatic activity, the values showed that straw and peanut management affects the higher activity of β-glucosidase and arylsulfatase, with differences of 75 and 74% compared to the control. The incorporation of straw and peanuts in fallow land improves the chemical and biological quality of the soil. The use of herbicides has no effect on the soil dynamics or peanut development in the presence of straw and the presence of peanuts provides a better soil quality index and increases the β-glucosidase and arylsulfatase activity in the soil.

Keywords: *Arachis hypogaea*; soil quality; microorganisms; sugarcane

Academic Editor: Tie Cai

Received: 9 December 2024
Revised: 14 February 2025
Accepted: 17 February 2025
Published: 7 April 2025

Citation: Martins, H.L.; Korasaki, V.; Campalle, A.N.; Zanqueta, J.F.D.; de Oliveira, A.B.; Parreira, M.C.; Alves, P.L.d.C.A. Effects of Peanut Insertion on Soil Dynamics in Fallow Areas. *Agronomy* **2025**, *15*, 912. https://doi.org/10.3390/agronomy15040912

1. Introduction

Fallow areas with bare soil, although traditionally used in many countries as a strategy to "rest" the soil, can have negative impacts on its dynamics and quality over time. When soil remains inactive, the lack of vegetation cover and biological activity limits essential processes such as nutrient cycling, maintenance of the soil structure and water retention. This scenario contributes to physical (soil loss and degradation through flooding, surface runoff, etc.), chemical (nutrient loss, acidification) and biological (reduction of microbial activity through destructive biochemical reactions) soil degradation, reducing its fertility and its ability to sustain agricultural crops in the long term [1,2].

In this context, the introduction of crops capable of assisting the soil emerges as an alternative to reverse the harmful effects of prolonged fallow periods. These crops, by occupying the soil, promote increased vegetation cover, stimulate microbial activity, and improve soil quality through the addition of organic matter. Legumes, in particular, stand out for their ability to fix atmospheric nitrogen, a fundamental resource for restoring the fertility of degraded soils [3–5].

Peanut (*Arachis hypogaea* L.), as a legume, presents great potential for revitalizing fallow soils. Its nitrogen-fixing ability not only enhances soil fertility but also stimulates biological processes, such as microbial activity and organic matter disponibilization. Moreover, the peanut's root system promotes the formation of aggregates, increasing soil's structural stability and reducing the risk of erosion [6–8].

Although peanut cultivation predominantly takes place during sugarcane field renovations [9], in areas where there is significant accumulation of straw on the soil (up to 20 t/ha), this oilseed crop is also grown in conjunction with pasture restoration and as a rotational crop in other production systems. However, since peanuts produce their pods underground, it is not common to cultivate them in a no-tillage system [10,11]. Nevertheless, with advancements in research, various groups have conducted studies to assess the effects of direct seeding on the agronomic performance of peanuts, although conservationist practices remain a highlight [12–14]. The literature still lacks studies on the integration of peanuts into no-till systems (NTSs), creating opportunities for experiments to address these gaps.

Thus, in addition to the benefits of the legume, the incorporation of crop residue into the system can promote greater soil structuring, reduce soil water evaporation, and improve the chemical quality and the dynamics of the soil microbiota, which are directly linked to healthy soil [4].

In recent years, studies on soil quality and regenerative agriculture have been conducted to understand the influence of different agricultural management practices [15–17]. Among these approaches, the use of enzymes has proven effective in diagnosing soil changes that benefit crops, supporting the notion that healthy soil is not solely defined by chemical and physical assessments but also by biological indicators, such as the β-glucosidase and arylsulfatase activity in the soil [18–20].

These enzymes have been identified as sensitive biological indicators for detecting changes resulting from soil use and management [19,20]. Studies have demonstrated significant relationships between the activities of these enzymes, soil organic matter—a fundamental parameters of soil quality—and grain productivity, a basic economic indicator of crops. These correlations were observed in clayey Oxisols in the Cerrado for soybean and corn crops [21–26]. However, no studies have yet been conducted on the interaction of these bioindicators with peanut cultivation, justifying the present research. This work expands agronomic knowledge on the importance of incorporating peanut crops for land restoration, integrating biological, chemical, and physical aspects of the soil and offering a practical and innovative approach to sustainable and regenerative management. This study provides a novel perspective on how fallow areas can be transformed into productive and ecologically balanced systems.

Thus, the objective of this study was to evaluate the effects of straw incorporation and peanut cultivation in fallow areas on the soil's chemical and biological quality, and to determine whether the introduction of these elements contributes to improvements in soil fertility parameters and enzymatic activity. The hypotheses are as follows:

(1) the incorporation of straw and peanuts in fallow areas improves the soil's chemical and biological quality; and (2) herbicide application does not influence the soil dynamics or peanut development in the presence of straw.

2. Materials and Methods

2.1. Experimental Design and Presentation of the Experiments

2.1.1. Experiment I—Tests in a Masonry Frame

The experiment was conducted in an open area, using experimental plots of 1.10 m^2 demarcated by a masonry frame on a dark red Oxisol (10R 3/6, moist) with a clayey texture, in the autumn–winter period of 2023. The area is located at latitude 21°14′39.83″ S and longitude 48°17′56.84″ W, at an altitude of 606 m, in the city of Jaboticabal, in the northern region of the state of São Paulo, Brazil. Before setting up the experiment, soil samples were taken with Dutch auger from 0–20 cm deep for chemical and physical analysis purposes.

The chemical analysis showed the following results: pH (CaCl2) = 5.6, OM (organic matter) = 16 g dm^{-3}, P (phosphorus) = 6 mg dm^{-3}, K (potassium) = 3 mmolc.dm^{-3}, Ca (calcium) = 33 mmolc.dm^{-3}, Mg (magnesium) = 8 mmolc.dm^{-3}, H+Al (potential acidity) = 20 mmolc.dm^{-3}, SB (sum of bases) = 44.1 mmolc.dm^{-3}, CEC (cation exchange capacity) = 63.9 mmolc.dm^{-3}, V (base saturation) = 69%. The results of the granulometric analysis showed the following: clay = 53%; silt = 21% and sand = 26%. The peanut cultivar used was IAC 503.

The cultivar has a low growth habit, with moderate resistance to foliar diseases (black spot and rust). It has markedly indeterminate vegetative growth, with vigorous plants. Its cycle is long, 130 to 140 days, and can extend to 145 to 150 days depending on the year's weather conditions. Its average productivity is 4500 kg ha^{-1} in bark and its productive potential is 6500 kg ha^{-1}. The grains contain around 48% oil, with 70% to 80% oleic acid. Cultivars with "normal oleic" have oil with 40% to 50% of this acid [27].

The region's climate is type Cwa, subtropical, dry in winter, with summer rain [28], with an average annual temperature of 22.7 °C and average precipitation of 1353 mm. During the experiment, climate data on the rainfall, maximum, minimum and average temperatures and humidity were recorded for the Jaboticabal region (Figure 1).

The experimental design involved randomized blocks, consisting of 12 treatments, with four replications, whose treatments were as follows: (T1) peanuts (A) + equivalent to 10 tons of sugarcane straw (P) + application of herbicide (H) (Plateau); (T2) peanuts + equivalent to 5 tons of sugarcane straw + application of herbicide (Plateau); (T3) peanuts + equivalent to 10 tons of sugarcane straw + without herbicide application; (T4) peanuts + equivalent to 5 tons of sugar cane + without herbicide application; (T5) peanuts + no sugarcane straw + application of herbicide (Plateau); (T6) peanuts + no sugarcane straw + no herbicide application; (T7) equivalent to 10 tons of sugarcane straw + application of herbicide (Plateau); (T8) equivalent to 5 tons of sugarcane straw + application of herbicide (Plateau); (T9) equivalent to 10 tons of sugarcane straw + without herbicide application; (T10) equivalent to 5 tons of sugar cane + without herbicide application; (T11) no sugarcane straw + application of herbicide (Plateau); (T12) uncovered soil (Figure 2).

For the variables measured for the plant, the first six treatments (1–6) were considered, and for the soil variables, the twelve treatments were considered. Each plot consisted of two lines spaced 0.9 m apart, 6 m long, with the two central lines being considered as useful areas. Sowing was carried out by depositing 23 seeds per meter, with fertilizer equivalent to 300 kg ha^{-1} of formula 4-14-8, with this being the need for fertilizer.

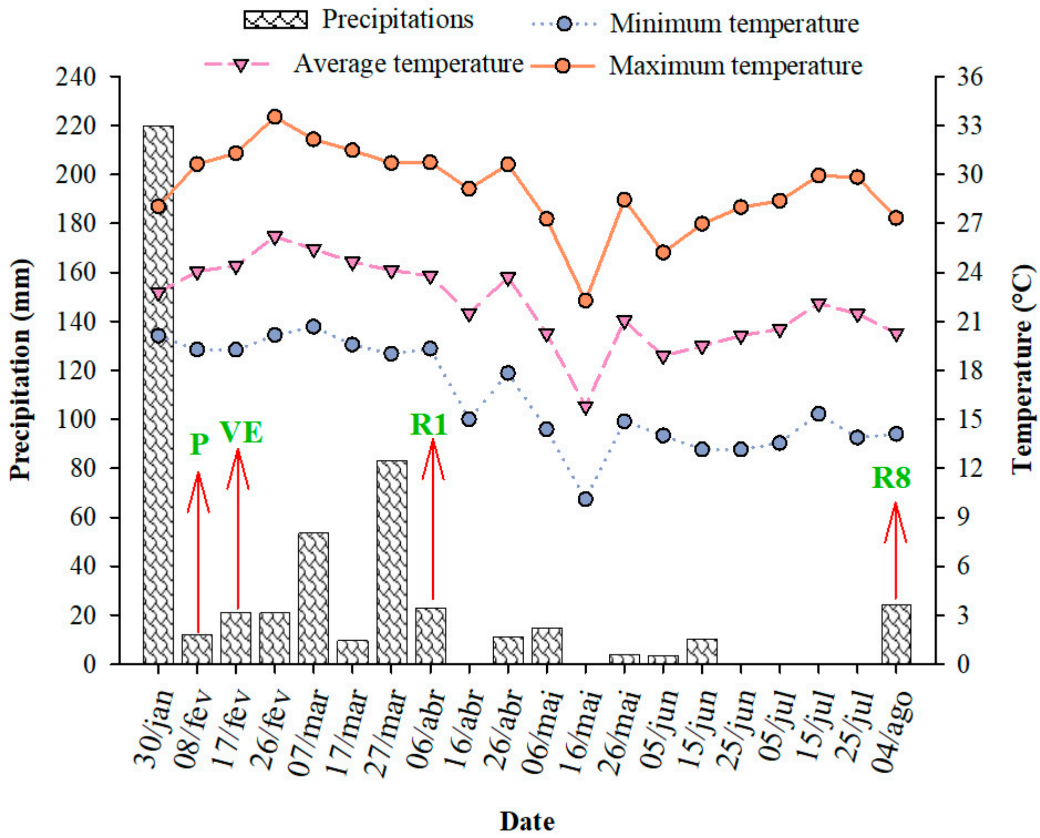

Figure 1. Climatological data of the area during the experiment between January and August 2023. Latitude: 21°14′05″ S, longitude: 48°17′09″ W, altitude: 615.01 m. P = planting; VE = plant emergency; R1 = beginning of flowering and R8 = end of the cycle.

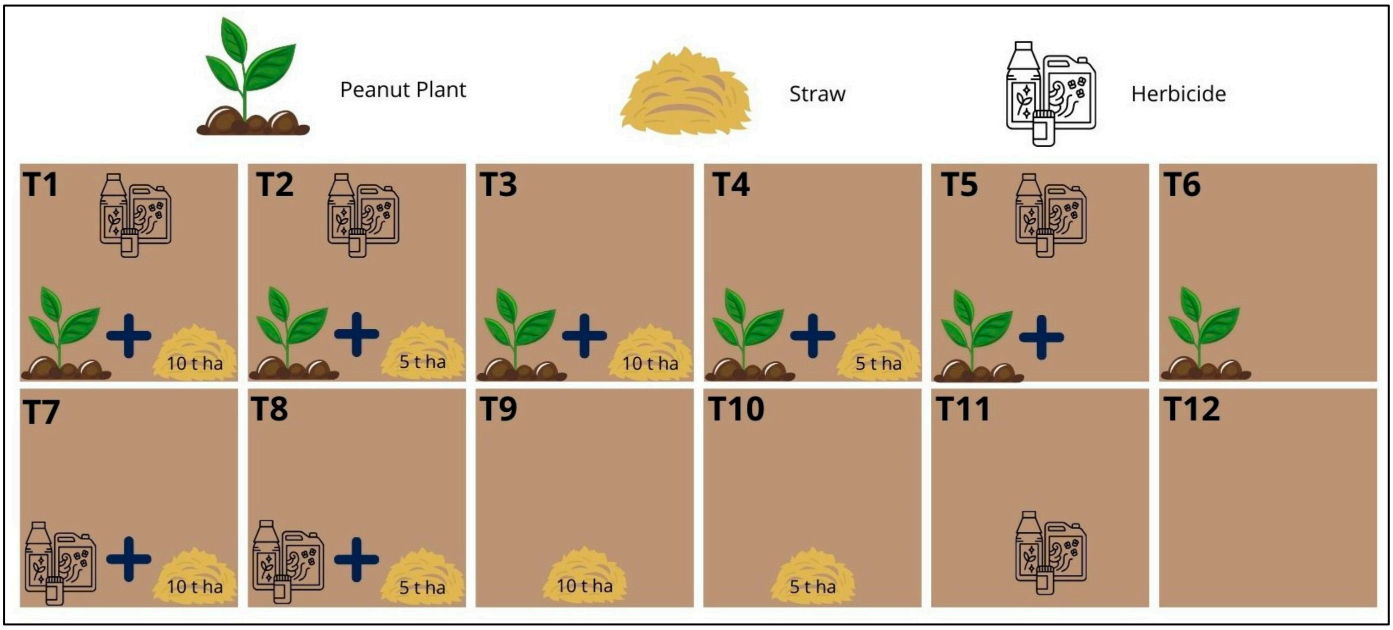

Figure 2. Representation of the experimental treatments.

The sugarcane straw collected in the Jaboticabal-SP region was transported to the study area, where quantities equivalent to 5 and 10 t ha^{-1} (0.550 and 1.10 kg m^2) were deposited in the plots. A conventional sprinkler irrigation system was installed in the area, with a rule shift every 5 days, corresponding to approximately 30 mm of water depth, totaling 390 mm of water depth, plus 292 mm via rainfall.

The herbicide used was Plateau® (imazapic), applied 15 days after emergence (DAE), at a dose of 98.0 g a.i. ha^{-1}. For the applications, a backpack sprayer at a constant pressure (CO_2) was used, equipped with a bar with four 110.02 tips spaced 0.5 m apart, making up a range of 2 m, and adjusted to distribute 200 L ha^{-1} of spray, with 2.8 bar of pressure. At the time of the applications, the following information was recorded: start of application at 6:12 pm; end of application at 6:42 pm; clear sky; air temperature 26 °C; wind speed: 9 km h^{-1}; relative air humidity of 70%.

2.1.2. Experiment II—Field

The experiment was installed in an experimental area of the Teaching, Research and Extension Farm of FCAV/UNESP in the autumn–winter period of 2023. The area is located at latitude 21°14′48.14″ S and longitude 48°18′6.86″ W, at an altitude of 594 m, in the city of Jaboticabal, in the northern region of the state of São Paulo, Brazil. Before setting up the experiment, soil samples were taken from 0–20 cm deep for chemical and physical analysis purposes. The soil is classified as a eutrophic dark red latosol (Oxisol) with a clayey texture.

The chemical analysis presented the following results: pH ($CaCl_2$) = 5.1, OM = 12 g dm^{-3}, P = 9 mg dm^{-3}, K = 2.8 mmolc.dm^{-3}, Ca = 11 mmolc.dm^{-3}, Mg = 5 mmolc.dm^{-3}, H+Al = 26 mmolc.dm^{-3}, SB = 16.3 mmolc.dm^{-3}, CEC = 43.7 mmolc.dm^{-3}, V% = 37%. The results of the granulometric analysis showed the following: clay = 54%; silt = 7% and sand = 39%. The peanut cultivar used was IAC 503. The climatic data during the execution of the experiment are shown in Figure 1.

The experimental design involved randomized blocks, consisting of 12 treatments, with four replications, whose treatments were the same as those described in relation to Experiment I. Each plot consisted of four lines spaced 0.9 m apart, 6 m long, being considered as useful area the two central lines. Sowing was carried out by depositing 23 seeds per meter, with fertilizer equivalent to 300 kg ha^{-1} of formula 4-14-8.

The sugarcane straw collected at latitude 21°06′23.24″ S and longitude 48°16′02.38″ W, at an altitude of 545 m, in the region of Jaboticabal-SP was transported to the study area, where amounts equivalent to 5 and 10 t ha^{-1} (6.25 and 12.50 kg m^2) were deposited on the plots. A conventional sprinkler irrigation system was installed in the area, with a rule shift every 5 days, corresponding to approximately 30 mm of water depth, totaling 390 mm of water depth, plus 292 mm via rainfall.

The herbicide used was Plateau® (imazapic), applied 15 days after emergence (DAE), at a dose of 98.0 g a.i. ha^{-1}. For the applications, a backpack sprayer at a constant pressure (CO_2) was used, equipped with a bar with four 110.02 tips spaced 0.5 m apart, making up a range of 2 m, and adjusted to distribute 200 L ha^{-1} of spray, with 2.8 bar of pressure. At the time of application, the following information was recorded: start of application at 5:03 pm; end of application at 5:22 pm; clear sky; air temperature 25 °C; wind speed: 11 km h^{-1}; relative air humidity of 65%.

2.2. Variables Analyzed

2.2.1. Soil Chemistry

For the chemical analysis of the soil, samples were collected at 30 and 60 DAE, which were sent to Athenas - Consultoria Agrícola e Laboratórios, a specialized laboratory for analyzing the pH, OM, N, P, K, S, Ca, Mg, Al, H+Al, SB, CEC, and V%. The methodology for analyzing was Teixeira [29].

2.2.2. Activity of β-Glucosidase and Arylsulfatase

The β-glucosidase (BG) and arylsulfatase (ARYL) activities were measured according to [23]. These procedures are based on the determination of the p-nitrophenol formed after the addition of specific substrates for each enzyme. To quantify the activities of BG and

ARYL, *pnitrophenyl-β-D-glycopyranoside* (PNG) and *p-nitrophenyl sulfate* (PNS) were added as substrates, respectively. Due to their short incubation periods (one hour), toluene was omitted from the assays. These determinations were performed directly on air-dried soil samples, according to [20]. The enzymatic activity of the two enzymes was expressed in μg *p*-nitrophenol g^{-1} soil h^{-1}.

2.2.3. Leaf Area and Dry Matter

The leaf area (LA) and relative total chlorophyll content of the bean plant were evaluated at 156 days. To determine the relative content of total chlorophyll, a chlorophyllometer (ChlorofiLog, Falker, Porto Alegre, Brazil) was used, positioned in the middle of the asymmetrical leaflet of the third fully expanded trefoil. On the same occasion, four plants were collected, which were cut close to the ground, measured (height) and taken to the laboratory, where the leaves, stem, flowers and pods were separated, with the latter being counted and peeled to obtain the grains. The leaf area was determined using a leaf area meter (LI 3000A, LiCor, Lincoln, NE, USA). After the measurements, the parts of the plants were taken to the greenhouse with forced air circulation, at 60 °C, until they reached a constant mass to determine the mass of dry matter with the aid of an analytical balance.

2.2.4. Productivity

At the time of harvest (156 DAE), the grain yields of each plot were estimated, expressed in kg ha^{-1}, through the processing of plants harvested in the three central rows of each plot.

2.3. Data Analysis

To evaluate the soil's chemical properties, a Pearson correlation analysis was initially conducted to understand the interactions between the variables and to select those that best represent them for the subsequent analysis of variance. Another correlation analysis was performed to understand the relationship between the soil chemical and enzymatic variables. The correlation analysis was conducted using R software (version 4.4.2), utilizing the *GGally* package [30].

To verify the normality of the data, a Shapiro–Wilk test was used, and for the homogeneity of variances, a Levene test was used. To determine the relationship between the soil variables, principal component analysis (PCA) was used. Statistical differences were considered at a significance level of 95% ($\alpha = 0.05$).

To evaluate the difference between the treatments in both experiments, they were initially tested for normality and homoscedasticity and then subjected to analysis of variance (F test) at 5% significance. When there was significance using the F test, the treatment means were compared using the Skott–Knot test at 5% significance.

3. Results

3.1. Experiment I—Tests in a Masonry Frame

3.1.1. Biometric and Productive Evaluation of Peanuts

For the peanut biometric and productive variables, it was observed that, for the plant height (ALT) and grain dry matter (DMG), treatments T1 and T2 provided better results in relation to the other treatments. For the leaf area (LA) and number of pods (PN), T1 and T2 presented higher values, followed by T3 and T4, with T5 and T6 being those with the lowest values obtained for the leaf area and number of pods (Table 1).

Table 1. Plant and productive parameters of peanut IAC 503 subjected to development under straw and with and without herbicide application. Alt. = height; PN = pod number; LA = leaf area; TDM = total dry mass; DMG = dry mass of grains; relative total chlorophyll content (TRCT); Canopeo (CAN) and Prod. = productivity.

Trat.	Alt.	PN	LA	TDM	DMG	TRCT	CAN.	Prod.
	cm	-	cm^2	g	g	UR	%	kg ha^{-1}
T1	30.00 a	36 a	1934.42 a	84.46 a	21.02 a	58.7 a	81.5 a	3460 a
T2	28.00 a	29 a	1792.12 a	57.96 b	14.47 a	50.30 a	57.13 b	2424 b
T3	24.00 b	22 b	1395.48 b	57.04 b	6.36 b	47.75 a	51.9 b	2382 b
T4	23.66 b	22 b	1165.30 b	47.23 b	5.89 b	47.40 a	48.7 b	1974 b
T5	23.33 b	12 c	607.55 c	31.79 b	3.80 b	27.23 b	48.63 b	1048 c
T6	21.66 b	11 c	418.92 c	26.38 c	2.45 b	21.36 b	46.93 b	484 c
Factor	8.16 **	20.49 **	22.31	4.88 **	8.24 *	12.21 **	1.26 *	4.0 *
CV (%)	7.68	23.08	18.43	32.12	40.10	18.45	26.18	42.28

(1) Peanut + straw (10 t ha^{-1}) + herbicide; (2) peanut + straw (5 t ha^{-1}) + herbicide; (3) peanut + straw (10 t ha^{-1}); (4) peanut + straw (5 t ha^{-1}); (5) peanut + herbicide; (6) peanuts. Means followed by different letters differ by the Tukey test at the 5% probability level. * and ** = Significant at the 5% and 1% probability levels, respectively, by the F-test. CV (%) = Coefficient of variation.

Plants from T1 presented higher values for the total dry matter (TDM) and Canopeo (CAN), followed by the other treatments, with T6 being the one with the lowest observed value and different from all the others. The relative content of total chlorophyll (TRCT) was higher in plants subjected to straw development (T1-T4), presenting significantly higher values than those without the presence of straw (Table 1).

The peanut productivity was higher in plots with the presence of straw, with higher values in T1 and significantly lower values in treatments T5 and T6, in which there was no presence of straw.

3.1.2. Soil Chemical Assessment

For the brightness matrix analysis, the results showed positive and negative, weak and strong correlations (Figure S1). The sulfur (S) variable was not present with any of the other variables submitted in the Pearson transparency analysis (r). The correlations not shown in the figure do not have a significant difference at the 5% level. The aluminum saturation (H+Al) was the only variable to present negative brightness, showing strong luminosity with the variables P, Mg, SB, K and pH, showing itself to be inversely proportional to the effects of such variables in the ground. Ca showed correlation with the SB (very strong positive), Mg (strong positive) and SatB, P and CEC (moderate) variables. SB showed moderate positive brightness with K and pH and strong positive brightness with the SatB.

The CEC, in turn, had strong positive correlations with the P, SB, and SatB variables and a moderate correlation with the Mg and K. For the P variable, all the correlations found were very strong with the pH, Mg, SB, SatB variables. Finally, the K and pH variables show strong correlations with the organic matter (Figure S1).

The treatments with the presence of peanuts presented higher values than those in which the soil was left fallow and the other treatments without the plant. For the variables found in Table 2, without exception, the presence of peanut + straw + herbicide (T2) presented higher values, showing an efficient treatment for the soil condition.

Table 2. Soil parameters with and without IAC 503 peanut cultivation when subjected to development under straw with and without herbicide application. OM = organic matter; SOC = soil organic carbon; P = phosphorus; K = potassium; SB = sum of bases; CEC = cation exchange capacity.

Treats.	pH	OM		SOC	P	K	SB	CEC
	-	g dm^3	%	g kg^{-1}	mg dm^3	mmolc dm^3	-	-
T1	6.48 b	17.15 b	1.71	29.59 b	71.82 b	3.41 b	51.53 c	65.68 d
T2	6.70 a	20.50 a	2.05	35.36 a	91.72 a	4.03 a	60.93 a	74.92 a
T3	6.33 c	15.02 d	1.50	25.92 d	51.92 c	3.12 c	50.00 c	66.40 d
T4	6.36 c	14.12 d	1.41	24.35 d	41.71 c	1.80 f	42.19 f	60.02 f
T5	6.37 c	17.52 b	1.75	30.22 b	66.69 b	2.22 e	50.31 c	68.72 c
T6	6.44 b	16.47 c	1.64	28.41 b	46.57 c	3.63 b	51.87 c	66.65 d
T7	6.25 d	17.53 b	1.75	30.25 b	41.58 c	4.00 a	51.07 c	68.72 c
T8	6.17 d	14.72 d	1.47	25.40 d	29.42 d	2.78 d	45.05 e	64.45 e
T9	6.21 d	17.02 b	1.70	31.43 b	34.04 d	3.96 a	46.33 d	64.36 e
T10	6.11 e	15.94 c	1.59	27.50 c	51.56 c	3.31 c	47.23 d	64.33 e
T11	6.05 e	4.72 e	0.47	4.84 e	35.88 d	2.77 d	53.86 b	71.14 b
T12	6.10 e	2.80 f	0.28	5.14 e	28.44 d	2.33 e	37.52 g	55.26 g
Causes of variation								
Ftrat	31.51 **	92.10 **		92.25 *	16.42 **	51.26 **	64.86 **	108.39 **
CV (%)	0.91	6.62		6.61	15.63	5.79	2.07	1.27

Treatments: (1) A + P (10 t.ha^{-1}) + H; (2) A + P (5 t.ha^{-1}) + H; (3) A + P (10 t.ha^{-1}); (4) A + P (5 t.ha^{-1}); (5) A + H; (6) A; (7) P (10 t.ha^{-1}) + H; (8) P (5 t.ha^{-1}) + H; (9) P (10 t.ha^{-1}); (10) P (5 t.ha^{-1}); (11) H; (12) uncovered soil. Means followed by different letters differ by the Tukey test at the 5% probability level. * and ** = Significant at the 5% and 1% probability levels, respectively, by the F-test. CV (%) = Coefficient of variation.

The pH was slightly acidic, tending toward neutrality in all the treatments. The soil OM, P, K, CEC and soil organic carbon (SOC) were higher in the treatments with straw and plants, showing a greater role for them in retaining organic carbon and decomposition in the system.

It is noteworthy that, when comparing the treatments with the presence of straw and plants with the control (uncovered soil), there was an increase in the variables, highlighting 10% for pH, 86% for O.M. and 68% for phosphorus.

3.1.3. Assessment of Soil Enzyme Activity

The enzymatic activity of arylsulfatase had values below those considered optimal for healthy soil [19–21], with the only treatment with a moderate value being that with the presence of peanuts. For β-glucosidase, the treatments with peanuts, straw and herbicide presented higher values than the others and, according to the interpretation, they had adequate health for the management used. The treatments from T5 to T9 presented moderate management values that were superior to the T10–T12 treatments, showing that the adopted managements presented higher values than the control (Figure 3).

The activity of the enzyme β-glucosidase showed a significant correlation with the pH (R = 0.637 ***) and P (R = 0.501 *) variables. Arylsulfatase also exhibited a positive correlation with the pH (R = 0.653 *), P (R = 0.415 *), and Ca (R = 0.608 **). The results indicate that the enzymatic variables are highly influenced by the soil's chemical conditions, particularly the pH and P levels, as well as by the organic matter content, which did not show a direct significant correlation with the enzymes (Figure S2).

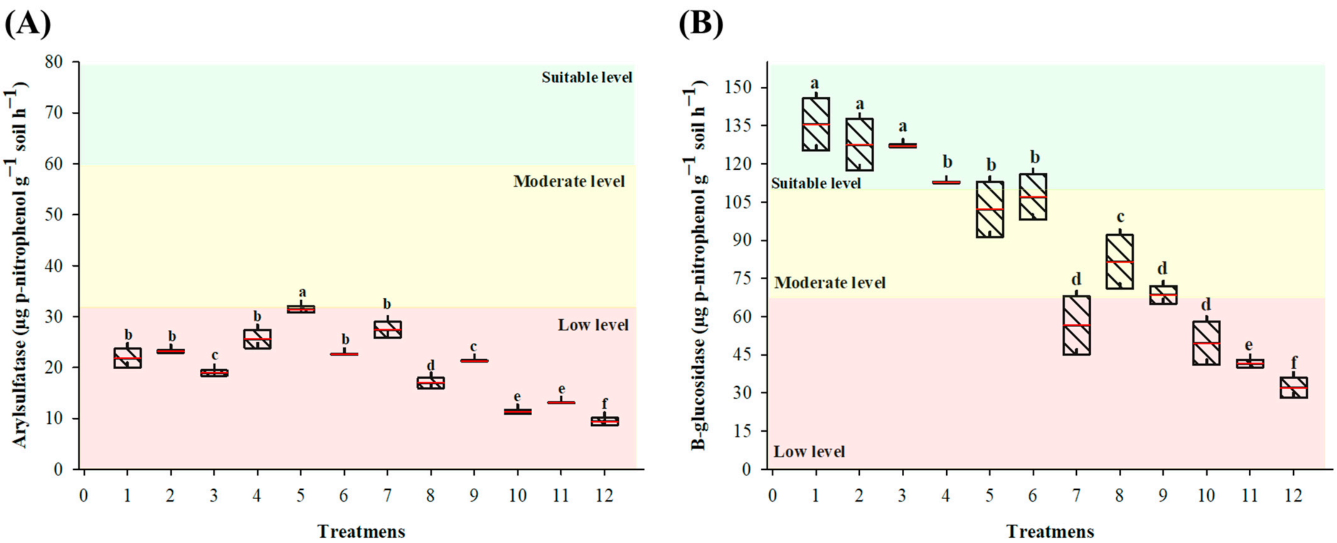

Figure 3. (**A**) Arylsulfatase (F = 21.14 **) and (**B**) β-glucosidase activity (F = 41.76 **) of soil with and without IAC 503 peanut cultivation subjected to development under straw, with and without herbicide application. (1) A + P (10 t.ha^{-1}) + H; (2) A + P (5 t.ha^{-1}) + H; (3) A + P (10 t.ha^{-1}); (4) A + P (5 t.ha^{-1}); (5) A + H; (6) A; (7) P (10 t.ha^{-1}) + H; (8) P (5 t.ha^{-1}) + H; (9) P (10 t.ha^{-1}); (10) P (5 t.ha^{-1}); (11) H; (12) uncovered soil. Means followed by different letters differ by the Tukey test at the 5% probability level.

3.2. Experiment II—Field

3.2.1. Peanut Evaluation

For the evaluation of the peanut plant and productive parameters, only the TDM did not show a significant difference between the treatments. For the Alt and PN variables, plants from the treatments with straw without and with herbicide application (T1–T4) presented the highest values in relation to the treatment without straw with and without herbicide (Table 3).

Table 3. Plant and productive parameters of peanut IAC 503 subjected to development under straw and with and without herbicide application. LA= leaf area; PN = pod number; DPM = dry pod mass; Alt. = height; TDM = total dry mass; DMG = dry mass of grains and Prod. = productivity.

Trat.	Alt.	PN	DPM	LA	TDM	DMG	Prod.
	cm	-	-	cm^2	g	g	kg ha^{-1}
T1	28.00 a	18 a	14.81 a	1341.92 a	42.28 a	7.81 a	1722 a
T2	29.33 a	15 a	10.40 a	1917.95 a	45.97 a	7.77 a	1381 a
T3	29.66 a	13 a	8.64 b	826.73 b	36.96 a	8.12 a	1430 a
T4	30.00 a	14 a	4.27 b	667.38 b	36.16 a	6.10 a	1084 a
T5	24.33 b	6 b	2.14 c	470.21 b	34.51 a	1.65 b	562 b
T6	20.00 c	3 b	1.89 c	408.92 b	29.16 a	1.23 b	457 b
Causes of variation							
Ftrat	3.43 *	11.58 **	3.43 *	8.86 **	0.25 ^{ns}	4.09 *	3.45 *
CV (%)	13.32	29.17	30.50	36.03	42.92	20.10	42.28

(1) Peanut + straw (10 t ha^{-1}) + herbicide; (2) peanut + straw (5 t ha^{-1}) + herbicide; (3) peanut + straw (10 t ha^{-1}); (4) peanut + straw (5 t ha^{-1}); (5) peanut + herbicide; (6) peanuts. Means followed by different letters differ by the Tukey test at the 5% probability level. * and ** = Significant at the 5% and 1% probability levels, respectively, by the F-test. ns = Not significant by the F-test. CV (%) = Coefficient of variation.

For the DPM, plants from the treatments (T1 and T2) with the application of herbicide and straw (regardless of quantity) showed higher value compared to the other treatments (T3–T6). Plants that were not subjected to herbicide application (T3 and T4), regardless of the amount of straw, showed better results than those observed for peanuts without straw with herbicide application (T5) and for those that were grown in a conventional system (T6) (Table 3).

Plants subjected to treatment with herbicide application, regardless of the amount of straw (T1 and T2), showed higher AF compared to the other treatments (T3–T6). The largest DMG and Prod. were observed in the treatments where the plant was grown with straw and with and without herbicide application (T1–T4), with the lowest values being in the treatments (T5 and T6) that had straw, one with herbicide application and the other without application, respectively (Table 3).

Multivariate Analysis of Plant Data

When performing the principal component analysis (PCA), it is verified that PC1 represents 63.49% of the data variation and PC2 19.85%, representing 83.34% of the total data in the sum of the two. Checking the relationship of the PC axes with the variables, PN, MP, DMP, GM, LA, Prod. and Straw are representative for axis 1, while for axis 2, the Alt., NB, and TDM variables are representative (Figure 4). The complementary herbicide variable is opposite the quadrant where all the variables are located, showing that it has no influence on the response of these parameters.

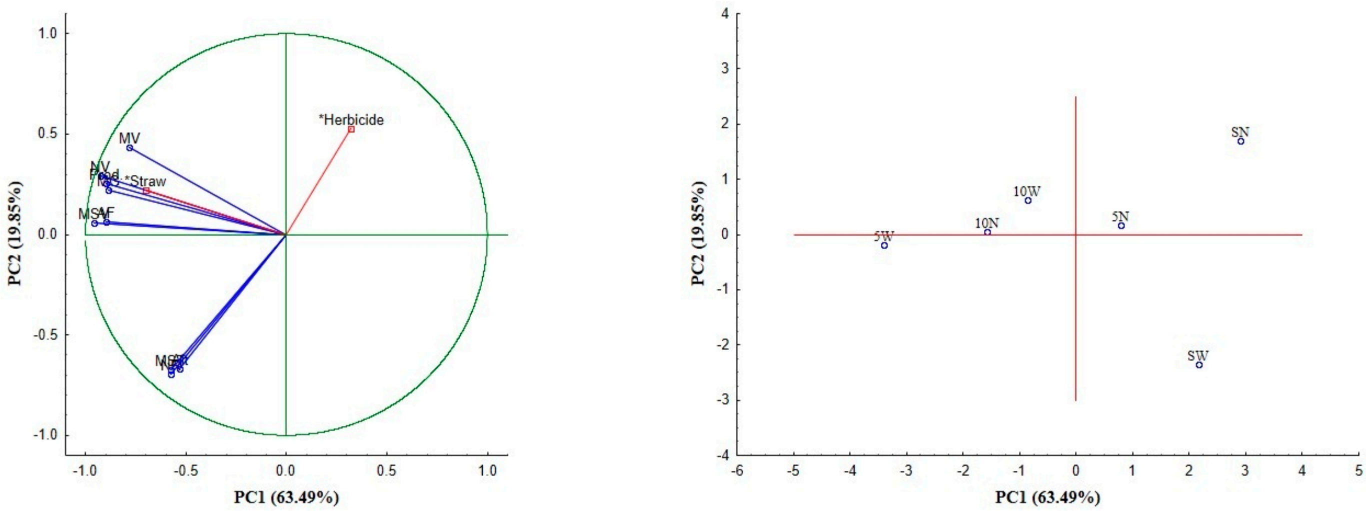

Figure 4. Analysis of the main components of the agronomic parameters of peanut IAC 503 subjected to planting with straw and herbicide application. Alt = height. NV = number of pods. MV = mass of pods. MSV = dry mass of pods. MG = grain mass. NR = number of branches. MST = total dry mass. AF = leaf area and Prod = productivity. SN = without straw and herbicide. SW = without straw + herbicide. 5N = 5 t ha^{-1} + without herbicide. 5W = 5 t ha^{-1} + with herbicide. 10N = 10 t ha^{-1} + without herbicide. 10W = 10 t ha^{-1} + with herbicide. * Factors evaluated (Herbicide Plant).

Another issue observable in the PCA is that, regardless of the amount of straw, there is the same influence on the peanut development variables and productivity, making it possible to observe the positioning of the factors 5W (5 t ha^{-1} + with herbicide), 10N (10 t ha^{-1} + without herbicide) and 10W (10 t ha^{-1} + with herbicide) and 5N (5 t ha^{-1} + without herbicide) that are positioned in the variable quadrants and are represented by PC1. The treatments without straw are in the opposite region.

3.2.2. Soil Chemical Assessment

Figure 5 shows the results of the soil chemical analysis. For the Al content in the soil, it was observed that, in relation to the control (T11 and T12) and the other treatments without plants, the presence of peanuts (T1–T6) influenced the reduction of Al in the soil. The same was observed for the H+Al variable.

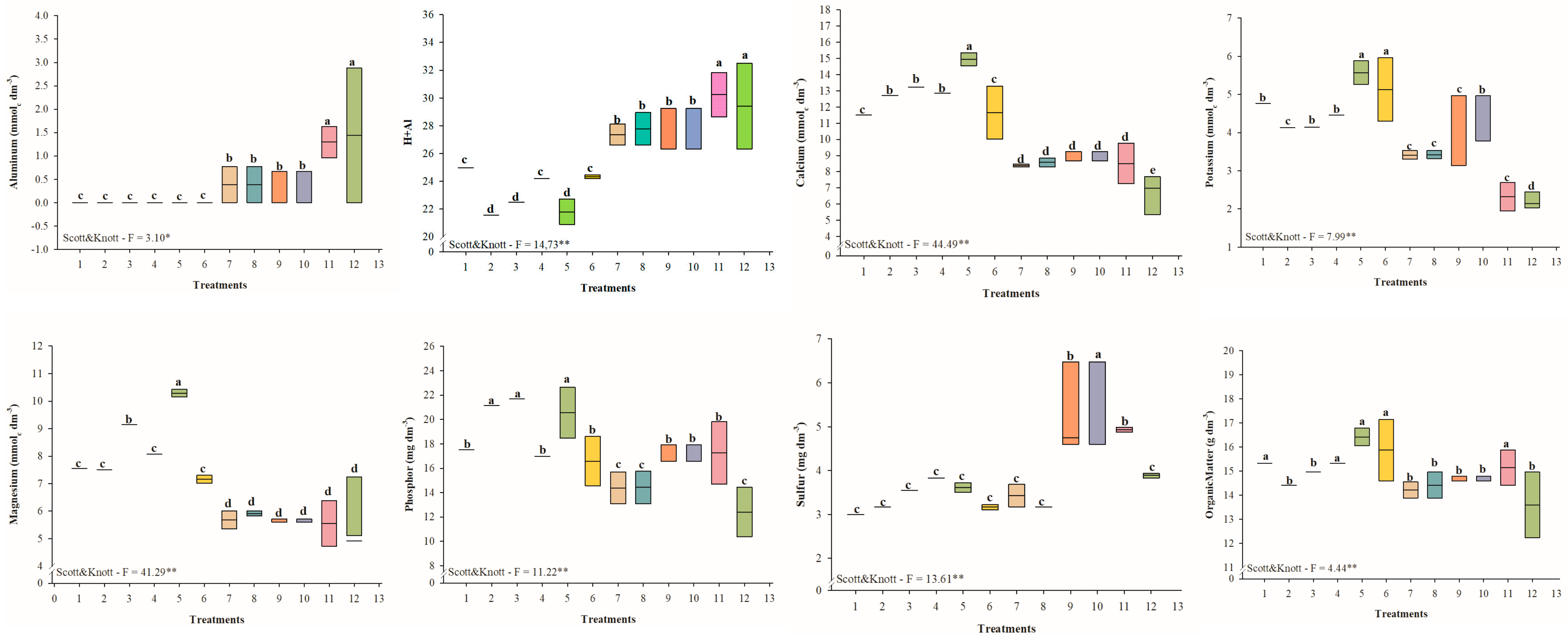

Figure 5. *Cont.*

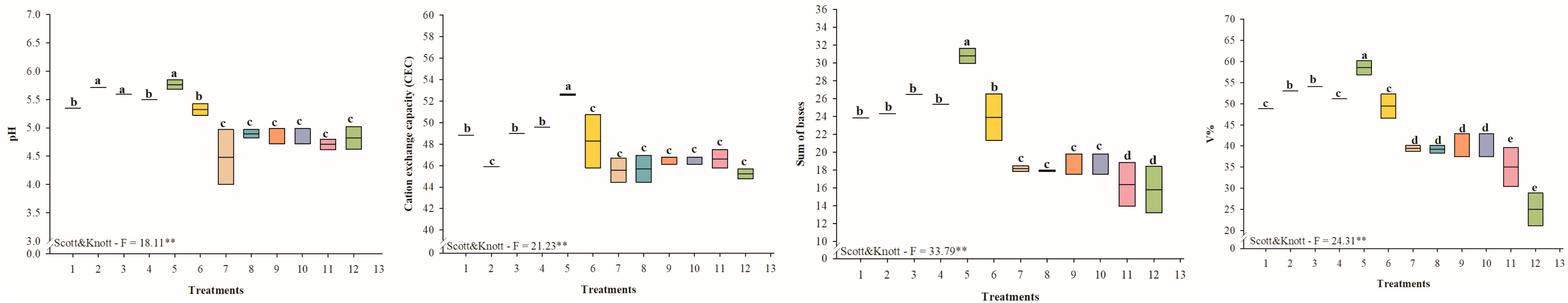

Figure 5. Soil parameters with and without IAC 503 peanut cultivation subjected to development under straw, with and without herbicide application. (1) A + P (10 $t.ha^{-1}$) + H; (2) A + P (5 $t.ha^{-1}$) + H; (3) A + P (10 $t.ha^{-1}$); (4) A + P (5 $t.ha^{-1}$); (5) A + H; (6) A; (7) P (10 $t.ha^{-1}$) + H; (8) P (5 $t.ha^{-1}$) + H; (9) P (10 $t.ha^{-1}$); (10) P (5 $t.ha^{-1}$); (11) H; (12) uncovered soil. Means followed by different letters differ by the Tukey test at the 5% probability level. * and ** = Significant at the 5% and 1% probability levels, respectively, by the F-test.

For the Ca variable, the treatments with the presence of the plant provided higher concentrations than those without peanuts. Among them, peanut cultivation with herbicide application (T5) was the one with the highest Ca, followed by T2, T3 and T4), which presented higher values than treatments 1 and 6.

Treatments 5 and 6 showed higher concentrations of K compared to the other treatments. However, it was observed that the treatments where there was the presence of peanuts (T1–T6) and where there was the presence of straw (T7–T10) presented better K values compared to the controls (T11 and T12). For the concentration of Mg found in the soil, it is possible to observe that the plant treatments (T1–T6) caused it to increase, with T5 being the one that provided the highest Mg content, followed by T3, T1, T2 and T4. The other treatments, without the presence of the plant, did not differ in terms of the Mg concentration (Figure 5).

3.2.3. Assessment of Soil Enzyme Activity

For the enzymatic evaluation of the soil (Figure 6), it was observed that for the arylsulfatase activity, except for treatments 2 and 6, all were low, indicating that the conditions for the activity of this enzyme were not favorable. On the other hand, it was possible to observe that, even though still below the values used as standard, the treatments with the presence of peanuts (T1–T6) presented higher values than the control (T12), with the higher values varying from 9.84 to 23.13 μg *p-nitrophenol* g^{-1} soil h^{-1}.

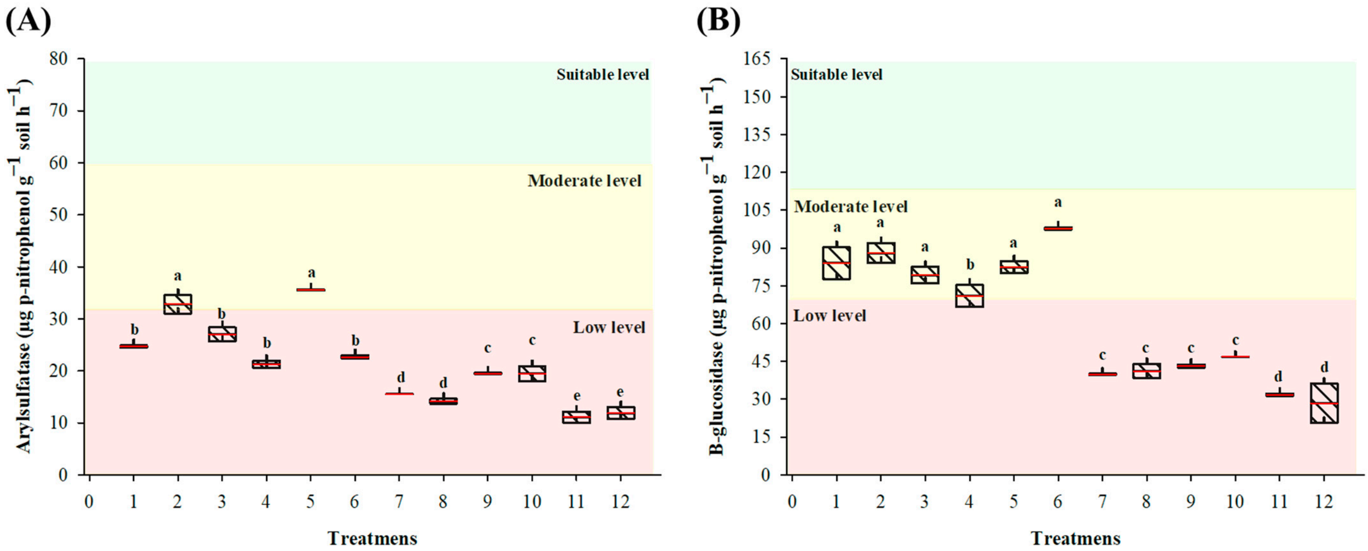

Figure 6. (**A**) Arylsulfatase (F = 40.52 **) and (**B**) β-glucosidase (F = 79.81 **) activity of soil with and without IAC 503 peanut cultivation subjected to development under straw, with and without herbicide application. (1) A + P (10 $t.ha^{-1}$) + H; (2) A + P (5 $t.ha^{-1}$) + H; (3) A + P (10 $t.ha^{-1}$); (4) A + P (5 $t.ha^{-1}$); (5) A + H; (6) A; (7) P (10 $t.ha^{-1}$) + H; (8) P (5 $t.ha^{-1}$) + H; (9) P (10 $t.ha^{-1}$); (10) P (5 $t.ha^{-1}$); (11) H; (12) uncovered soil. Means followed by different letters differ by the Tukey test at the 5% probability level.

For the soil β-glucosidase activity, all the treatments (T1–T11) showed a significant difference in relation to the control (T12), with the highest activity values observed for the treatments with plants, straw and herbicide. According to the interpretation class, the presence of peanuts positively influenced the transformation of a soil with low enzymatic activity into a soil with moderate activity, which could improve over time (Figure 6).

β-glucosidase, essential in the carbon cycle, showed a positive correlation with the SOC (R = 0.346 *), reinforcing its direct relationship with the available carbon content. However, there was a negative correlation between β-glucosidase and sulfur (S) (R = −0.718 *), suggesting a possible competitive effect or soil conditions that hinder the simultaneous availability of carbon and sulfur for microbiological processes. Arylsulfatase, associated with the sulfur cycle, exhibited a moderate negative correlation with S (R = −0.566 *), indicating that the presence of available organic sulfur may modulate its activity. Arylsulfatase also showed low correlation with other variables, such as the pH and nutrients, suggesting that its activity is more influenced by specific factors of the sulfur cycle than by the general soil conditions (Figure S3).

3.2.4. Multivariate Analysis of Soil Data

When performing the principal component analysis (PCA), it was found that PC1 represents 74.73% of the data variation and PC2 8.80%, representing 83.53% of the total data in the sum of the two. Checking the relationship of the PC axes with the variables, the Plant (complementary variable), pH, SatB, P, CEC, OM, SB, K, Ca, Mg, SatAl and H+Al are representative for axis 1, while for axis 2, only the complementary variable Straw is representative (Figure 7). The complementary variable Herbicide has no influence on the response of these parameters.

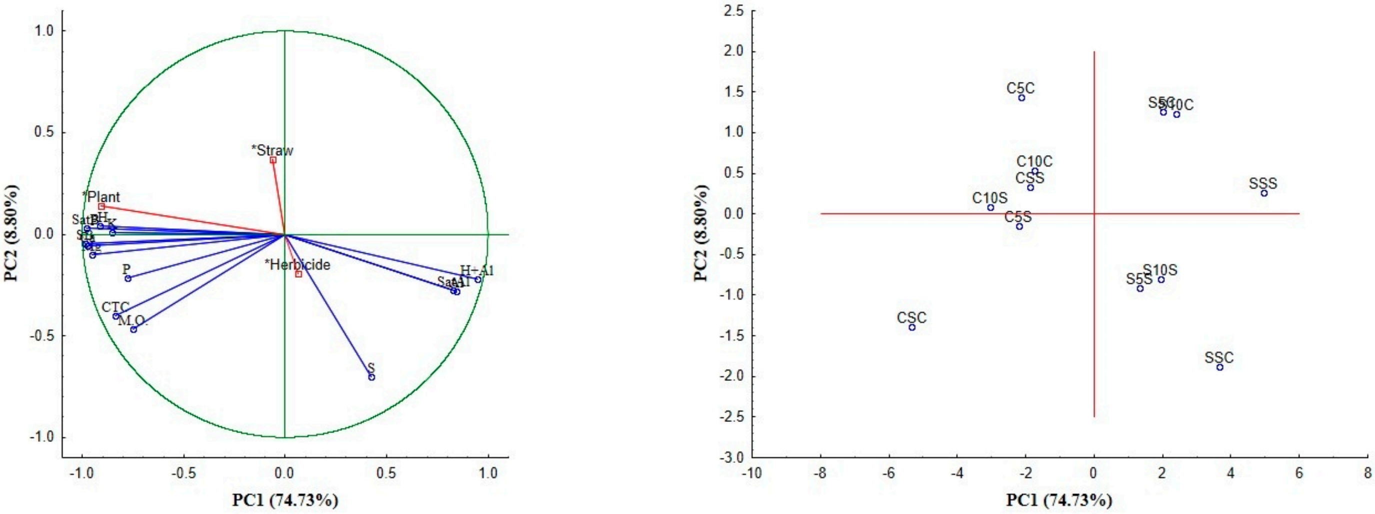

Figure 7. Analysis of the main components of the agronomic parameters of peanut IAC 503 subjected to planting with straw and herbicide application. CSC = with plant, without straw and with herbicide. C5C = with plant, 5 t ha^{-1}, with herbicide; C10C = with plant, 10 t ha^{-1}, with herbicide; CSS = with plant, no straw and no herbicide; C5S = with plant, 5 t ha^{-1}, no herbicide; C10S = with plant, 10 t ha^{-1}, no herbicide; SSC = no plant, without straw and with herbicide; S5C = no plant, 5 t ha^{-1}, with herbicide; S10C = no plant, 10 t ha^{-1}, with herbicide; SSS = no plant, no straw and no herbicide; S5S = no plant, 5 t ha^{-1}, no herbicide; S10S = no plant, 10 t ha^{-1}, no herbicide. * Factors evaluated (Herbicide Plant).

Another issue observable in the PCA is that, regardless of the amount of straw, there is the same influence on the development variables and peanut productivity, making it possible to observe the positioning of the CSC (with plant, without straw and with herbicide), C5S (with plant, 5 t ha^{-1}, no herbicide), C10S (with plant, 10 t ha^{-1}, no herbicide), CSS (with plant, no straw and no herbicide), C10C (with plant, 10 t ha^{-1}, with herbicide) and C5S (with plant, 5 t ha^{-1}, no herbicide) factors in the quadrants toward the greatest set of variables and which are represented by PC1. The treatments without the presence of plants (SSS—no plant, no straw and no herbicide, SSC—no plant, without straw and with herbicide, S5S—no plant, 5 t ha^{-1}, no herbicide, S10S—no plant, 10 t ha^{-1}, no herbicide, S5C— no plant, 5 t ha^{-1}, with herbicide and S10C—no plant, 10 t ha^{-1}, with herbicide) are in the opposite region, relating to the concentrations of sulfur and aluminum in the soil.

4. Discussion

The use of sugarcane straw in peanut cultivation has several agronomic advantages that lead to a significant improvement in plant growth and productivity [31]. In this study, the presence of straw was found to have a significant effect on several characteristics of the peanut plant. These traits include the plant height (Alt), number of pods (NP), pod mass (PM), pod dry mass (PDM) and number of kernels (NG).

Peanut cultivation is predominantly performed in the conventional system, but this system leads to soil loss as the plant has a distance of 0.90 m between rows, making it more exposed between rows and vulnerable to the action of rain and irrigation, which can lead to soil and nutrient loss and even loss of seeds, reducing the number of plants per area due to runoff [32–34]. This can be observed in this work: where no straw was present, peanuts showed the lowest values for all the variables analyzed, especially in the number of pods and productivity, with a decrease of about 63 and 81%, respectively.

These reductions can be related to various factors, such as the pH and OM. Low soil pH levels are able to alter different chemical structures in the soil and in the plant, as this factor interrupts metabolic processes, leading to a reduction in root development and the uptake of nutrients from the soil, such as calcium (Ca) uptake, which is an important nutrient for pod development [35,36]. This component acts on the structural and functional integrity of the cell, mainly in the transport and exchange of ions, and serves as a secondary messenger for cell signaling [37,38].

In contrast to the plants subjected to the conventional system, the plants grown under sugarcane straw showed higher values for all the variables, indicating an improvement in the plant height, number of pods, pod mass and, consequently, productivity. Few results are available for peanuts in rotation with sugarcane, with most showing little or no statistical difference between the management regimens [31,39,40]. Therefore, it is difficult to compare productivity or biometric data with other studies as there are few studies.

However, straw management for legumes in general can be considered a direction for discussing such results. Straw that remains on the cultivated land or is introduced into the environment contributes significantly to the development and optimization of agricultural production, as shown by several studies on the cultivation of beans [41] and soybeans [42,43] and some on peanuts [13,40].

The action of straw as a physical barrier promotes soil protection by helping to maintain moisture and reduce evaporation [44]. Such maintenance is essential as water is essential for plant growth, especially during the reproductive period [45,46]. In addition, thatch helps to protect against weeds and provides an environment without competition for important resources such as nutrients and water [47,48].

Previous research has also emphasized the great benefits of straw in increasing the productivity of subsequent crops [49,50]. The data obtained in this trial showed that the straw treatment increased the total dry matter accumulation, nitrogen (N) accumulation and pod productivity. This effect can be attributed to differences in the soil structure, temperature and nutrient availability. The reincorporation and decomposition of straw reduces the soil compaction, increases the temperature, intensifies the enzymatic activity and increases the nutrient concentration in the soil [51]. All these improvements in the physical and chemical properties of the soil can favor nutrient uptake and plant development, leading to a greater accumulation of dry matter and consequently higher productivity [52,53].

Barrow [54] reported that the increase in the phosphorus (P) content ($H_2PO_4^-$) in soil is associated with an increase in pH in the range of 5.8 to 7.0. Below this range, P is complexed by iron (Fe) and aluminum (Al), while above it, P is complexed by calcium (Ca). Despite the low levels of P, their study showed that the use of basalt rock powder promotes higher availability and better utilization of phosphorus due to the physico-chemical changes it induces in the soil solution. A similar effect was observed for the content of calcium (Ca), magnesium (Mg) and potassium (K). This study also confirms these results, as it was found that the incorporation of straw had similar effects to those described above.

This process occurs because P is an essential macronutrient that often limits plant productivity in natural and agricultural ecosystems [55,56]. Its availability and mobility are generally low in most soils, especially in acidic soils where the P availability is mainly limited by adsorption reactions due to the low pH and high levels of Al and Fe oxides and hydroxides [57,58] and sorption on clay particles and organic matter [59].

In addition to chemical variables, the results also demonstrated the potential of peanut for soil enzyme activity. Soil enzymes play a key role in the entire biochemical system of the soil ecosystem [60–62]. Therefore, a better understanding of soil enzyme activity in different cropping systems with mulch and herbicide effects may provide better insights into how cropping systems improve soil fertility.

Some studies showed that the monoculture system can impair the enzymatic function of the soil, leading to a significant reduction in the enzyme activity [22,63,64]. In this study, a considerable increase in enzymatic activity was observed in the soil where the straw had been deposited and with the presence of the peanut plant, so it can be emphasized that peanuts per se can promote an increase in enzymatic activity in the soil.

The increase in enzymatic activity in this study shows that β-glucosidase exhibited greater differences between the treatments, which is justified by its involvement in the carbon cycle, as it is more active in the presence of organic matter in the soil and these molecules are used as a substrate for the activity of this enzyme [19,65]. Thus, the presence of straw in the system increases the enzymatic activity of the soil, especially for β-glucosidase, which acts in the degradation of cellobiose, a disaccharide.

The arylsulfatase showed no major differences, but the highest activity values were found in the treatments with straw. The function of the enzyme arylsulfatase is to catalyze the hydrolysis of sulphate esters in the soil to make sulfur available to plants, thus showing a direct relationship with the nutrient concentration and increased enzyme activity [66]. Thus, this enzyme utilizes the complex structure of the plant and converts it into an assimilable structure that is in the form of sulfur trioxide (SO^3) and sulphates (SO_4^{2-}) and in elemental form, which has important functions for soil fertility and plant development as it is responsible for immunity, amino acid formation, enzymatic activity and photosynthesis [67,68].

Conventional soil assessment, which includes physical and chemical parameters, may no longer be sufficient to verify soil health [18,20], since less discrepant variations are found when compared to soil enzymatic activity, which is more affected, making it a more sensitive and crucial indicator of productivity. In this study, the enzymatic activity presented values that indicate healthy soil when straw is introduced into the system (values above 110 μg p-nitrophenol g^{-1} soil h^{-1}), and soils without straw and with the plant present moderate values according to the indices of [18,21]

The use of soil enzymes has proven to be a promising tool for diagnosing management changes in agricultural systems. Studies conducted by [18,20] in soybean cultivation areas with a direct planting system (SPD) and conventional system (SC) revealed a similar dynamic, showing that between the direct planting system and conventional system there was a reduction in productivity, with a difference of 30 bags per hectare [18,20]. Enzymes such as β-glucosidase and arylsulfatase, found in the soil, are essential to indicate environmental changes [22,69] reflecting the state of the soil, as they are associated with the non-living fraction, being adsorbed by clay particles and organic matter [65,66]. Soils with a greater capacity to store and stabilize organic matter offer better conditions to protect enzymes from the action of proteases and denaturation [53,70,71]. This effect can be observed in the peanut biometric variables and productivity, where the greater amount of straw promoted a significant increase. Even in the treatments without plants, the presence of straw already positively influenced the enzymatic activity.

5. Conclusions

The insertion of straw and peanuts in a fallow area provides an improvement in the chemical and biological quality of the soil, increasing the productivity by up to 80%, as well as the pH, O.M., P (10%, 86%, 68%, respectively) and B-glucosidase (68–75%) and arylsulfatase (60–74%) activity when compared with uncovered soil (T12).

The application of herbicide does not influence the soil dynamics or peanut development.

The presence of peanuts provides a better soil quality index, that is, increasing the activity of β-glucosidase and arylsulfatase in the soil.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy15040912/s1, Figure S1: Pearson correlation matrix at the 5% level of significance of the physical and chemical variables of peanut cultivation soil under different amounts of coverage and herbicide application; Figure S2: Pearson correlation matrix at the 5% level of significance of the chemical and enzymatic variables of peanut cultivation soil under different amounts of coverage and herbicide application. OM (g dm^3), SOC (g kg−1), P (mg dm^3), K (mmolc dm^3) and Beta and Aryl (μg p-nitrophenol g^{-1} soil h^{-1}) (in a Masonry Frame); Figure S3: Pearson correlation matrix at the 5% level of significance of the chemical and enzymatic variables of peanut cultivation soil under different amounts of coverage and herbicide application. OM (g dm^3), SOC (g kg^{-1}), P (mg dm^3), K (mmolc dm^3) and Beta and Aryl (μg p-nitrophenol g^{-1} soil h^{-1}) (Field).

Author Contributions: Conceptualization: H.L.M. and P.L.d.C.A.A.; methodology: H.L.M., A.B.d.O. and J.F.D.Z.; formal analysis and investigation: H.L.M., A.N.C. and A.B.d.O.; data analysis H.L.M., A.N.C. and V.K.; writing—preparation of the original draft: H.L.M., A.N.C., J.F.D.Z. and M.C.P.; writing—review and editing: H.L.M., M.C.P., P.L.d.C.A.A. and V.K.; obtaining financing: H.L.M.; supervision: P.L.d.C.A.A. and V.K. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by the University of the State of Minas Gerais, the University of the Azores - Gaspar Frutuoso Foundation, and São Paulo State University, through the Postgraduate Program in Agronomy (Plant Production) under the PROEX/CAPES Program - AUXPE No. 2454/2023, Project No. 88887.914801/2023-00 - UNESP/JAB - Agronomy (Plant Production) - 33004102001P4 (Process No. 88881.914803/2023-01).

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy.

Acknowledgments: The first author would like to thank the Coordination for the Improvement of Higher Education Personnel Foundation (CAPES) for the scholarship granted (Process: 88887.640945/2021-00 and 88881.980652/2024-01. V.K. thanks Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) for the financial support.

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

References

1. Almeida, C.L.; Oliveira, J.G.B.; Araújo, J.C. Impacto da recuperação de área degradada sobre as respostas hidrológicas e sedimentológicas em ambiente semiárido. *Water Resour. Irrig. Manag.* **2012**, *1*, 39–50.
2. Rangel Vasconcelos, L.G.T.; Kato, O.R.; Vasconcelos, S.S. Matéria orgânica leve do solo em sistema agroflorestal de corte e trituração sob manejo de capoeira. *Pesqui. Agropecu. Bras.* **2012**, *47*, 1142–1149. [CrossRef]
3. Cherr, C.M.; Scholberg, J.M.S.; McSorley, R. Green Manure Approaches to Crop Production: A Synthesis. *Agron. J.* **2006**, *98*, 302–319. [CrossRef]

4. Balbinot, A.A., Jr.; Moraes, A.; Pelissari, A.; Dieckow, J.; Veiga, M. Formas de uso do solo no inverno e sua relação com a infestação de plantas daninhas em milho (*Zea mays*) cultivado em sucessão. *Planta Daninha* **2008**, *26*, 569–576. [CrossRef]
5. Zhang, D.; Yao, P.; Na, Z.; Yu, C.; Cao, W.; Gao, Y. Contribution of green manure legumes to nitrogen dynamics in traditional winter wheat cropping system in the Loess Plateau of China. *Eur. J. Agron.* **2016**, *72*, 47–55. [CrossRef]
6. Ferreira, T. Aspectos sanitários da cultura do amendoim. *Rev. Eletrôn. Biol.* **2014**, *7*, 301–320.
7. Peixoto, C.P.; Gonçalves, J.A.; de Fátima da Silva Pinto Peixoto, M.; Carmo, D.O.D. Características agronômicas e produtividade de amendoim em diferentes espaçamentos e épocas de semeadura no Recôncavo Baiano. *Bragantia* **2008**, *67*, 673–684. [CrossRef]
8. CONAB. *Acompanhamento da Safra Brasileira de Grãos*; Companhia Nacional de Abastecimento: Sobral, Brazil, 2023.
9. Ambrosio, L.M.S.; Bolonhezi, D.; Barini, R.T.; Betiol, V.; Gonçalves, L.H.O.; Leal, E.R.P.; Scarpellini, J.R. Análise de Crescimento de Cultivares de Amendoim em Diferentes Sistemas de Manejo do Solo na Palhada de Cana Crua. In *Anais*; Instituto Agronômico: Campinas, Brazil, 2017.
10. Sholar, J.R.; Mozingo, R.W.; Beasley, J.P., Jr. Peanut cultural practices. In *Advances in Peanut Science. Stillwater*; American Peanut Research and Education Society: Alexandria, VA, USA, 1995; pp. 354–382.
11. Wright, F.S.; Porter, D.M. Digging Date and Conservational Tillage Influence on Peanut Production1. *Peanut Sci.* **1991**, *18*, 72–75. [CrossRef]
12. Balkcom, K.S.; Tubbs, R.S.; Balkcom, K.B. Strip Tillage Implements for Single and Twin Row Peanut. *Agron. J.* **2018**, *110*, 1136–1146. [CrossRef]
13. Betiol, O.; Bolonhezi, D.; Leal, É.R.P.; Gruener, C.E.; Michelotto, M.D.; Furlani, C.E.A.; Ruiz, F.F. Conservation agriculture practices in a peanut cropping system: Effects on pod yield and soil penetration resistance. *Rev. Bras. Ciência Solo* **2023**, *47*, e0230004. [CrossRef]
14. Tubbs, R.S. The Future of Peanut Agronomic Research–The Sky is Not the Limit. *Peanut Sci.* **2019**, *46*, 99–103. [CrossRef]
15. Schreefel, L.; Schulte, R.P.O.; de Boer, I.J.M.; Schrijver, A.P.; van Zanten, H.H.E. Regenerative agriculture—The soil is the base. *Glob. Food Secur.* **2020**, *26*, 100404. [CrossRef]
16. Jaworski, C.C.; Krzywoszynska, A.; Leake, J.R.; Dicks, L.v. Sustainable soil management in the United Kingdom: A survey of current practices and how they relate to the principles of regenerative agriculture. *Soil Use Manag.* **2024**, *40*, e12908. [CrossRef]
17. Cavalieri-Polizeli, K.M.V.; Guedes Filho, O.; Romanoski, V.S.; Ruthes, B.E.S.; Calábria, Z.P.; de Oliveira, L.B. Conservative farming systems and their effects on soil organic carbon and structural quality. *Soil Tillage Res.* **2024**, *242*, 106143. [CrossRef]
18. Mendes, I.C.; Sousa, D.M.G.; Reis, F.B., Jr.; Kappes, C.; Ono, F.B.; Semler, T.D.; Zancanaro, L.; Lopes, A.A.C. Qualidade biológica do solo: Por que e como avaliar. In *Boletim de Pesquisa da Fundação*; EMBRAPA: Brasília, Brazil, 2017; Volume 1, pp. 98–105.
19. Mendes, I.C.; Ono, F.B.; Oliveira, M.I.; Silva, R.G.; Kappes, C.; Reis Junior, F.B.; Zancanaro, L. Bioanálise de solo: A mais nova aliada para a sustentabilidade agrícola.Informações Agronômicas. 2020. Available online: https://www.alice.cnptia.embrapa.br/alice/handle/doc/1128778 (accessed on 8 December 2024).
20. de Carvalho Mendes, I.; de Souza, L.M.; de Sousa, D.M.G.; de Castro Lopes, A.A.; dos Reis, F.B., Jr.; Lacerda, M.P.C.; Malaquias, J.V. Critical limits for microbial indicators in tropical Oxisols at post-harvest: The FERTBIO soil sample concept. *Appl. Soil Ecol.* **2019**, *139*, 85–93. [CrossRef]
21. Mendes, I.C.; Martinhão Gomes Sousa, D.; Dario Dantas, O.; Alves Castro Lopes, A.; Bueno Reis Junior, F.; Ines Oliveira, M.; Montandon Chaer, G. Soil quality and grain yield: A win–win combination in clayey tropical oxisols. *Geoderma* **2021**, *388*, 114880. [CrossRef]
22. Carneiro, R.G.; de Figueiredo, C.C.; Malaquias, J.V.; Mendes, I.C. A soil health assessment tool for vegetable cropping systems in tropical soils based on beta-glucosidase, arylsulfatase, and soil organic carbon. *Appl. Soil Ecol.* **2024**, *198*, 105394. [CrossRef]
23. Lopes, A.A.C.; Sousa, D.M.G.; Reis, F.B., Jr.; Figueiredo, C.C.; Malaquias, J.V.; Souza, L.M.; Mendes, I.C. Temporal variation and critical limits of microbial indicators in oxisols in the Cerrado, Brazil. *Geoderma Reg.* **2018**, *12*, 72–82. [CrossRef]
24. Lopes, A.A.C.; Sousa, D.M.G.; Chaer, G.M.; Reis Junior, F.B.; Goedert, W.J.; Mendes, I.C. Interpretation of microbial soil indicators as a function of crop yield and organic carbon. *Soil Sci. Soc. Am. J.* **2013**, *77*, 461–472. [CrossRef]
25. Serafim, M.E.; Zeviani, W.M.; Ono, F.B.; Neves, L.G.; Silva, B.M.; Lal, R. Reference values and soil quality in areas of high soybean yield in Cerrado region, Brazil. *Soil Tillage Res.* **2019**, *195*, 104362. [CrossRef]
26. Mendes, I.C.; Chaer, G.M.; Reis Junior, F.B.; Dantas, O.D.; Malaquias, J.V.; Oliveira, M.I.L.; Nogueira, M.A.; Hungira, M. Soil Bioanalysis (SoilBio): A Sensitive, Calibrated, and Simple Assessment of Soil Health for Brazil. In *Soil Health Series: Volume 3 Soil Health and Sustainable Agriculture in Brazil*; Soil Science Society of America, Inc.: Madison, WI, USA, 2024; pp. 292–326. [CrossRef]
27. Fávero, A.P.; Pádua, J.G.; Costa, T.S.; Gimenes, M.A.; Godoy, I.J.; Moretzsohn, M.C.; Michelotto, M.D. New hybrids from peanut (*Arachis hypogaea* L.) and synthetic amphidiploid crosses show promise in increasing pest and disease tolerance. *Genet. Mol. Res.* **2015**, *14*, 16694–16703. [CrossRef] [PubMed]
28. Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; de Moraes Gonçalves, J.L.; Sparovek, G. Köppen's climate classification map for Brazil. *Meteorol. Z.* **2013**, *22*, 711–728. [CrossRef]

29. Teixeira, P.C.; Donagemma, G.K.; Fontana, A.; Teixeira, W.G. *Manual de Métodos de Análise de Solo*, 3rd ed.; EMBRAPA: Dourados, Brazil, 2017.
30. Wickham, H.; Chang, W.; Wickham, M.H. Package 'ggplot2'. Create elegant data visualisations using the grammar of graphics. *Version* **2016**, *2*, 1–189.
31. Leonel, C.L. Influência do Preparo do Solo em Área de Reforma de Canavial na Qualidade Física do Solo e na Cultura do Amendoim. Ph.D. Thesis, Universidade Estadual Paulista, Faculdade de Ciências Agrárias e Veterinárias, São José do Rio Preto, Brazil, 2010.
32. Bolonhezi, D.; Leal, R.P. Manejo conservador do solo para amendoim. In *A Cultura do Amendoim e Seus Reflexos Econômicos, Sociais e Técnicos*; Foundation for Research, Education and Extension Support: Jaboticabal, Brazil, 2019; Volume 1, pp. 30–44.
33. Anache, J.A.A.; Wendland, E.C.; Oliveira, P.T.S.; Flanagan, D.C.; Nearing, M.A. Runoff and soil erosion plot-scale studies under natural rainfall: A meta-analysis of the Brazilian experience. *CATENA* **2017**, *152*, 29–39. [CrossRef]
34. McCarty, J.A.; Ramsey, S.; Sandefur, H.N. A Historical Analysis of the Environmental Footprint of Peanut Production in the United States from 1980 to 2014. *Peanut Sci.* **2016**, *43*, 157–167. [CrossRef]
35. Taiz, L.; Zeiger, E.; Møller, I.M.; Murphy, A. *Fisiologia e Desenvolvimento Vegetal*; Artmed Editora: São Paulo, Brazil, 2017.
36. Walker, M.E. Calcium requirements for peanuts. *Commun. Soil Sci. Plant Anal.* **1975**, *6*, 299–313. [CrossRef]
37. Paiva, E.A.S. Are calcium oxalate crystals a dynamic calcium store in plants? *New Phytol.* **2019**, *223*, 1707–1711. [CrossRef]
38. Hadi, M.R.; Karimi, N. The role of calcium in plants' salt tolerance. *J. Plant Nutr.* **2012**, *35*, 2037–2054. [CrossRef]
39. Bolonhezi, D.; Mutton, M.Â.; Martins, A.L.M. Sistemas conservacionistas de manejo do solo para amendoim cultivado em sucessão à cana crua. *Pesqui. Agropecu. Bras.* **2007**, *42*, 939–947. [CrossRef]
40. Bolonhezi, D.; Valochi, R.; Zanandrea, P.C.; Scarpelline, J.R.; Ambrosio, L.M.S.; Gonçalves, L.H.O.; Barini, R.T.; Bolonhezi, A.C. Peanut pod yield and soil compaction in conservation agriculture system. In Proceedings in 1st World Conference on Soil and Water Conservation Under Global Change 2017, Lledia, Spain, 12 June–16 June 2017; Spain, L., Simó, I., Poch, R.M., Eds.; pp. 173–176.
41. D'Amico-Damião, V.; Barroso, A.A.M.; da Costa Aguiar Alves, P.L.; Lemos, L.B. Intercropping maize and succession crops alters the weed community in common bean under no-tillage. *Pesqui. Agropecu. Trop.* **2020**, *50*, e65244. [CrossRef]
42. Chen, S.; Wang, Y.; Gao, J.; Chen, X.; Qi, J.; Peng, Z.; Chen, B.; Pan, H.; Liang, C.; Liu, J.; et al. Agricultural tillage practice and rhizosphere selection interactively drive the improvement of soybean plant biomass. *Plant Cell Environ.* **2023**, *46*, 3542–3557. [CrossRef] [PubMed]
43. Verma, G.; Dhaka, A.K.; Singh, B.; Kumar, A.; Choudhary, A.K.; Kumar, A.; Kamboj, N.K.; Hasanain, M.; Singh, S.; Bhupenchandra, I.; et al. Productivity, soil health, and carbon management index of soybean-wheat cropping system under double zero-tillage and natural-farming based organic nutrient management in north-Indian plains. *Sci. Total Environ.* **2024**, *917*, 170418. [CrossRef] [PubMed]
44. Thorburn, P.J.; Biggs, J.S.; Palmer, J.; Meier, E.A.; Verburg, K.; Skocaj, D.M. Prioritizing crop management to increase nitrogen use efficiency in Australian sugarcane crops. *Front. Plant Sci.* **2017**, *8*, 1504. [CrossRef] [PubMed]
45. Palmero, F.; Carcedo, A.J.P.; Haro, R.J.; Bigatton, E.D.; Salvagiotti, F.; Ciampitti, I.A. Modeling drought stress impacts under current and future climate for peanut in the semiarid pampas region of Argentina. *Field Crops Res.* **2022**, *286*, 108615. [CrossRef]
46. Ovando, G.; Haro, R.J. Uso do modelo CSM-CROPGRO-Peanut para estimar a época ideal de semeadura e produtividade da água da cultura sob diferentes teores de água no solo na Argentina. *S. Am. Sci.* **2022**, *3*, e22188. [CrossRef]
47. Concenço, G.; Leme Filho, J.R.A.; Silva, C.J. O aleiramento do palhiço de cana-de-açúcar agrava a infestação de plantas daninhas. In *Embrapa Agropecuária Oeste-Comunicado Técnico*; Embrapa: Dourados, Brazil, 2017.
48. Mingotte, F.L.C.; Lemos, L.B.; Jardim, C.A.; Fornasieri Filho, D. Crop systems and topdressing nitrogen on grain yield and technological attributes of common bean under no-tillage. *Pesqui. Agropecu. Trop.* **2019**, *49*, e54003. [CrossRef]
49. Zhu, B.; Yi, L.; Hu, Y.; Zeng, Z.; Lin, C.; Tang, H.; Yang, G.; Xiao, X. Nitrogen release from incorporated 15N-labelled Chinese milk vetch (*Astragalus sinicus* L.) residue and its dynamics in a double rice cropping system. *Plant Soil* **2014**, *374*, 331–344. [CrossRef]
50. Xia, L.; Lam, S.K.; Wolf, B.; Kiese, R.; Chen, D.; Butterbach-Bahl, K. Trade-offs between soil carbon sequestration and reactive nitrogen losses under straw return in global agroecosystems. *Glob. Change Biol.* **2018**, *24*, 5919–5932. [CrossRef] [PubMed]
51. Fahad, S.; Hussain, S.; Saud, S.; Hassan, S.; Tanveer, M.; Ihsan, M.Z.; Shah, A.N.; Ullah, A.; Nasrullah; Khan, F.; et al. A combined application of biochar and phosphorus alleviates heat-induced adversities on physiological, agronomical and quality attributes of rice. *Plant Physiol. Biochem.* **2016**, *103*, 191–198. [CrossRef]
52. Yang, H.; Feng, J.; Zhai, S.; Dai, Y.; Xu, M.; Wu, J.; Shen, M.; Bian, X.; Koide, R.T.; Liu, J. Long-term ditch-buried straw return alters soil water potential, temperature, and microbial communities in a rice-wheat rotation system. *Soil Tillage Res.* **2016**, *163*, 21–31. [CrossRef]
53. Zhao, J.; Liu, Z.; Gao, F.; Wang, Y.; Lai, H.; Pan, X.; Yang, D.; Li, X. A 2-year study on the effects of tillage and straw management on the soil quality and peanut yield in a wheat–peanut rotation system. *J. Soils Sediments* **2018**, *21*, 1698–1712. [CrossRef]
54. Barrow, N.J. The effects of pH on phosphate uptake from the soil. *Plant Soil* **2017**, *410*, 401–410. [CrossRef]

55. Hou, E.; Luo, Y.; Kuang, Y.; Chen, C.; Lu, X.; Jiang, L.; Luo, X.; Wen, D. Global meta-analysis shows pervasive phosphorus limitation of aboveground plant production in natural terrestrial ecosystems. *Nat. Commun.* **2020**, *11*, 637. [CrossRef] [PubMed]
56. Mogollón, J.M.; Beusen, A.H.W.; van Grinsven, H.J.M.; Westhoek, H.; Bouwman, A.F. Future agricultural phosphorus demand according to the shared socioeconomic pathways. *Glob. Environ. Change* **2018**, *50*, 149–163. [CrossRef]
57. McDowell, R.W.; Condron, L.M. Chemical nature and potential mobility of phosphorus in fertilized grassland soils. *Nutr. Cycl. Agroecosyst.* **2000**, *57*, 225–233. [CrossRef]
58. Gessa, C.E.; Mimmo, T.; Deiana, S.; Marzadori, C. Effect of aluminium and pH on the mobility of phosphate through a soil-root interface model. *Plant Soil* **2005**, *272*, 301–311. [CrossRef]
59. Asomaning, S.K. Processes and factors affecting phosphorus sorption in soils. In *Sorption in 2020s*; IntechOpen: London, UK, 2020; Volume 45, pp. 1–16.
60. Dick, R.P. *Defining Soil Quality for a Sustainable Environment*; Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A., Eds.; Soil Science Society of America and American Society of Agronomy: Madison, WI, USA, 1994. [CrossRef]
61. Rasool, B.; ur-Rahman, M.; Adnan Ramzani, P.M.; Zubair, M.; Khan, M.A.; Lewińska, K.; Turan, V.; Karczewska, A.; Khan, S.A.; Farhad, M.; et al. Impacts of oxalic acid-activated phosphate rock and root-induced changes on Pb bioavailability in the rhizosphere and its distribution in mung bean plant. *Environ. Pollut.* **2021**, *280*, 116903. [CrossRef]
62. Maurya, P.R.; Lal, R. Effects of different mulch materials on soil properties and on the root growth and yield of maize (*Zea mays*) and cowpea (*Vigna unguiculata*). *Field Crops Res.* **1981**, *4*, 33–45. [CrossRef]
63. Sherene, T. Role of soil enzymes in nutrient transformation: A review. *Bio Bull.* **2017**, *3*, 109–131.
64. Serafim, M.E.; Mendes, I.C.; Wu, J.; Ono, F.B.; Zancanaro, L.; Valendorff, J.D.P.; Zeviani, W.M.; Pierangeli, M.A.P.; Fan, M.; Lal, R. Soil physicochemical and biological properties in soybean areas under no-till Systems in the Brazilian Cerrado. *Sci. Total Environ.* **2023**, *862*, 160674. [CrossRef] [PubMed]
65. Huang, X.; He, J.; Yan, X.; Hong, Q.; Chen, K.; He, Q.; Zhang, L.; Liu, X.; Chuang, S.; Li, S.; et al. Microbial catabolism of chemical herbicides: Microbial resources, metabolic pathways and catabolic genes. *Pestic. Biochem. Physiol.* **2017**, *143*, 272–297. [CrossRef]
66. Tabatabai, M.A.; Bremner, J.M. Factors Affecting Soil Arylsulfatase Activity. *Soil Sci. Soc. Am. J.* **1970**, *34*, 427–429. [CrossRef]
67. Vitti, G.C.; Otto, R.; Savieto, J. Manejo do enxofre na agricultura. In *Informações Agronômica*; Internacional Plant Nutrition Institute: Piracicaba, Brazil, 2015; pp. 1–14.
68. Funkler, R.; Pedroso, R.M.; Stein, R.T.; Lazzarini, P.R.C. *Ciência do Solo e Fertilidade*; Grupo A: Porto Alegre, Brazil, 2018; Volume 1.
69. Santos Bastos, T.R.; Barreto-Garcia, P.A.B.; de Carvalho Mendes, I.; Monroe, P.H.M.; de Carvalho, F.F. Response of soil microbial biomass and enzyme activity in coffee-based agroforestry systems in a high-altitude tropical climate region of Brazil. *Catena* **2023**, *230*, 107270. [CrossRef]
70. Dick, R.P.; Burns, R.G. *Methods of Soil Enzymology*; Dick, R.P., Ed.; American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America: Madison, WI, USA, 2011. [CrossRef]
71. Hojjati, S.; Nourbakhsh, F. Effects of cow manure and sewage sludge on the activity and kinetics of l-glutaminase in soil. *Biol. Fertil. Soils* **2007**, *43*, 491–494. [CrossRef]