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CO_2 Fluxes and Soil Responses to Straw and Herbicide in Peanut

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ABSTRACT

Peanut cultivation plays an important agronomic role in Brazil, especially in rotation with sugarcane, promoting biological nitrogen fixation and improving soil quality. This study aimed to test the hypothesis that the combined use of sugarcane mulch, peanut cultivation, and herbicide application would affect soil CO_2 fluxes, soil chemical attributes (pH, organic matter, soil organic carbon—SOC, phosphorus, potassium, calcium, magnesium, cation exchange capacity—CEC, and base saturation—V%), enzymatic activity (β-glucosidase and arylsulfatase), and the soil quality index (SQI). The experiment, conducted in Jaboticabal (São Paulo), employed different combinations of mulch, peanut cultivation, and imazapic herbicide. Treatments with mulch and peanut increased enzymatic activity, SOC, and pH, resulting in higher SQI values, while bare soil showed marked degradation. CO_2 fluxes were higher in treatments with both plants and mulch, reflecting greater biological activity; however, in the context of soil degradation, elevated CO_2 emissions may also indicate accelerated decomposition and potential organic matter losses. β-glucosidase proved to be a sensitive bioindicator of soil quality. Integrated analysis using the SQI and the four-quadrant model revealed that treatments with mulch and peanut promoted healthy and biologically active soils. It is concluded that conservation practices, such as the maintenance of surface mulch and the cultivation of legumes, are effective strategies for enhancing soil health and sustainability, whereas the absence of vegetation cover leads to soil degradation.

1 | Introduction

Peanut cultivation holds significant economic importance in Brazil (IEA 2024), with the main production regions located in the southeastern and central-western parts of the country, totaling 927.1 thousand tons in the 2022/23 harvest season (CONAB 2025). In these regions, peanuts are primarily grown in rotation with sugarcane. The crop offers agronomic benefits through biological nitrogen fixation and contributes to soil decompaction (Silva et al. 2020). Additionally, the peanut cultivated area in Brazil has increased substantially, expanding from 97 thousand hectares in 2012/13 to approximately 220 thousand hectares in the 2022/23 season and reaching around 255 thousand hectares in 2023/24 (IEA 2024).

These positive effects on soil quality and structure are essential not only for maintaining soil functionality but also for contributing to climate change mitigation. Soil is the only natural resource with a significant potential to remove atmospheric carbon dioxide (CO_2), being the largest terrestrial reservoir of organic

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carbon (Canadell and Monteiro 2021; Lal 2018). However, under natural conditions, soil emits CO_2 due to microbial and root respiration, as well as organic matter decomposition (Machado et al. 2023). Soil respiration is critical for understanding the dynamics of soil organic matter, assessing biological functionality, and developing adaptive and mitigation strategies to climate change (Souza et al. 2022).

One of the key components for maintaining sustainability in agricultural systems is the presence of surface mulch (Barbosa et al. 2024). Physically, mulch protects the soil by reducing erosion, preventing surface sealing, buffering temperature fluctuations, and conserving moisture by limiting evaporation. Biologically, mulch serves as the main substrate for soil microbiota, enhancing microbial activity and continuously supplying organic matter (Machado et al. 2023). Additionally, it reduces weed seed germination and emergence (Gazola et al. 2022; Kaur et al. 2021). This dynamic promotes organic carbon accumulation and facilitates the gradual release of nutrients, playing a central role in nutrient cycling (Lima et al. 2023). Given these benefits, several studies are currently exploring the feasibility of direct seeding of peanut crops into sugarcane mulch residues (Bolonhezi and Leal 2019; Betiol et al. 2023; Martins et al. 2025).

However, as with most crops, peanut cultivation is negatively affected by weed interference (Kavosi et al. 2015; Carrega et al. 2022), which is most commonly managed through herbicide application. Several studies have shown that frequent exposure to certain herbicide active ingredients can alter the structure and functional activity of microbial communities, thereby disrupting biogeochemical processes, impairing organic matter decomposition, and affecting nitrogen cycling (Ferreira et al. 2023; Ma et al. 2023; Ji et al. 2023; Bhardwaj et al. 2024; Yu et al. 2024). These microbial alterations can also influence the emission of greenhouse gases from the soil, especially CO_2 and nitrous oxide (N_2O) (Santos et al. 2022).

Given the complexity and importance of these biological processes, soil quality indices (SQIs) are essential tools for integrating multiple soil attributes—physical, chemical, and biological—into a single standardized metric. This approach enables a more precise identification of soil health status and provides a useful proxy for decision-making in sustainable land management (Andrade et al. 2022).

Within this context, it is crucial to deepen investigations into the relationship between sugarcane mulch and greenhouse gas emissions, especially in cropping systems where peanut is used in rotation with sugarcane. The abundant presence of mulch (dead plant material after harvest), commonly incorporated into sugarcane fields, favors microbial activity and nutrient cycling and may help reduce soil CO_2 emissions (Wang et al. 2018). However, such benefits can be diminished by the application of herbicides. Thus, there is a clear need for studies addressing the interactions among mulch management, herbicide use, and greenhouse gas emissions in peanut cropping systems (Santos et al. 2022).

Accordingly, this study tested the following hypotheses: (1) Sugarcane mulch increases soil CO_2 emissions by enhancing microbial and enzymatic activity; (2) Herbicide application negatively affects soil biological activity; and (3) The combination of mulch and peanut cultivation contributes positively to soil health, as reflected by higher SQI values. Therefore, the main objective of this work was to evaluate the effects of sugarcane mulch and imazapic herbicide (Plateau) on soil CO_2 emissions, chemical attributes, enzymatic activity, and soil quality indices in a peanut cropping system.

2 | Materials and Methods

2.1 | Study Area and Experimental Design

The experiment was conducted in the northern region of the state of São Paulo, in the municipality of Jaboticabal, Brazil (21°14′39.83″ S and 48°17′56.84″ W, at an altitude of 606 m). The regional climate is classified as Cwa—subtropical, with dry winters and rainy summers, an average annual temperature of 22.7°C, and an average annual rainfall of 1353 mm (Alvares et al. 2013). During the experimental period, climatic data were recorded for the Jaboticabal region, including rainfall, maximum, minimum, and average temperatures, as well as relative air humidity (Figure 1).

The experiment was conducted in an open field using experimental plots of 1.10 m^2, outlined with masonry frames and filled with Dark Red Latosol (10R 3/6, moist), with a clayey texture, during the fall–winter season of 2023. The trial lasted for 6 months, from January to June, characterizing a short-term experiment covering a single cropping season. Prior to the installation of the experiment, soil samples were collected using a Dutch auger at a depth of 0–20 cm for chemical and physical analyses.

The soil profile was characterized as follows: pH ($CaCl_2$, 0.01 mol L^{-1}, potentiometry) = 5.6; organic matter (Walkley–Black method) = 16 g dm^{-3}; phosphorus (extracted by ion exchange resin, colorimetry) = 6 mg dm^{-3}; potassium (ion exchange resin, flame photometry) = 3 mmolc dm^{-3}; calcium and magnesium (ion exchange resin, atomic absorption spectrophotometry) = 33 and 8 mmolc dm^{-3}, respectively; potential acidity—H + Al (extraction with calcium acetate, pH 7.0) = 20 mmolc dm^{-3}; sum of bases = 44.1 mmolc dm^{-3}; cation exchange capacity (CEC) = 63.9 mmolc dm^{-3}; and base saturation (V%) = 69%. The particle size distribution, determined by the pipette method with chemical dispersion (NaOH), was: 53% clay, 21% silt, and 26% sand.

The peanut cultivar used was IAC 503, developed by the Agronomic Institute of Campinas (Instituto Agronômico de Campinas—IAC), Brazil. This cultivar has a prostrate growth habit, indeterminate vegetative growth, and moderate resistance to foliar diseases such as early leaf spot and rust.

The experimental design was a randomized complete block, consisting of 12 treatments with four replicates each, as described in Table 1.

For plant-related variables, only the first six treatments (T1 to T6) were considered. For soil-related variables, all 12 treatments were included in the analysis. Each plot consisted of two rows

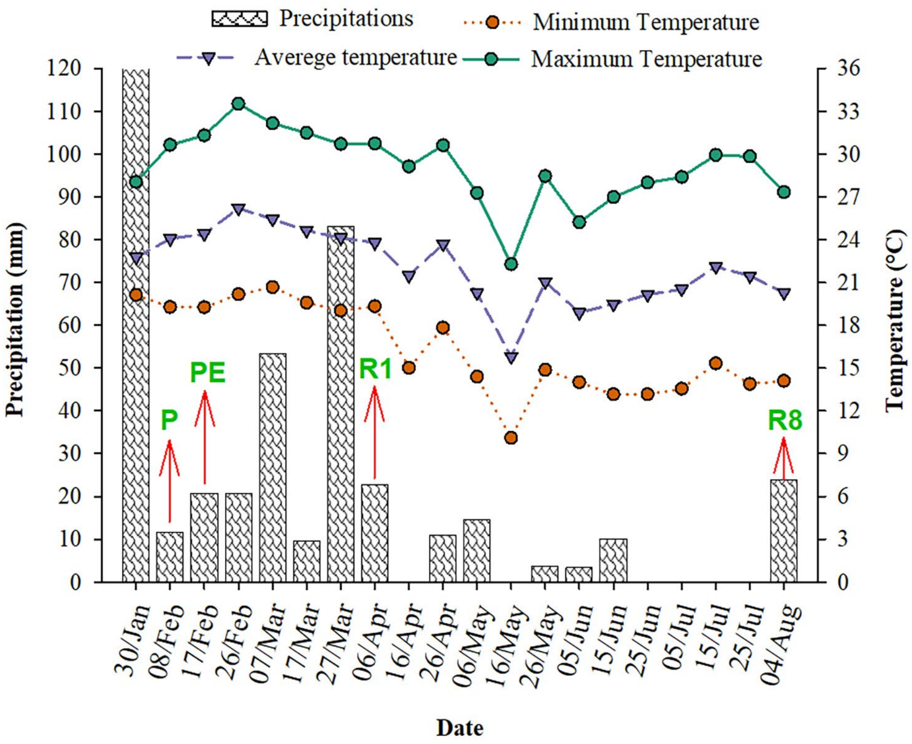

FIGURE 1 | Climatological data of the area during the experiment between January and August 2023. Latitude: 21°14′05″S, longitude: 48°17′09″W, altitude: 615.01 m. P, planting; PE, plant emergence; R1, beginning of flowering and R8, end of cycle. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 | Description of experimental treatments.

Treatment	Peanut	Straw	Herbicide	Acronym	Control type
1	Present	10	With	AP10H	—
2	Present	5	With	AP5H	—
3	Present	10	Without	AP10	—
4	Present	5	Without	AP5	—
5	Present	0	With	AH	—
6	Present	0	Without	A	Crop control
7	Absent	10	With	P10H	—
8	Absent	5	With	P5H	—
9	Absent	10	Without	P10	—
10	Absent	5	Without	P5	—
11	Absent	0	With	H	—
12	Absent	0	Without	S	Absolute control

Note: Treatment 12 (S) was considered the absolute control (bare soil, without peanut, straw, or herbicide). Treatment 6 (A) was considered the crop control (peanut cultivation without straw or herbicide).

spaced 0.9 m apart, with a length of 6 m; these two rows were considered the usable area.

Sowing was carried out at a density of 23 seeds per meter, with fertilization corresponding to 300 kg ha^{-1} of the 4–14–8 formulation, as recommended for the crop. Sugarcane mulch was collected in the Jaboticabal-SP region and applied at 5 and 10 t ha^{-1} (0.550 and 1.10 kg m^2, respectively). Irrigation was performed with a conventional sprinkler system at 5-day intervals, applying approximately 30 mm per cycle (390 mm in total), in addition to 292 mm of rainfall. The cumulative water input (682 mm) was within the typical requirement for peanut (≈500–700 mm) and consistent with local fall–winter conditions in Jaboticabal. These management practices were implemented to establish the experimental treatments and evaluate their effects on CO_2 fluxes and soil property responses.

The herbicide used was imazapic (Plateau), applied 15 days after plant emergence (DAE) at a rate of 98.0 g a.i. ha^{-1}. Applications were performed using a CO_2-pressurized backpack sprayer, fitted with a boom containing four 110.02 nozzles spaced 0.5 m apart, covering a 2 m swath. The sprayer was calibrated to deliver 200 L ha^{-1} of spray solution at a pressure of 2.8 bar. During application, the following conditions were recorded: start time at 18:12; end time at 18:42; clear skies; air temperature of 26°C; wind speed of 9 km h^{-1}; and relative humidity of 70%.

2.2 | Soil Chemistry

For soil chemical analysis, samples were collected at 60 days after emergence (DAE) and sent to Athenas–Agricultural Consulting and Laboratories, a laboratory specialized in the analysis of pH, organic matter (OM), nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), aluminum (Al), potential acidity (H + Al), sum of bases (SB), cation exchange capacity (CEC), and base saturation (V%). The analytical procedures followed the methodology described by Teixeira et al. (2017).

2.3 | β-Glucosidase and Arylsulfatase Activity

Soil samples were air-dried, passed through a 2 mm sieve, and stored at 4°C until analysis, following the recommendations of Mendes, Sousa, et al. (2019). The activities of the enzymes arylsulfatase and β-glucosidase were measured according to the methodology proposed by Tabatabai (1994). The analytical methods were based on the colorimetric determination of p-nitrophenol, following the addition of specific substrates for each enzyme: p-nitrophenyl sulfate for ARYL and p-nitrophenyl-β-D-glucopyranoside for BG. ARYL was selected due to its role in the sulfur cycle (arylsulfatase), and BG due to its role in the carbon cycle (β-glucosidase). Enzyme activity for both enzymes was expressed in μg of p-nitrophenol per gram of soil (μg pNP g^{-1}).

2.4 | Assessments of Soil CO_2 Emissions, Soil Temperature and Soil Moisture

Soil CO_2 flux (FCO_2, $\mu mol\, m^{-2} s^{-1}$) was quantified using an LI-8100 soil CO_2 flux system (LI-COR, Lincoln, NE, USA). Soil moisture was determined using a Time Domain Reflectometry system (Hydrosense, Campbell Scientific Inc., Logan, UT, USA) using 12 cm probes inserted 10 cm from each collar, whereas soil temperature was measured using a digital thermometer.

Measurements were conducted at four points per plot, spaced at least 0.5 m apart, where PVC collars (0.10 m in diameter and 15 cm in height) were installed. A total of 12 measurement campaigns were performed: 3 days before herbicide application and on nine consecutive days thereafter, between April 20 and May 2, 2023 (except April 23), always between 7:00 and 11:00.

2.5 | Average Specific Enzyme Activity (ASEA)

To normalize enzyme activities based on the amount of soil organic carbon (SOC), each enzyme (GLU and ARYL) was divided by SOC, resulting in the specific activity of β-glucosidase (S-GLU) and the specific activity of arylsulfatase (S-ARYL) (Trasar-Cepeda, Leiros, Seoane, and Gil-Sotres 2008; Trasar-Cepeda, Leiros, and Gil-Stores 2008).

2.6 | Soil Health (SH) Assessment Combining IQS and 4QM Approaches

Due to the difficulty in obtaining yield data for all treatments—since some included plants and others did not, the Soil Quality Index (SQI) was adopted as the primary evaluation metric. SQI was calculated using an indexing technique known for its strong performance in small-scale applications like field-level studies for which soil health was defined as the management goal. Methodology proposed by Andrews et al. (2002).

2.7 | Peanut Management Evaluations Combining CASH and 4QM

As the data exhibited low variability and were collected under homogeneous edaphic conditions, cumulative normal distribution (CND) interpolation was applied to each individual variable (SOC and ASEA). This statistical approach allows the assignment of scores between 0 and 100 based on the relative position of the observed value within its distribution as recommended by Moebius-Clune et al. (2016) and Carneiro et al. (2024). Based on these scores, a threshold value of 50 was established as the critical level for both SOC and ASEA. A score of 50% was proposed by Chaer et al. (2023) and represents the minimum acceptable values of SOC and ASEA to be maintained from both an economic and soil functionality perspective. Values below this threshold strongly indicate that the management practice compromises both soil quality and health.

Similarly, SOC and ASEA values from soil samples associated with the SQI were analyzed using a four-quadrant graphical visualization, by plotting ASEA on the *x*-axis and SOC on the *y*-axis (Chaer et al. 2023). The thresholds derived from the SQI approach were used to divide the ASEA vs. SOC scatter plot into four quadrants. The interpretation of each quadrant is summarized in Table 2.

2.8 | Statistical Analysis

For each dataset, normality was tested using the Shapiro–Wilk test, and homogeneity of variances (homoscedasticity) was assessed using the Breusch–Pagan test. As these assumptions were not met, non-parametric tests were applied: the Wilcoxon test for comparisons between two independent groups, and the Kruskal–Wallis test for comparisons among more than two independent groups.

A subset of variables was selected from the initial dataset using the PRINCOMP procedure (Principal Component Analysis—PCA). The indicators retained through PCA were subsequently subjected to a correlation analysis using the CORR procedure.

An additional ANOVA was also performed on the overall Soil Quality Index (SQI) and on the soil quality indicators selected by

TABLE 2 | Interpretation of the Four Quadrant Model (4QM) applied to soil quality assessment.

Quadrant	Position relative to thresholds	Soil condition	Interpretation
Q1	High SOC – High ASEA	Healthy soils	Favorable soil quality and biological activity
Q2	High SOC – Low ASEA	Moderate soils	Good carbon levels but limited enzymatic activity; potential restriction to nutrient cycling
Q3	Low SOC – Low ASEA	Degraded soils	Loss of organic matter, low enzymatic activity, and poor edaphic health indicators
Q4	Low SOC – High ASEA	Transitional soils	Some biological activity but constrained by low carbon availability; unstable condition

the MDS in order to assess the effects of crop succession, straw management, and fertilizer treatments on soil quality.

Boxplot representations of descriptive statistics were used to illustrate SOC and ASEA distributions within each quadrant of the four-quadrant model (4QM).

3 | Results

3.1 | Soil CO_2 Emission (FCO2)

A significant effect of treatments ($F = 58.53$; $p < 0.001$), evaluation days ($F = 11.33$; $p < 0.001$), and their interaction ($F = 1.66$; $p < 0.001$) was observed on soil CO_2 emissions (FCO_2) (Figure 2). Treatments T1 (AP10H) and T2 (AP5H), which combined peanut plants, herbicide, and sugarcane straw at 10 and 5 t ha^{-1}, respectively, showed the highest CO_2 fluxes, with averages of 3.42 and 3.56 μmol m^{-2} s^{-1}. These values were up to 61.4% higher than those recorded in treatments T11 (H) and T12 (S), both without plants or straw, which presented the lowest emission values (1.60 and 1.32 μmol m^{-2} s^{-1}, respectively).

Treatments with plants but no herbicide, such as T4 (AP5), also showed elevated fluxes (2.83 μmol m^{-2} s^{-1}) compared to T6 (A), which had no straw (2.32 μmol m^{-2} s^{-1}). Additionally, T4 significantly outperformed the plant-free treatments T8 (P5H), T9 (P10), and T10 (P5), reinforcing the role of plant cover and biomass in promoting soil respiration. Treatment T3 (AP10), with peanut and 10 t ha^{-1} of straw, also exhibited significantly higher emissions than T9 and T10, highlighting the relevance of organic residue input.

Over time, treatments T1 and T2 maintained the highest FCO_2 values, especially in the early days, with T2 peaking on day 1 at 4.54 μmol m^{-2} s^{-1}. Meanwhile, T12 (bare soil) consistently recorded the lowest emissions throughout the assessment period, with significant differences compared to most other treatments on almost all days. The data indicate that the greater the system complexity (presence of plants, straw, and herbicide), the higher the biological activity, as reflected in CO_2 emissions.

Marked temporal variations were also observed within treatments. In T4, for instance, day 2 showed the highest FCO_2 (4.15 μmol m^{-2} s^{-1}), while T7 (P10H) exhibited a progressive decline from 3.63 μmol m^{-2} s^{-1} (day 1) to 1.69 μmol m^{-2} s^{-1} (day 11). In T8, emissions significantly decreased from 3.24 μmol m^{-2} s^{-1} (day 1) to 1.81 μmol m^{-2} s^{-1} (day 9). In contrast, treatments T11 and T12 maintained low and stable levels, highlighting the low biological activity in soils devoid of cover and vegetation.

3.2 | Soil Temperature (St)

A significant effect was observed for treatments ($F = 23.64$; df = 11; $p < 0.001$; Figure 2a), days ($F = 150.53$; df = 10; $p < 0.001$), and the interaction between treatments and evaluation days ($F = 3.08$; df = 110; $p < 0.001$) (Figure 3b and Table S1). The lowest soil temperature (20.2°C) was recorded in treatments T5 (AH) and T6 (A), and both differed significantly from the other treatments ($p < 0.001$), except for T6 (A), which was not statistically different from treatments T9 (20.5°C) and T12 (20.9°C).

The highest soil temperatures were observed in treatments T7 (P10H) and T8 (P5H), both reaching 21.0°C. These treatments not only showed higher temperatures than T5 and T6 but also significantly exceeded the temperatures recorded in treatments T3 (20.6°C), T4 (20.6°C), T9 (20.5°C), T10 (20.5°C), T11 (20.7°C), and T12 (20.5°C). Furthermore, treatment T8 (21.0°C) also differed from T1 (20.7°C). Treatment T2 (20.9°C) likewise showed significantly higher temperatures ($p < 0.001$) compared to T3, T9, T10, and T12.

3.3 | Soil Moisture (Sm)

A significant effect was observed for treatments ($F = 21.46$; df = 11; $p < 0.001$) (Figure 4) and for days ($F = 18.98$; df = 10; $p < 0.001$) (Table S1); however, there was no significant interaction between these two factors (F = 0.91; df = 110; $p = 0.73$). The highest soil moisture values were recorded in treatments T3 (AP10) and T4 (AP5), with 26.6% and 27.0%, respectively. These differed significantly from treatments T5, T7, T8, T9, T11, and T12, as well as between T4 and T6.

Statistical differences were observed between soil moisture (Sm) in treatments T5 (AH) and T6 (A), which exhibited the lowest moisture values (22.6% and 22.8%, respectively) compared to the other treatments, except for T11 (H) and T12 (S), which also showed low moisture levels (23.0% and 23.8%, respectively), following T5 and T6.

Soil moisture in treatments T11 and T12 was significantly lower than in treatments T1 (25.6%), T2 (25.8%), T3 (26.6%),

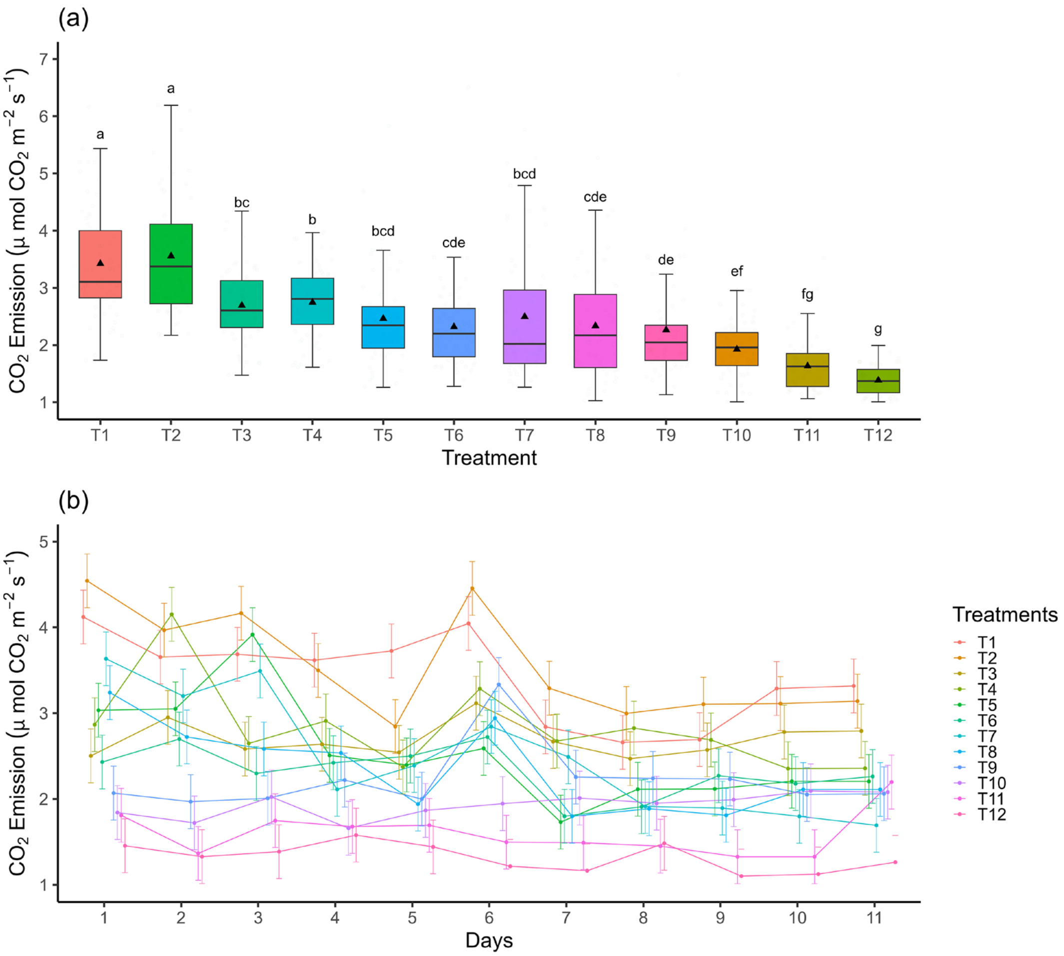

FIGURE 2 | (a) Box plot of the analysis of means between treatments by the Tukey test at 5% significance. The black triangles indicate the mean, the black horizontal line the median. (b) Graph of temporal variability of the treatments. Dots indicate the daily mean per treatment and the lines above and below these indicate ± the standard error of the mean. Different letters indicate significant differences. [Colour figure can be viewed at wileyonlinelibrary.com]

T4 (27.0%), and T10 (25.5%) ($p < 0.001$), with significant differences also found between T11 and treatments T6 (25.1%) and T8 (24.9%).

The days with the highest moisture levels were day 2 (26.4%) and day 7 (26.6%), which were statistically different from days 3 (24.7%), 5 (21.9%), 6 (24.3%), 8 (24.4%), and 11 (24.8%). Moisture on day 7 also differed from days 4 (23.4%) and 10 (24.9%). The lowest soil moisture was recorded on day 5 (21.9%), followed by day 4 (23.4%), which were significantly different from days 1, 9, and 10, as well as from days 3, 6, 8, and 11.

Treatments that included peanut cultivation exhibited higher values compared to those where the soil was left fallow or subjected to treatments without the crop. For the variables presented in Table 3—except for arylsulfatase (ARYL) and potential acidity (H + Al)—the treatment with Peanut + Mulch + Herbicide (T2) showed the highest values, standing out as the most efficient treatment for improving soil conditions (Table 3). ARYL showed higher values in T5, while H + Al peaked in T12, the fallow soil.

The soil pH was slightly acidic, tending toward neutrality across all treatments. Soil organic matter (OM), phosphorus (P), potassium (K), cation exchange capacity (CEC), soil organic carbon (SOC), sulfur (S), calcium (Ca), magnesium (Mg), base saturation (BS), and β-glucosidase activity (β-glucosidase) were all higher in treatments that included both mulch and plants. These findings highlight the key role of plant biomass and surface residue in enhancing organic carbon retention and facilitating decomposition processes in the cropping system.

3.4 | Soil Quality Index (SQI)

Considering the 17 previously mentioned chemical and physical soil attributes, the Principal Component Analysis (PCA) generated 17 principal components (PCs). According to Kaiser's criterion, the minimum number of components to retain was four, since eigenvalues dropped below 1 starting from PC5 (Table 4). In the Scree plot (Figure 5), however, the inflection point occurred at PC3, suggesting that the first three PCs should be retained based on this criterion. Kaiser's rule tends to retain a large number of components, and the decision to include or exclude a component may be questionable when its eigenvalue is close to 1 (Norman and Streiner 2008). Therefore, following the Scree plot, three PCs were retained to represent the original variability of the dataset. These three principal components explained

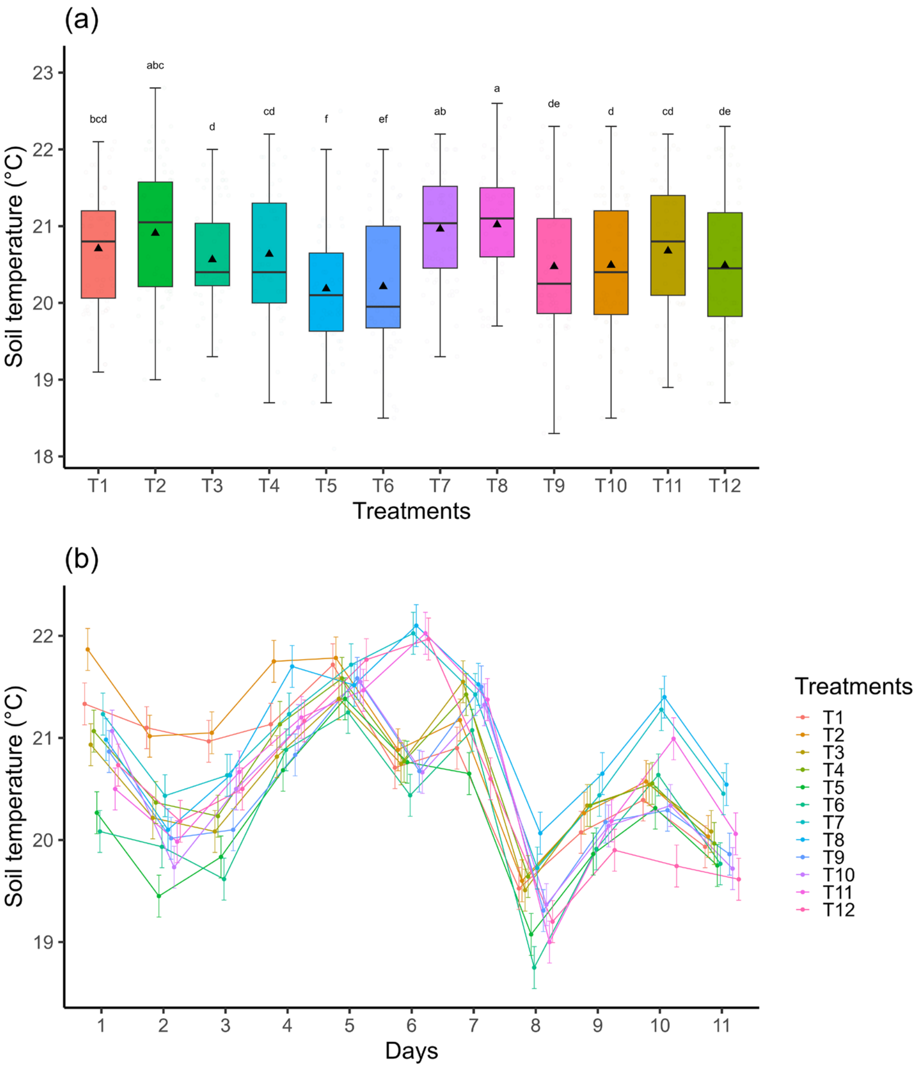

FIGURE 3 | (a) Box plot of temperature between evaluated treatments. The black triangles indicate the mean, the black horizontal line the median. (b) Graph of temporal variability of temperature of treatments according to the days of evaluation. Dots indicate the daily mean per treatment and the lines above and below these indicate ± the standard error of the mean. Different letters indicate significant differences. [Colour figure can be viewed at wileyonlinelibrary.com]

78.7% of the total variance (Table 4), while the remaining components contributed relatively little. Individually, PC1, PC2, and PC3 explained 49.09%, 15.56%, and 14.05% of the total variance, respectively.

The principal component loading matrix (Table 4) showed that the first principal component (PC1) had four highly weighted variables: pH, magnesium (Mg), sum of bases, and base saturation. However, the variable "sum of bases" was excluded because it is a composite value derived from the other variables obtained in the study. This group of indicators suggests that PC1 is mainly associated with pH and the chemical properties of the soil. The pattern and magnitude of the component loadings in PC2 indicate that this component is primarily related to soil organic matter activity, as the highly weighted variables were organic matter, soil organic carbon, and β-glucosidase activity. The variable retained in PC3 was sulfur (S).

Correlation analysis was employed to identify redundant variables within each principal component (Table 5). The highly weighted variables in PC1 (pH, Mg, and base saturation) were all significantly correlated; consequently, only pH was included in the Minimum Data Set (MDS). In PC2, SOC and β-glucosidase did not show autocorrelation and were therefore both included in the MDS. In PC3, since sulfur (S) was the only retained variable, it was automatically included in the MDS. The final MDS consisted of: pH, SOC, β-glucosidase, and S.

Nonlinear scoring functions were used to transform the MDS soil properties into values ranging from 0 to 1 (Figure 6). "More is better" functions were applied to β-glucosidase, SOC, and sulfur (S), due to their positive influence on crop productivity (i.e., the management goal), and thus on soil quality. An "optimum" function was used to score soil pH, considering its role in the soil solution and the thresholds for optimal plant development. The appropriate critical limits (Table 6) were established based on values reported in the literature (Glover et al. 2000; Hussain et al. 1999; Masto et al. 2008) and taking into account site-specific characteristics as well as the management objective.

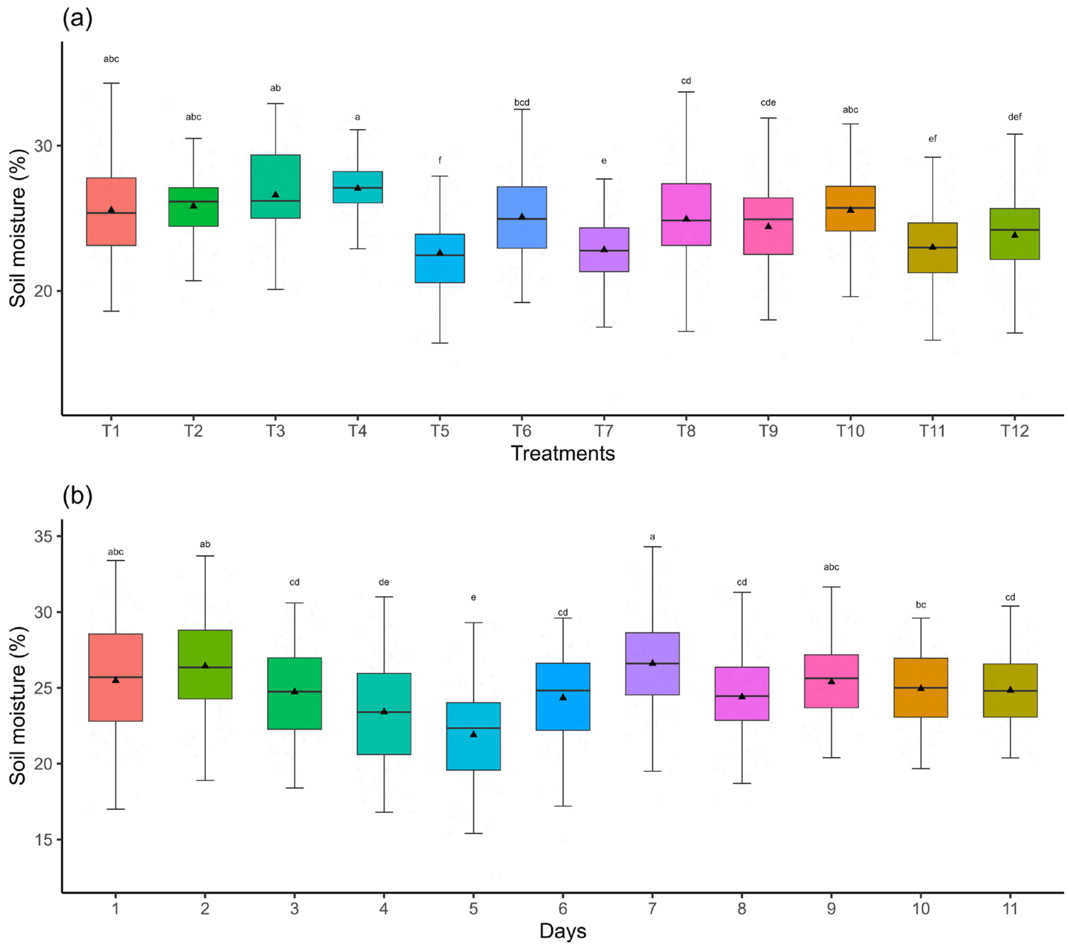

FIGURE 4 | (a) Box plot of soil moisture (%) among the evaluated treatments. Black triangles represent the mean values, and the horizontal black line indicates the median. (b) Temporal variability graph of soil moisture (%) according to the evaluation days. Dots represent the daily mean per treatment, and the lines above and below represent ± the standard error of the mean. Different letters indicate statistically significant differences. [Colour figure can be viewed at wileyonlinelibrary.com]

The weights (Table 5) were assigned to the MDS indicators based on the outcomes of the PCA (Table 4) and were equal to the percentage of variance explained by each principal component (total value for non-correlated variables, divided among correlated ones), standardized to unity. Specifically, pH was the only variable selected from PC1 and thus received the full weight of 0.49. SOC and β-glucosidase were strongly correlated in PC2, so the weight of 0.155 was assigned for the two parameters. The total weight of 0.14 was assigned to sulfur (S) from PC3.

The SQI was calculated as follows:

$$\mathrm{SQI} = \frac{0.49.\,S_{pH} + 0.155.\,S_{COS} + 0.155.\,S_{Beta} + 0.14.\,S_{S}}{0.94}$$

$$\mathrm{SQI} = 0.52.\,S_{pH} + 0.165.\,S_{COS} + 0.165.\,S_{Beta} + 0.149.\,S_{S}$$

where S is the score of the subscript variable and the coefficients are the weighting factors.

Significant differences were observed inthe Soil Quality (SQI), which ranged from 0.43 to 0.80. Treatments T1, T2, T4 and T8 are responsible for the highest values (0.74 to 0.80). indicating better soil quality conditions under systems that included peanut cultivation, sugarcane straw addition, and herbicide application. Treatments T10, T11 and T12, presented the lowest SQI values (Table 7).

Treatment T4 (Peanut +5 t/ha straw without herbicide) presented the highest SQI value (0.80), supported by high scores for pH (1.00) and S (0.85), despite a moderate score for SOC (0.54). Similarly, treatment T2 (Peanut +5 t/ha straw + herbicide) showed balanced scores across all indicators, resulting in an SQI of 0.75. Treatments T1 and T8 also achieved high SQI values (0.75 and 0.78, respectively), highlighting the benefits of combining mulch and chemical control.

On the other hand, treatment T12 (bare soil) showed the lowest SQI (0.43), reflecting degraded soil conditions, particularly for SOC (0.33) and β-glucosidase activity (0.19). Treatments T10 and T11 also displayed low SQI values (0.52 and 0.58, respectively), indicating that the absence of plant cover or organic residues, even with herbicide application, is detrimental to soil functionality.

β-Glucosidase activity (Beta) proved to be highly sensitive to management practices, showing significant variation between

TABLE 3 | Summary of analysis of variance (ANOVA) for measured physical and chemical soil properties.

	pH	OM	SOC	P	K	SB	CEC	S	Ca	Mg	H + Al	SatB	Beta	Aril
Treats. [a]		g dm^3	g kg^{-1}	mg dm^3	mmol$_c$ dm^3			mg dm^3	mmol$_c$ dm^3			V%	µg pNP g^{-1} solo h^{-1}	
Treatments														
T1[b]	6.48b	17.15b	29.59b	71.82b	3.41b	51.53c	65.68d	7.40a	38.48c	9.64b	14.14d	78.46b	135.47a	21.29c
T2[b]	6.70a	20.50a	35.36a	91.72a	4.03a	60.93a	74.92a	7.50a	46.10a	10.79a	13.99d	81.31a	127.53a	23.15c
T3[b]	6.33c	15.02d	25.92d	51.92c	3.12c	50.00c	66.40d	6.87b	37.94c	8.92c	16.40c	75.30c	127.03a	18.90c
T4[b]	6.36c	14.12d	24.35d	41.71c	1.80f	42.19f	60.02f	7.62a	34.44d	5.94f	17.83b	70.29f	112.75b	25.56b
T5[b]	6.37c	17.52b	30.22b	66.69b	2.22e	50.31c	68.72c	3.27d	44.80a	9.78b	17.96b	73.21d	102.17b	31.40a
T6[b]	6.44b	16.47c	28.41b	46.57c	3.63b	51.87c	66.65d	3.66d	42.55b	10.57a	17.27b	74.71c	70.50b	22.59c
T7[b]	6.25d	17.53b	30.25b	41.58c	4.00a	51.07c	68.72c	7.37a	39.35c	8.88c	14.77c	77.75b	56.50d	27.37b
T8[b]	6.17d	14.72d	25.40d	29.42d	2.78d	45.05e	64.45e	7.62a	38.89c	9.28c	15.38c	76.85b	81.52b	16.95f
T9	6.21d	18.22b	31.43b	34.04d	3.96a	46.33d	64.36e	6.97b	38.56c	8.50d	17.64b	74.35c	68.50c	21.29d
T10[b]	6.11e	15.94c	27.50c	51.56c	3.31c	47.23d	64.33e	5.56c	35.15d	7.10e	19.40a	69.70f	49.50d	11.29h
T11[b]	6.05e	4.72e	4.84e	35.88d	2.77d	53.86b	71.14b	4.75d	34.76d	7.60e	18.02b	71.99f	41.50e	13.08g
T12[b]	6.10e	2.80f	5.14e	28.44d	2.33e	37.52g	55.26g	3.27d	33.59d	8.32e	20.26a	68.89f	32.00e	9.38i
Causes of variation														
Ftrat	31.51**	92.10**	92.25*	16.42**	51.26**	64.86**	108.39**	53.03**	64.02**	60.57**	25.74**	40.88**	63.42**	125.29**
CV (%)	0.91	6.62	6.61	15.63	5.79	2.07	1.27	5.59	2.14	3.56	3.59	1.22	9.40	5.06

*$p \leq 0.01$.

**$p \leq 0.05$.

[a] pH, soil pH; OM, organic matter; P, available phosphorus; S, sulfur content; Ca, exchangeable calcium; Mg, exchangeable magnesium; K, exchangeable potassium; H + Al, potential acidity (hydrogen plus aluminum); SB, Sum of Bases (Ca, Mg, K, and Na); CEC, cation exchange capacity; SatB, base saturation; SOC, soil organic carbon; Beta, β-glucosidase activity; Aryl, arylsulfatase activity; RWC, relative water content; Temp, soil temperature; FCO_2, soil CO_2 flux.

[b] Boldface *P* values indicate significant treatment effects. (1) AP10H; (2) AP5H; (3) AP10; (4) AP5; (5) AH; (6) A; (7) P10H; (8) P5H; (9) P10; (10) P5; (11) H; (12) S—uncovered soil.

TABLE 4 | Results of principal component analysis of soil quality indicators for the first five PCs.

Main components	PC1	PC2	PC3	PC4	PC5
Eigen value	8.33[a]	2.64	2.38	1.06	0.68
Percent	49.02	15.56	14.05	6.05	4.02
Cumulative percent	49.02	64.58	78.63	84.88	88.90
Eigen vectors[b]					
pH	**-0.298**[c]	−0.141	−0.120	0.085	0.282
MO	−0.242	**0.350**[e]	0.028	0.310	0.273
P	−0.285	−0.066	−0.128	−0.083	−0.216
S	0.002	−0.275	**0.516**	0.035	0.232
Ca	−0.293	0.112	−0.258	−0.205	−0.079
Mg	**−0.302**	0.166	−0.086	−0.103	−0.366
K	−0.140	0.285	0.458	0.217	0.087
H + Al	0.260	0.218	−0.282	0.128	0.043
Sum_Bases	**−0.327**[de]	0.082	0.097	−0.115	−0.139
CEC	−0.293	0.216	−0.016	−0.084	−0.158
Base saturation	**−0.312**	−0.077	0.210	−0.137	−0.126
SOC	−0.242	**0.350**	0.028	0.310	0.273
Beta	−0.183	**−0.368**[d]	−0.190	0.225	0.022
Aril	−0.174	−0.175	−0.375	−0.067	0.514
RWC	−0.047	−0.263	−0.084	0.751	−0.422
TEMP	−0.168	−0.311	0.310	−0.131	−0.002
FCO$_2$	−0.255	−0.309	−0.068	0.017	0.142

[a] The values in bold correspond to the principal components (PCs) analyzed for the index.
[b] pH, soil pH; OM, organic matter; P, available phosphorus; S, sulfur content; Ca, exchangeable calcium; Mg, exchangeable magnesium; K, exchangeable potassium; H + Al, potential acidity (hydrogen plus aluminum); Sum Bases, sum of exchangeable bases (Ca, Mg, K and Na); CEC, cation exchange capacity; Sat Bases, base saturation; SOC, soil organic carbon; Beta, β-glucosidase activity; Aryl, arylsulfatase activity; RWC, relative water content; Temp, soil temperature; FCO$_2$, soil CO$_2$ flux.
[c] Component loadings underlined and in bold correspond to indicators included in the MDS (minimum data set).
[d] Component loads in bold are considered to be highly weighted.
[e] variables that fit into the analysis but were removed because they were the result of calculations originating from the other variables.

treatments (F = 71.87**), followed by pH (F = 21.36**) and soil organic carbon (SOC) (F = 10.59**). The lowest Beta scores were observed in treatments without plant cover or straw, such as T11 (0.24) and T12 (0.19), while the highest values were recorded in treatments T1 and T2 (0.89 and 0.86, respectively).

3.5 | Soil Health Assessment in a Peanut Cropping System Combining IQS and the 4QM

The soil health (SH) assessment tool, combining the CASH and 4QM approaches, was applied to the treatments under different management strategies (Figure 6). Thresholds for SOC (26.30 g kg^{-1} of soil) and ASEA (1.96) were equivalent to a score of 50, arbitrarily defined as the minimally acceptable values of SOC and ASEA from both an economic and soil functional perspective in these tropical soils (Chaer et al. 2023). These threshold values established the four quadrants in the ASEA vs. SOC scatter plot.

The distribution of the points in the 4Q graph is shown in Figure 7. As observed by Chaer et al. (2023), based on the ASEA vs. SOC scatter plot, it was possible to categorize the treatments into four quadrants. Quadrants 1 (high SOC/high ASEA) and 3 (low SOC/low ASEA) represented stable patterns of healthy and unhealthy soils, respectively. Quadrants 2 (high SOC/low ASEA) and 4 (low SOC/high ASEA) reflected transitional patterns—soils undergoing biological degradation (declining health) and soils in the process of regeneration, respectively.

In Q1 (high SOC/high ASEA), corresponding to a healthy soil condition, most treatments that included peanut cultivation combined with straw and herbicide were found. However, the treatment with peanut alone fell into Q2 (soils undergoing biological degradation), along with the treatment that included straw (10 t ha^{-1}) and herbicide. On the other hand, Q3 (low SOC/low ASEA), indicative of unhealthy soils, included the fallow soil, which was the most distant point, as well as the treatment

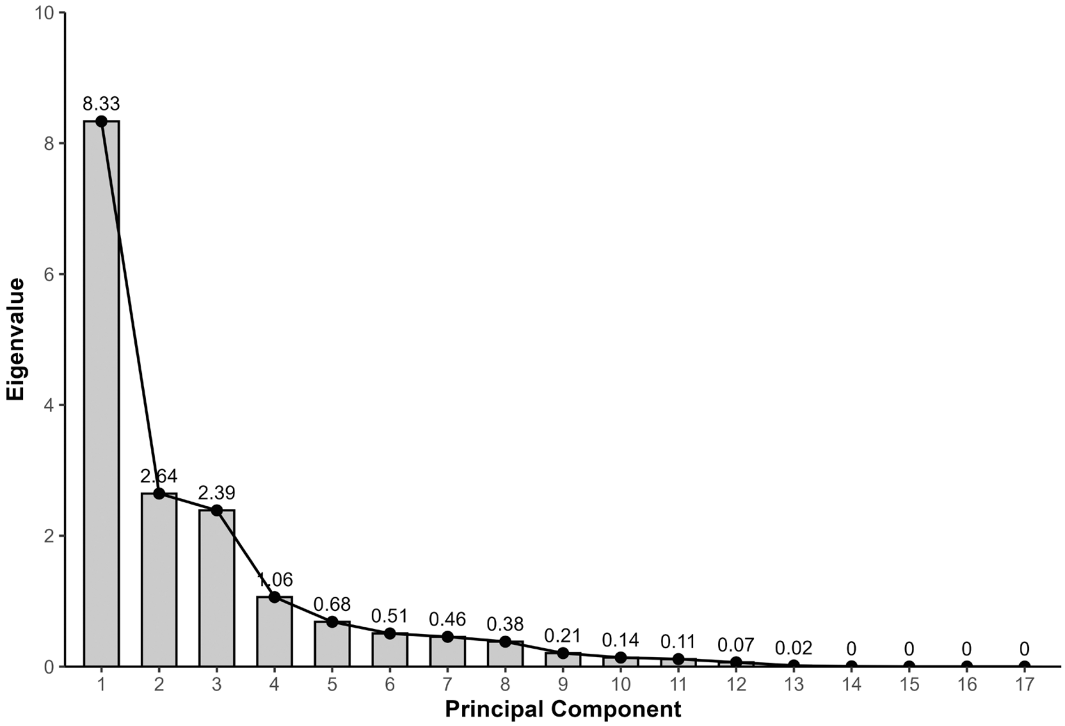

FIGURE 5 | Scree chart for the 17 PCs.

TABLE 5 | Correlation matrix for the highly weighted variables in the first four PCs.

	pH	Mg	S	SOC	Beta	Base saturation
pH						
Mg	0.618**					
S	−0.307	−0.305				
COS	0.531**	0.656**	−0.177			
Beta	0.654**	0.296	0.090	0.086		
Base saturation	0.654**	0.774**	0.278	0.491*	0.431**	

*$p \leq 0.05$.
**$p \leq 0.01$.

with only herbicide and straw (5 t ha^{-1}). In quadrant Q4 (low SOC/high ASEA), only the P10 treatment was found.

The distribution properties of the four groups representing the management strategies in this study are presented in Figure 8A. The values in quadrants Q1 and Q4 were higher than those in Q2 and Q3 (Figure 7A). The mean ASEA values for Q1, Q2, Q3, and Q4 were 2.47, 1.41, 1.53, and 2.31, respectively. The boxplot distributions of SOC (Soil Organic Carbon) values for soil samples in quadrants Q1 and Q2 were similar. Likewise, a comparable SOC distribution was observed for samples in Q3 and Q4 (Figure 8B).

On average, SOC values in Q1 and Q2 ranged from 29.4 to 30.4 g kg^{-1}, whereas in Q3 and Q4, they ranged from 19.8 to 21.1 g kg^{-1} (Figure 7B). The mean SOC content in soil samples from quadrants Q1 and Q2 was 29.96 g kg^{-1}, significantly higher than the mean observed in Q3 and Q4, which was 20.4 g kg^{-1}.

4 | Discussion

4.1 | CO_2 Emission as an Indicator of Biological Activity

The treatments that combined peanut cultivation with straw cover (T1, T2, T3, and T4) exhibited the highest CO_2 fluxes, reflecting greater microbial respiratory activity, likely enhanced by root respiration (Zhang et al. 2022), which was absent in treatments T11 and T12 which had the lowest CO_2 emissions. Curtin et al. (1997) and Moitinho et al. (2018) attribute increased FCO_2 to the availability of organic substrate and the microclimatic protection provided by the straw cover.

Soil moisture and temperature are fundamental drivers of biological activity (Lal 2009; Ball 2013), and their influence can be observed through FCO_2 emissions (Wang et al. 2015), especially

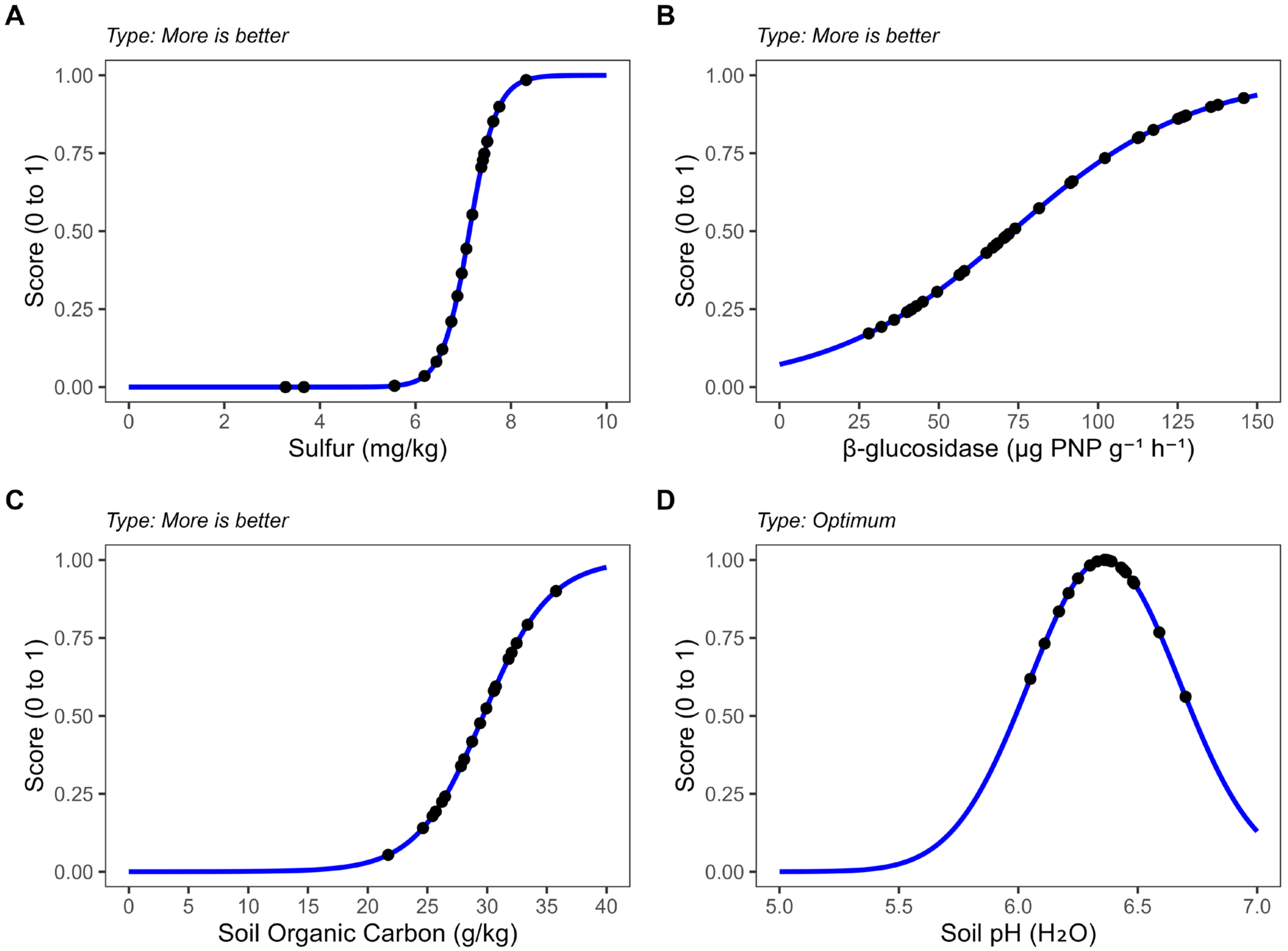

FIGURE 6 | Nonlinear scoring functions were used to transform the MDS soil properties. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 6 | Scoring functions (FS), threshold values and weights for MDS indicators.

Indicator	SF	L[a]	B[a]	U[a]	B1[a]	O[a]	B2[a]	Slope at baseline	Weight
S	More is better	3.28	7.13	7.75				0.87	0.521
COS	More is better	24.63	29.67	35.77				0.09	0.165
Beta	More is better	35.0	73.0	136.02				0.0087	0.165
pH	Optimum				6.21	6.36	6.44	4.62	0.149

[a] L lower threshold, at which or below score is 0; B baseline, at which score is 0.5; U upper threshold, at which or above score is 1; O optimum level, at which score is 1 with a bell-shaped relationship; B1 lower baseline, at which score is 0.5 with a bell-shaped relationship; B2 upper baseline, at which score is 0.5 with a bell-shaped relationship.

under straw addition. These interactions between FCO_2 and environmental variables are adequate to predict the effects of management practices.

The presence of peanut plants may also have contributed through the release of root exudates rich in easily assimilable organic compounds, stimulating rhizospheric microbial activity and favoring organic matter mineralization, as discussed by Jiang et al. (2025). Furthermore, the straw mulch aids in moisture retention and soil temperature modulation, creating optimal conditions for microbial respiration and enzymatic activity, as shown by Moitinho et al. (2018).

In the fallow area, chemical analyses indicated improvement, as the initial pH of 5.6 (Table 3)—characteristic of slightly acidic soils—was outside the optimal range (6–7) for nutrient uptake. pH values below 6 tend to promote the solubilization of toxic metals, which compete with essential nutrients like phosphorus for absorption sites (Brady and Weil 2016; Barrow and Hartemink 2023). Throughout the experiment, treatments

TABLE 7 | Effect of different managements on soil quality indicator scores and overall IQS.

Treats.[a]	pH	SOC	Beta	S	IQS
T1	0.89b	0.51b	0.89a	0.69a	0.80a
T2	0.56c	0.90a	0.86a	0.78a	0.70a
T3	0.99a	0.78a	0.86a	0.32a	0.75b
T4	1.00a	0.54b	0.80b	0.85a	0.80a
T5	0.99a	0.57b	0.73b	0.00b	0.73b
T6	0.93b	0.73a	0.47d	0.00b	0.68c
T7	0.96a	0.43c	0.36e	0.59a	0.72b
T8	0.98a	0.36c	0.57c	0.85a	0.79a
T9	0.88b	0.58b	0.46d	0.43a	0.7b
T10	0.83b	0.19c	0.30e	0.004b	0.52e
T11	0.89b	0.18c	0.24f	0.749b	0.58d
T12	0.61c	0.33c	0.19f	0.210b	0.43f
Causes of variation					
Ftrat	21.36**	10.59**	71.87**	8.79**	31.58**
CV (%)	6.21	25.35	9.35	33.58	4.85

**$p \leq 0.05$.

[a] (1) AP10H; (2) AP5H; (3) AP10; (4) AP5; (5) AH; (6) A; (7) P10H; (8) P5H; (9) P10; (10) P5; (11) H; (12) S—uncovered soil.

adjusted pH into a more suitable range, varying from 6.05 (T11) to 6.70 (T2). pH and β-glucosidase activity were key factors distinguishing management practices, as shown in the IQS results (Tables 4 and 7, Figure 9).

Treatments with the best performance (T1–T4, T8) had near-neutral pH values, supporting enzymatic stability and nutrient bioavailability (Table 4) (Wang et al. 2015). The interaction between pH and soil moisture was decisive in modulating microbial activity and, consequently, CO_2 emissions. The treatments with the highest FCO_2 values (T1, T2, and T4) also exhibited pH values close to neutrality (6.48–6.70), which are considered optimal for enzymatic function and nutrient solubilization, as discussed by Nannipieri et al. (2017). These findings underscore the relevance of pH as an integrative variable for soil health, directly influencing microbiota, nutrient availability, and organic matter decomposition.

Regarding soil moisture (Sm), treatments with straw, particularly T3 and T4, resulted in the highest water content (26.6% and 27.0%, respectively), which favored biological activity, as evidenced by increased respiration. Moisture also improves the availability of nutrients such as K, Ca, and Mg, as reported by Júnior et al. (2015) under varying water regimes. This effect was less evident in treatments T5, T6, and T12, which had average soil moisture levels below 23%, potentially limiting microbial activity. The correlation between Sm and FCO_2 supports the findings of Wang et al. (2015), who demonstrated that low water

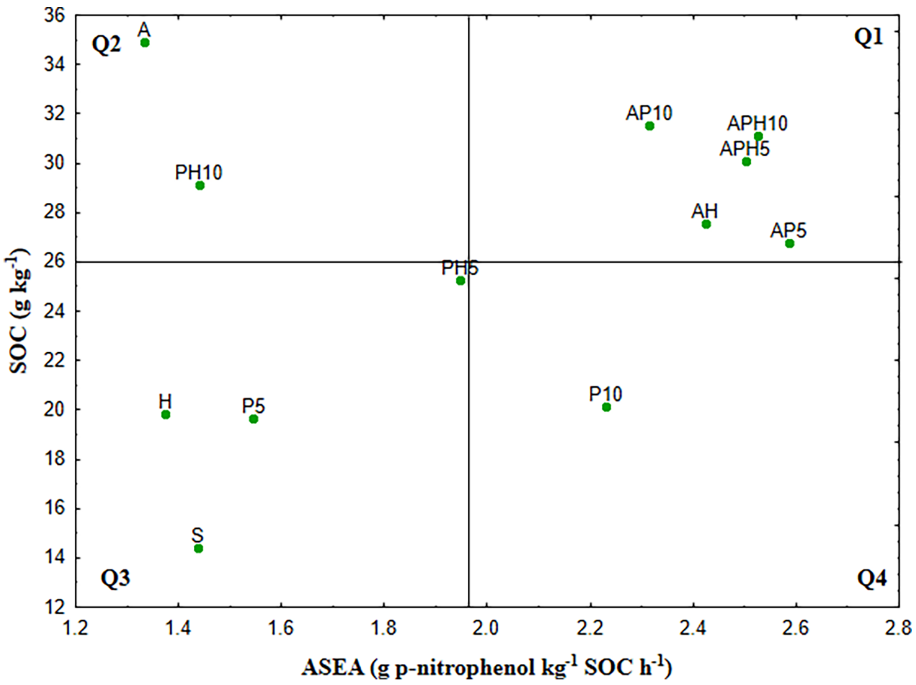

FIGURE 7 | Scatterplot between soil organic carbon (SOC) and average specific enzyme activity (ASEA) of soil samples. AP10H = Peanuts (A) + equivalent to 10 tons of sugarcane straw (P) + herbicide application (H); AP5H = Peanuts + equivalent to 5 tons of sugarcane straw + herbicide application; AP10 = Peanuts + equivalent to 10 tons of sugarcane straw + no herbicide application; AP5 = Peanuts + equivalent to 5 tons of sugarcane straw + no herbicide application; AH = Peanuts + no sugarcane straw + herbicide application; A = Peanuts + no sugarcane straw + no herbicide application; P10H = equivalent to 10 tons of sugarcane straw + herbicide application; P5H = equivalent to 5 tons of sugarcane straw + herbicide application; P10 = equivalent to 10 tons of sugarcane straw + no herbicide application; P5 = equivalent to 5 tons of sugarcane straw + no herbicide application (P5); H = no sugarcane straw + herbicide application; S = Bare soil. [Colour figure can be viewed at wileyonlinelibrary.com]

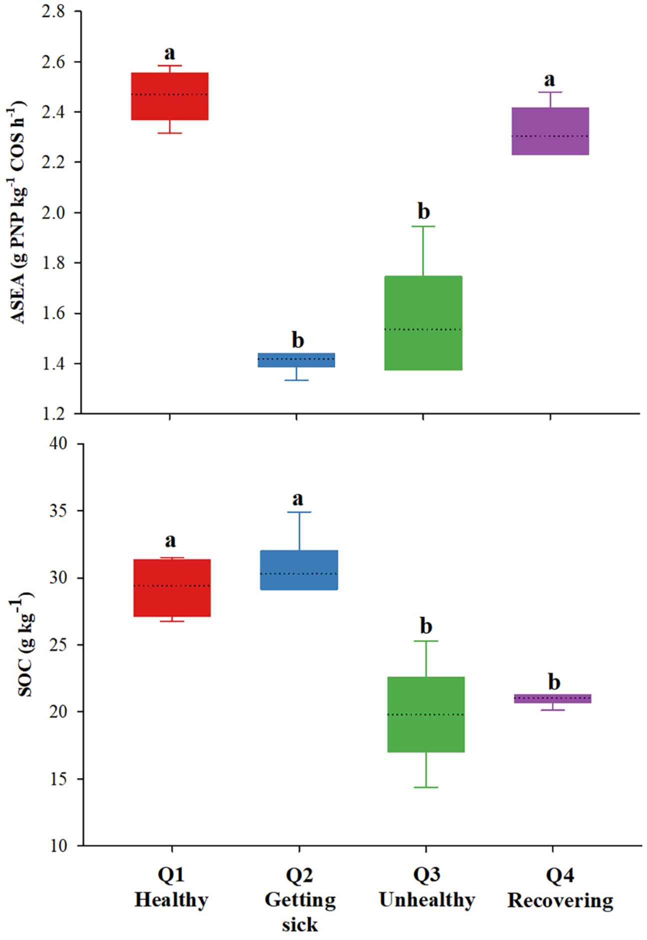

FIGURE 8 | Boxplot with soil organic carbon (SOC) (A) and average specific enzyme activity (ASEA) (B) data from peanut samples. Soil quality classifications are based on data matching with the four-quadrant model. Boxplots labeled with similar letters do not differ according to the Kruskal-Wallis test ($p < 0.05$). [Colour figure can be viewed at wileyonlinelibrary.com]

availability is one of the main limiting factors for microbial respiration in tropical soils.

4.2 | Effects of Straw and Organic Matter on Soil Quality

The data show that the addition of sugarcane straw, particularly in treatments T1, T2, and T3, resulted in significant increases in soil organic matter (OM) and soil organic carbon (SOC), as well as higher cation exchange capacity (CEC). These effects indicate an improvement in both the chemical quality and structural integrity of the soil. Organic matter acts as a buffering agent, promoting the retention of essential nutrients such as Ca^{2+}, Mg^{2+}, and K^{+} (Table 3), while also enhancing the formation of stable aggregates, which are fundamental for soil porosity and aeration (Brady and Weil 2016; Bashir et al. 2021).

Treatment T2 (AP5H), for instance, stood out not only for the highest values of SOC (35.36 g kg^{-1}) and CEC (74.92 mmolc dm^{-3}), but also for achieving a high soil quality index score (SQI = 0.75), evidencing the effectiveness of combining crop presence, cover material, and chemical management. This performance suggests that even moderate amounts of straw (5 t ha^{-1}) are sufficient to promote significant benefits when integrated with appropriate management practices.

The high values of OM and SOC observed in treatments with 5 t ha^{-1} of straw, compared to those with 10 t ha^{-1}, may be associated with the smaller amount of residue applied, which favors faster decomposition and more immediate nutrient release. This dynamic occurs because lower volumes of straw tend to decompose more rapidly, especially under favorable temperature and moisture conditions, due to a lower accumulation of lignin and cellulose and a higher surface-to-volume ratio exposed to microbial activity (Zhang et al. 2019).

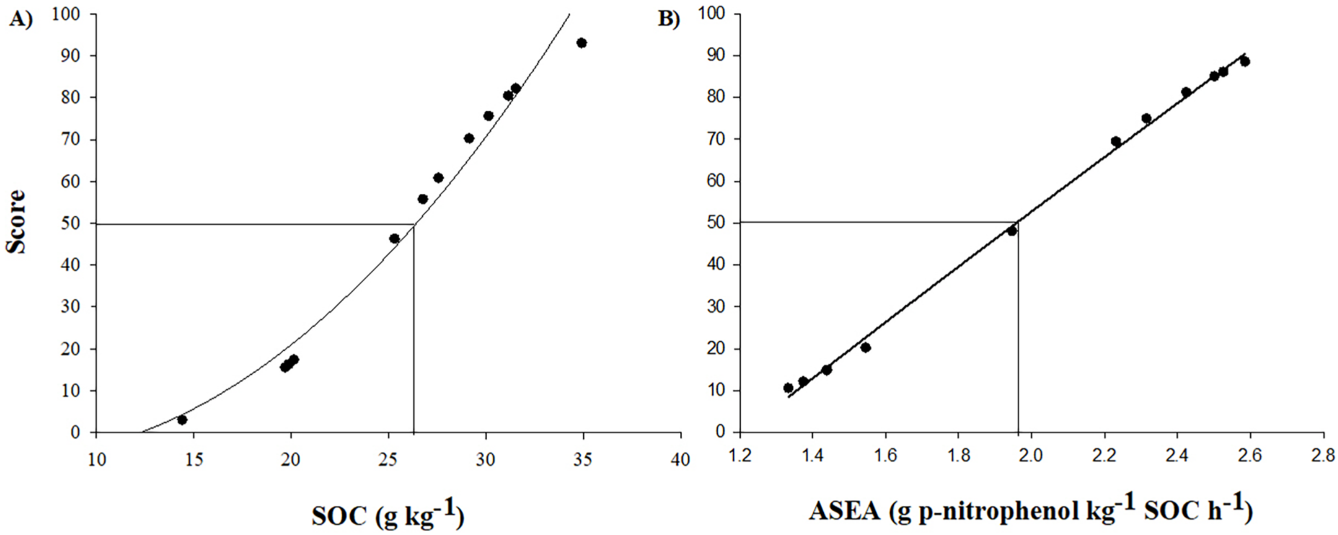

FIGURE 9 | Cumulative normal distribution (CND) for soil organic carbon (COS) score (A) and mean specific enzyme activity (ASEA) (B) in soils with straw, herbicide, and peanut plants. [Colour figure can be viewed at wileyonlinelibrary.com]

However, this does not imply that applying 10 t ha^{-1} is less efficient; on the contrary, this treatment tends to offer a more gradual and sustained release of organic matter and nutrients over time, potentially providing long-term benefits to soil structure and health.

Conversely, treatments without cover (T11 and T12) resulted in extremely low SOC values (<6 g kg^{-1}), which were reflected in low CEC and base saturation values, indicating reduced functionality and nutritional depletion of the soil. Similar results were reported by Zhang et al. (2019), who observed that uncovered soils exhibit significant reductions in chemical and microbiological composition. These findings reinforce the importance of organic matter not only as a carbon source but also as a structural pillar of soil fertility and health, as highlighted by Lal (2020), Ge et al. (2021), and Partovi et al. (2021).

4.3 | Correlation Between Enzymatic Indicators

Studies using bioindicators in the Cerrado region have been conducted for many years, and among them, two enzymes (arylsulfatase and β-glucosidase) have consistently demonstrated greater sensitivity in detecting soil changes due to different management systems. As such, they have been recommended for soil bioanalysis (Mendes, Sousa, Reis Junior, et al. 2019; Mendes et al. 2021). Several studies have been carried out in various crops, including cotton (de Castro Lopes et al. 2021), pastures (de Camargo et al. 2024), vegetables (Carneiro et al. 2024), coffee (Bastos et al. 2023), and grapes (Pawlowski et al. 2024). All point to the fact that more sustainable agricultural practices provide better conditions for increased enzymatic activity. However, no results have yet been reported for peanuts.

The activity of β-glucosidase (Beta) and arylsulfatase (Aril) enzymes proved to be among the most sensitive indicators of the adopted management practices. β-glucosidase, in particular, showed expressive variation between treatments, with treatments T1, T2, and T3 reaching the highest values (≥ 0.86). This enzyme is directly involved in cellulose degradation and sugar release, playing a central role in the carbon cycle (Deng and Popova 2011; Merino et al. 2016). Therefore, its increase is directly associated with greater availability of plant residues and stimulation of microbial activity, showing that peanut cultivation combined with straw is an effective strategy for maintaining good soil health.

On the other hand, arylsulfatase was less responsive to treatments involving plants and straw, reaching high levels in T5 and in treatments with overall lower performance, such as T10 and T12. This may indicate a response more related to stress conditions or the accumulation of undecomposed organic substrates, as this enzyme plays a role in the release of sulfur from organic compounds (Tabatabai 1994), a process often activated under nutrient-limited conditions (Klose et al. 2011).

Another relevant factor is the potential involvement of arylsulfatase in the degradation of organosulfur compounds present in the herbicide formulation used in this study. Arylsulfatase acts on the release of sulfur from sulfate ester bonds of organic compounds, as part of the natural sulfur cycle in soils (Tabatabai 1994; Klose et al. 2011). The herbicide applied in this experiment contains sodium alkyl naphthalene sulfonate, an aromatic sulfonated structure potentially susceptible to enzymatic breakdown by sulfatases. Thus, the increased activity of arylsulfatase observed in treatments such as T5 and T11 may suggest a potential enzymatic response to the herbicide, using it as a substrate.

The contrast between the high β-glucosidase activity in treatments with straw and peanuts and the low values observed in T11 and T12 highlights the importance of high-quality organic matter and the presence of legume roots, such as those of peanuts, in stimulating soil mineralization processes. Moreover, statistical analysis reinforces this trend, with β-glucosidase showing the highest F value among the indicators of the soil quality index ($F = 71.87^{**}$), confirming its high sensitivity to management. These findings support the proposition that soil enzymes are reliable bioindicators of biological functionality and should be integrated into soil health monitoring programs (Balota et al. 2014; Mendes, Sousa, Reis Junior, et al. 2019; Mendes, Souza, Souza, et al. 2019; Naves et al. 2020; Anghinoni and Vezzani 2021; Poggere et al. 2022).

4.4 | Integration of Soil Quality Indices

Integrated assessment of soil quality using the Soil Quality Index (SQI) and the Four Quadrant Model (4QM) revealed marked differences between management systems. Treatments T1, T2, T4, and T8 exhibited the highest SQI values (≥ 0.75), indicating environments with greater balance among chemical, physical, and biological dimensions of the soil. Treatment T4 (peanut +5 t ha^{-1} of straw without herbicide), in particular, stood out with the highest index value (0.80), supported by elevated scores for pH (1.00) and enzymatic activity ($S = 0.85$), demonstrating that the combination of conservation practices—even without herbicide application—can promote excellent soil quality.

These same treatments were also located in quadrant Q1 of the 4QM model, representing soils with high soil organic carbon (SOC) content and high specific enzymatic activity (ASEA) traits associated with healthy, functional, and biologically active soils. In contrast, treatments T10, T11, and T12, which had the lowest SQI values (≤ 0.58), were situated in quadrants Q3 and Q2, corresponding to degraded soils or those undergoing functional imbalance. Notably, the uncovered soil (T12), in addition to registering the lowest SQI value (0.43), also showed the lowest SOC (5.14 g kg^{-1}) and β-glucosidase activity (0.19), confirming its state of advanced degradation.

The multivariate analysis, which selected pH, SOC, β-glucosidase (Beta), and sulfur (S) as the minimum data set (MDS), demonstrated that these attributes effectively capture the impacts of management practices on soil health. The highest weight attributed to pH (44.6%) in the SQI calculation highlights its central role as a stabilizing parameter in edaphic processes. Overall, the results indicate that practices integrating straw, leguminous cover crops, and judicious chemical management enhance biologically active soils with greater nutrient cycling capacity, structural stability, and resilience to disturbances.

Thus, the combined use of biochemical indicators and composite indices such as SQI and 4QM represents a robust strategy for assessing the sustainability of agricultural systems. These findings reinforce that sustainable management, based on promoting organic matter and reducing degrading practices, should be prioritized to ensure soil functionality and agricultural productivity in both the short and long term.

5 | Conclusion

It was concluded that the addition of sugarcane straw promoted higher soil CO_2 emissions, particularly in treatments combining peanuts and straw, while herbicide application did not alter soil dynamics when associated with straw and plants. The integration of straw with peanut cultivation improved soil health indicators, as evidenced by increases in pH, soil organic carbon (SOC), moisture, enzymatic activity (notably β-glucosidase), and integrated indices. Even moderate amounts of straw proved to be an efficient practice for enhancing soil health. Furthermore, the Soil Quality Index (SQI) combined with the Four Quadrant Model (4QM) demonstrated that systems with straw and peanuts maintained healthier soils, whereas fallow and bare soil treatments were the most degraded, showing organic matter depletion, low enzymatic activity, and poor edaphic health indicators.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Adjusted means ± standard error of the adjusted mean of soil CO_2 emission (FCO_2), Soil temperature (St) and Soil moisture (Sm). **Table S2:** Adjusted means ± standard error of the adjusted mean of soil CO_2 emission (FCO_2), Soil temperature (St) and Soil moisture (Sm). **Table S3:** Adjusted means ± standard error of the adjusted mean of soil moisture (Sm) per assessment day.