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Short communication

The use of different coverages crop manegement in sugarcane field reform on humic substances contents and chemical attributes of a sandy soil

Lucas Augusto de Assis Moraes[1], Gabriela da Silva Machineski[1], Thadeu Rodrigues de Melo[1], Allan Remor Lopes[1], Francieli de Fátima Missio[1], Leila Bernart Vilela[1], Paula Pinheiro Sanches de Almeida[1], Luiz Henrique Campos de Almeida[1,*] and João Tavares Filho[1]

[1]Universidade Estadual de Londrina, Departamento de Agronomia, Centro de Ciências Agrárias, Rodovia Celso Garcia Cid, s/n, Campus Universitário, Londrina, PR, Brazil, CEP 86057-970.
Corresponding author, E-mail: luizalmeida@uel.br

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Abstract

Sugarcane cultivation, a major activity in the Brazilian sugar-energy sector, is commonly established on low-fertility sandy soils. Improving soil organic carbon stocks and humic substances is essential to enhance soil quality and sustainability. This study evaluated the effects of different cover crop managements during sugarcane field reform on organic carbon, humic substances, and chemical attributes of a sandy Ultisol. The experiment was conducted in a commercial area using a completely randomized design with four treatments—conventional planting, soybean cover crop, Crotalaria spectabilis cover crop, and native forest as reference—and three replicates. Soil samples were collected 12 months after sugarcane planting (0–10 cm) and analyzed for organic carbon, fulvic and humic acids, and chemical attributes. Data were subjected to analysis of variance (ANOVA), Tukey's test ($p \leq 0.05$), and Pearson correlation analysis. The use of Crotalaria spectabilis significantly increased organic carbon and humic substance contents, reaching levels similar to the native forest, while soybean cover showed no improvement compared to conventional management. Increases in organic carbon and humic substances were positively correlated with potassium availability and negatively correlated with soil pH and phosphorus availability. The results demonstrate that Crotalaria spectabilis is an effective cover crop during sugarcane field reform, promoting improvements in soil organic fractions and chemical attributes, contributing to more sustainable sugarcane production in sandy soils.

Keywords: Energy crop, bioenergy systems, physicochemical properties of soils, crop yields, natural fertility, incorporation of plant residues, soil fertility, soil health.

Introduction

Sugarcane (*Saccharum spp*.) stands out as one of the most strategic crops for tropical agriculture, underpinning the Brazilian sugar–energy sector, accounting for nearly 80% of global sugar production, and playing an increasingly important role in sustainable bioenergy systems (Almeida et al., 2025). However, the Brazilian sugar–energy sector is developed across soils with contrasting physicochemical properties, many of which are far from ideal for achieving high crop yields, particularly sandy soils. Sandy soils occur worldwide, covering approximately 900 million hectares (Hartemink & Huting, 2008), and occupy nearly 50 million hectares in Brazil (Yost & Hartemink, 2019). These soils are predominantly composed of sand (≥70%), exhibit quartz-dominated mineralogy, and contain minor amounts of 1:1 clay minerals, mainly kaolinite, as well as Fe and Al oxyhydroxides such as goethite, hematite, and gibbsite (Zinn, Lal, Bigham, & Resck, 2007; Sposito, 2008). As a result, sandy soils generally present low nutrient and water retention capacity, reduced organic matter content, and low natural fertility, characterizing them as soils with low chemical reactivity (Murphy, 2015; Yost & Hartemink, 2019).

For the sustainable use of sandy soils in sugarcane production systems, management practices that enhance soil organic matter content and fertility are essential. Among these practices, the incorporation of plant residues into the soil has been widely recognized as an effective strategy to increase organic matter stocks and promote the accumulation of humic substances (Hayes & Swift, 2020). Humic substances originate from the decomposition and transformation of plant, animal, and microbial residues, including compounds such as lignin, tannins, cellulose, and cutins. Based on their solubility in water under acidic or alkaline conditions, humic substances are operationally classified into humic acids (HA), fulvic acids (FA), and humin (Stevenson, 1994; Swift, 1996).

Among these fractions, humin is considered the most recalcitrant and slowly decomposable component of soil organic matter. In contrast, humic and fulvic acids are more chemically reactive and dynamic, which explains the greater attention given to these fractions in studies addressing short- to medium-term changes in soil fertility and soil health (Fontana, Pereira, Anjos, & Benites, 2010; Canellas et al., 2010). Due to their functional groups and interaction with soil minerals, HA and FA play important roles in nutrient retention, cation exchange capacity, aggregation, and plant–soil interactions (Hayes & Swift, 2020; Ampong, Thilakarathna, & Gorim, 2022).

Because agricultural management directly influences residue inputs and organic matter turnover, it may substantially affect both the quantity and quality of humic substances in soil. In this context, the use of cover crops (green manures) represents a promising strategy for improving the chemical reactivity and fertility of sandy soils. Cover crops promote carbon inputs, stimulate humification processes, and enhance soil quality through nutrient cycling, extensive root exploration, rapid biomass production, and residue deposition (Wutke, Calegari, & Wildner, 2014; Nascimento, Souza, Silva, & Laurindo, 2023).

Despite these recognized benefits, the adoption of cover crops in the sugar–energy sector remains limited. Sugarcane field renovation is still predominantly conducted under conventional management, characterized by intensive soil tillage, reduced soil cover, and accelerated oxidation of soil organic matter (Bolonhezi & Gonçalves, 2015; Moitinho, Padovan, Panosso, & La Scala Jr, 2013). These effects are exacerbated by the high temperatures typical of sugarcane-producing regions, leading to significant reductions in soil organic carbon stocks during the renewal of sugarcane fields (Canellas et al., 2010; Zani et al., 2018). Furthermore, sugarcane is a semi-perennial crop, with cultivation cycles lasting up to five years after planting. Consequently, the use of cover crops is generally restricted to the reform period, which has led to the perception that their effects on soil attributes are limited (Bolonhezi &

Gonçalves, 2015).

The scientific literature addressing the use of cover crops during sugarcane field reform is still limited and presents contrasting results. Fernandes, Cora and Marcelo (2012) and Silva and Fernandes (2014) reported that reform systems involving cover crops such as soybean, millet, or crotalaria improved soil aggregation but had little influence on soil chemical attributes. Similarly, Furlani and Voltarelli (2015) suggested that changes in soil attributes during sugarcane reform may be more strongly associated with agricultural operations than with the specific crops used during the reform period.

In contrast, Moraes, Melo and Tavares Filho (2023) demonstrated that, in sandy soils, conventional reform systems incorporating Crotalaria as a cover crop resulted in higher total, macro-, and microporosity, greater aggregate stability, improvements in soil chemical attributes (organic carbon, Ca^{2+}, K^{+}, and cation exchange capacity), and increased stalk productivity compared with conventional management and soybean-based reform systems. Additionally, studies by Mamedov et al. (2016) and Nascimento et al. (2023) showed that improvements in soil fertility under sugarcane cultivation in sandy soils are positively correlated with increases in the organic fractions of soil organic matter.

Based on the hypothesis that the use of cover crops during sugarcane field reform in sandy soils positively contributes to the accumulation of humic substances—particularly fulvic and humic acids—and to the improvement of soil fertility, the objective of this study was to evaluate the effects of different reform management systems (conventional management, soybean, and Crotalaria spectabilis) on humic substance fractions (fulvic and humic acids) and on the chemical fertility attributes of a sandy soil.

Materials and Methods

Study site and soil characterization

The study was conducted in a commercial sugarcane production area supplying the ethanol industry in Brazil (21°13′40″ S, 50°52′06″ W). The soil is classified as a sandy Ultisol, with a particle-size distribution of 83.69% sand, 8.33% silt, and 7.98% clay.

Historically, the area was occupied by pasture from 1970 to 2000 and has been cultivated with sugarcane since 2000. Between 2000 and 2010, sugarcane harvesting was performed under a burned cane system. Since 2011, harvesting has been conducted under a green (unburned) cane system, with planting at 1.50 m spacing between rows.

After five harvest cycles, the sugarcane field underwent reform under a conventional tillage system. During soil preparation, corrective materials and industrial by-products were applied, including dolomitic limestone (2.3 t ha^{-1}), agricultural gypsum (1.5 t ha^{-1}), vinasse (1.5 m^3 ha^{-1}), and filter cake (3.5 m^3 ha^{-1}).

Experimental design and management systems

During the sugarcane field reform period, the experimental area was divided into three large plots of approximately 10 ha each. Within this area, three management systems involving cover crops were established:

(i) **Conventional sugarcane planting (C):** conventional planting under bare soil conditions, without the use of cover crops;

(ii) **Sugarcane planting with soybean cover crop (Soy):** soybean (*Glycine max* L. Merrill) was sown under a no-tillage system, cultivated for five months, and

subsequently replaced by sugarcane planting;

(iii) **Sugarcane planting with *Crotalaria spectabilis* cover crop (Crot):** *Crotalaria spectabilis* was sown, with seed incorporation performed using a leveling harrow, followed by sugarcane planting after five months of cover crop growth.

A native forest area (F) located within the same property was included as a reference system. The study sites and management systems are illustrated in Figure 1.



Figure 1. Study sites during the sugarcane field reform period in sandy soils: (A) native forest; (B) sugarcane planting with *Crotalaria spectabilis*; (C) conventional soil preparation with soybean; (D) conventional sugarcane planting.

The experiment followed a completely randomized design with four treatments (C, Soy, Crot, and F) and three replicates per treatment. Replicates consisted of randomly selected soil sampling points within each management system.

Soil sampling and sample preparation

Soil sampling was carried out 12 months after sugarcane planting. Samples were collected from the 0–10 cm soil layer, which corresponds to the surface horizon with higher concentrations of plant residues and microbial activity and is directly associated with changes in humic substances and soil chemical properties.

For each treatment, three composite samples were collected, each composed of subsamples taken at randomly selected points. Soil samples were air-dried in a forced-air circulation oven at 40 °C and sieved through a 2-mm mesh to obtain the fine earth fraction used for chemical and organic matter analyses.

Determination of organic carbon and humic substances

Soil organic carbon (OC) contents were determined using the Walkley–Black wet oxidation method, as described by Fontana et al. (2010). Chemical fractionation of humic substances was performed based on their differential solubility in alkaline and acidic media, following the procedure proposed by the International Humic

Substances Society and adapted by Benites, Madari and Machado (2003).

Fulvic acid (FA) and humic acid (HA) fractions were quantified after extraction and separation. Based on the measured OC, FA, and HA contents, the HA:FA ratio was calculated and used as an indicator of soil organic matter humification, as proposed by Stevenson (1994).

Soil chemical analyses

Soil chemical attributes were determined according to the methodology described by Teixeira, Donagemma, Fontana and Teixeira (2017). Available phosphorus (P) and potassium (K) were extracted using the Mehlich-1 solution. Exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}) were extracted using a 0.1 mol L^{-1} KCl solution. Soil pH was measured in a 0.01 mol L^{-1} $CaCl_2$ suspension.

Statistical analysis

Statistical analyses were performed using a completely randomized design. Initially, data were subjected to tests of homoscedasticity and normality using Bartlett's test and the Shapiro–Wilk test, respectively. Once these assumptions were satisfied, data were analyzed by analysis of variance (ANOVA) using the F test.

The statistical model adopted was:

$$Y_{ij} = \mu + T_i + \varepsilon_{ij}$$

where Y_{ij}represents the observed value of the variable under evaluation for the i-th treatment in the j-th replicate;
$\mu$is the overall mean;
$T_i$is the fixed effect of the i-th treatment ($i = 1,2,3,4$); and
$\varepsilon_{ij}$is the random error associated with the observation, assumed to be independently and normally distributed with mean zero and constant variance $\varepsilon_{ij} \sim N(0, \sigma^2)$.

When significant differences were detected by the F test, treatment means were compared using Tukey's test at a 5% probability level ($p \leq 0.05$).

Subsequently, Pearson's linear correlation analysis ($p \leq 0.05$) was performed to evaluate the relationships between humic substances (FA and HA) and soil chemical attributes. The Pearson correlation coefficient (r) was calculated as:

$$r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}}$$

where $X_i$and $Y_i$correspond to the individual observations of the analyzed variables, and $\bar{X}$and $\bar{Y}$represent their respective means.

All statistical analyses were performed using R software (R Core Team, 2017), employing the Agricolae (Mendiburu & Yaseen, 2020) and ISwR packages.

Results and Discussion

Soil organic fractions and humic substances

During the sugarcane field reform period, the use of Crotalaria spectabilis as a cover crop (Crot) promoted the greatest increases in soil organic fractions, reaching values statistically similar to those observed under the native forest reference (F) (Table 1). Specifically, OC, HA, and FA contents under Crot were higher than those

found under conventional reform without cover crop (C) and under soybean cover (Soy). In contrast, soybean used as a cover crop did not increase OC, HA, or FA relative to the conventional reform system, indicating limited short-term contribution of Soy to the build-up of organic fractions in this sandy Ultisol (Table 1).

Table 1. Organic fractions—organic carbon (OC), humic acids (HA), fulvic acids (FA), and HA:FA ratio—at 0–10 cm in a sandy Ultisol during sugarcane field reform under different cover-crop managements: conventional exposed soil (C), sugarcane + soybean (Soy), sugarcane + Crotalaria spectabilis (Crot), and native forest (F).

Organic Fractions ($g.dm^3$)	F	C	Soy	Crot
OC	8.73A[1]	3.83B	3.77B	8.56A
HA	1.35A	0.48B	0.68B	1.52A
FA	1.01AB	0.38C	0.62BC	1.10A
HA:FA	1.30A	1.45A	1.15A	1,38A

[1]Means followed by different letters differ by Tukey's test (p-value≤0.50).

These results reinforce the relevance of residue inputs for increasing organic matter stocks in sandy soils, where quartz-dominated mineralogy and low clay content restrict physicochemical protection and stabilization of organic compounds, making carbon accumulation particularly dependent on continuous biomass inputs (Yost & Hartemink, 2019; Murphy, 2015). In this context, increases in HA and FA are agronomically meaningful because these fractions are more reactive than humin and are frequently linked to short- to medium-term improvements in nutrient retention, aggregation, and soil functionality (Stevenson, 1994; Swift, 1996; Hayes & Swift, 2020).

The higher OC, HA, and FA under Crot are consistent with the high biomass production typically associated with leguminous cover crops and their capacity to enhance residue quality via biological N inputs, potentially reducing C:N ratios and favoring faster decomposition and transformation pathways (Wutke et al., 2014). In addition, reform under Crot likely increased surface residue persistence relative to conventional exposed-soil planting, contributing to more favorable conditions for biological activity and organic matter accumulation near the soil surface (0–10 cm), the layer most responsive to management changes. Similar improvements in soil quality following changes in sugarcane reformation systems using Crot have also been reported for tropical soils, where management practices influenced biological activity and crop performance (Oliveira et al., 2024).

In contrast, the lower organic fraction contents under C and Soy likely reflect conditions that favor oxidation and reduced net C input. Conventional operations disturb the soil and accelerate organic matter mineralization, whereas soybean residues may contribute comparatively less persistent surface biomass during the reform window, resulting in reduced accumulation of humic fractions. Another plausible mechanism is a priming effect, in which short-term inputs of labile carbon stimulate microbial activity and accelerate the decomposition of existing organic matter pools, particularly in soils originally low in carbon (Kuzyakov, 2010; Mehnaz, Corneo, Keitel, & Dijkstra, 2019). This explanation is compatible with the observation that systems receiving by-products and still showing low OC may experience rapid microbial turnover with limited stabilization under sandy-soil conditions (Yost & Hartemink, 2019).

Although OC, HA, and FA differed significantly among treatments, the HA:FA ratio was not affected by the management systems (Table 1). In all treatments, HA

predominated over FA, indicating a humic character of soil organic matter. This pattern is often observed in sandy soils due to selective losses of more soluble organic fractions (such as FA) via leaching, making soil texture and low colloid content dominant controls on this index relative to short-term management effects (Stevenson, 1994; Yost & Hartemink, 2019). Additionally, the functionality of humic substances depends not only on their concentration but also on molecular composition and conformational changes mediated by microbial communities and environmental conditions, which may shift reactivity without necessarily changing the HA:FA ratio over short periods (Lumactude, Gorim, & Thilakarathna, 2022; Yang, Tang, & Antonietti, 2021).

Soil chemical attributes

Soil chemical attributes (pH, Ca^{2+}, K^{+}, and available P) were influenced by cover-crop management during sugarcane reform, whereas Mg^{2+} did not differ among treatments (Table 2). Soil pH under C and Soy was comparable to that under the forest reference (F), while the Crot system showed a slight but significant reduction in pH, indicating a greater acidification potential in this treatment.

Table 2. Soil chemical attributes at 0–10 cm in a sandy Ultisol during sugarcane field reform under different cover-crop managements: conventional exposed soil (C), sugarcane + soybean (Soy), sugarcane + Crotalaria spectabilis (Crot), and native forest (F).

Chemical attibutes		F	C	Soy	Crot
pH	($CaCl_2$ 0.001 mol.L^{-1})	5.12A[1]	5.13A	5.12AB	4.91B
Mg^{2+}	($cmol_c$ dm^{-3})	0.60A	0.77A	0.60A	0.54A
Ca^{2+}	($cmol_c$ dm^{-3})	0.92AB	1.10AB	0.75B	1.55A
K^{+}	($cmol_c$ dm^{-3})	0.23A	0.03B	0.08B	0.23A
P	($mg.dm^{-3}$)	2.40B	20.20A	14.13A	5,73B

[1]Means followed by different letters differ by Tukey's test (p-value≤0.50).

The decrease in pH under Crot can be explained by intensified decomposition and mineralization processes associated with the larger residue input, which may increase the production of organic acids and contribute to proton release in the soil solution (Zhou, Han, Liu, & Li, 2019; Hong, Gan, & Chen, 2019). Although organic inputs may also alleviate acidity through complexation of Al and modulation of H^{+} activity, the net effect depends on residue quality, decomposition dynamics, and soil buffering capacity, which is typically low in sandy soils (Franchini, Hoffmann-Campo, Torres, Miyazawa, & Pavan, 2003; Franchini et al., 2012; Diehl, Miyazawa, & Takahashi, 2008).

Despite the reduction in pH, Crot presented the highest Ca^{2+} and K^{+} levels (Table 2), suggesting that nutrient cycling and residue-derived inputs outweighed potential pH constraints on base cation availability in the surface layer. Cover crops can enhance nutrient return to topsoil via residue decomposition, especially when biomass production is high and root systems explore larger soil volumes (Wutke et al., 2014; Nascimento et al., 2023). The increased K^{+} and Ca^{2+} under Crot is agronomically relevant because these nutrients are among those required in large amounts by sugarcane, and improved availability may support better crop performance in low-reactivity soils (Oliveira et al., 2010).

By contrast, C and Soy showed lower Ca^{2+} and K^{+} contents. Under conventional exposed-soil reform, the absence of protective cover can increase susceptibility to nutrient losses through runoff and erosion, particularly during rainfall events (Silva, Fernandes, & Barbosa, 2012). For Soy, nutrient export in harvested grains may also contribute to reduced surface cation pools, especially for K, which is highly demanded and exported by soybean (Kurihara et al., 2013).

The absence of differences in Mg^{2+} among treatments likely reflects the uniform application of dolomitic lime and the tendency for the strongest liming effects to concentrate in the 0–10 cm layer regardless of placement method, as previously observed in southern Brazilian soils under conservation systems (Auler et al., 2019).

Available P was markedly higher in C and Soy than in Crot and F (Table 2). This pattern may reflect contrasting short-term dynamics between P availability and organic matter accumulation. In Crot, lower pH and increased organic inputs may have favored P retention mechanisms, including enhanced ligand exchange reactions and P sorption in association with Fe and Al phases, reducing Mehlich-1 extractable P in the short term (Guppy, Menzies, Moody, & Blamey, 2005; Hue, 1991). Additionally, decomposition of large biomass inputs can temporarily increase microbial immobilization of P, reducing its availability in the soil solution, particularly when microbial demand is stimulated by fresh carbon inputs (Güsewell & Gessner, 2009; Kuzyakov, 2010). Importantly, higher OC under Crot may still represent a medium-term P source, as organic matter constitutes a relevant P pool in tropical soils and can contribute to gradual release over time during mineralization (Santos, Gatiboni, & Kaminski, 2008; Pavinato & Rosolem, 2008). Therefore, the lower extractable P in Crot should not necessarily be interpreted as reduced P supply potential over the crop cycle, but rather as a shift toward temporarily less extractable (yet potentially labile) pools.

Relationships between organic fractions and soil chemical attributes

Pearson correlation analysis indicated that pH was negatively correlated with HA and FA, suggesting that increases in the most reactive humic fractions were associated with lower soil pH (Table 3). This relationship is consistent with mechanisms of soil acidification linked to organic matter accumulation, including dissociation of functional groups and production of low-molecular-weight organic acids during decomposition (Zhou et al., 2019).

Table 3. Pearson correlations between organic fractions (OC, HA, FA) and chemical attributes (pH, Mg^{2+}, Ca^{2+}, K^{+}, P) in a sandy Ultisol during sugarcane reform.

OC	pH	r = NS[1]
	Mg^{2+}	r = NS
	Ca^{2+}	r = NS
	K^{+}	r = 0,88***
	P	r = -0,83***
HA	pH	r = - 0,57*
	Mg^{2+}	r = NS
	Ca^{2+}	r = NS
	K^{+}	r = 0,94***
	P	r = -0,69**
FA	pH	r = -0,45*
	Mg^{2+}	r = NS
	Ca^{2+}	r = NS
	K^{+}	r = 0,91***
	P	r = -0,63***

[1]Significance: (*)p ≤ 0,05; (**) ≤ 0,01; (***) ≤ 0,001; and, NS (Non-significant).

Potassium showed strong positive correlations with OC, HA, and FA (Table 3), indicating that higher organic matter content increased K retention in this sandy soil. This effect is expected because humic substances contain functional groups that contribute to negative charge generation and cation retention, which is critical in soils with low clay content and low effective CEC (Sposito, 2008; Hayes & Swift, 2020). Furthermore, humic and fulvic acids may influence K dynamics by reducing fixation and/or promoting release of fixed K, as shown in studies assessing humic interactions with clay minerals and K behavior (Tan, 1978).

In contrast, available P exhibited negative correlations with OC, HA, and FA (Table 3). Although many studies describe increased P availability with rising organic matter due to competition for adsorption sites and ligand exchange effects (Hue, 1991; Guppy et al., 2005; Cessa, Vitorino, Celi, Novelino, & Barberis, 2010), the observed negative relationship here suggests that, under the conditions of this sandy Ultisol and using Mehlich-1 extraction, part of the P pool may have been temporarily retained in organo–mineral complexes or immobilized in microbial biomass. One plausible mechanism is P sorption mediated by cation bridges (Al, Fe, or Ca) involving humic substances interacting with mineral surfaces, which can increase P retention and reduce extractability (Villapando & Graetz, 2001). Over time, mineralization and turnover of organic matter may release P, and organic acids may delay P fixation, increasing the likelihood of plant uptake during subsequent crop development (Pavinato & Rosolem, 2008). Thus, the negative correlation may indicate a short-term trade-off between humic substance build-up and Mehlich-1 extractable P, without excluding longer-term benefits for P supply.

Implications for sandy-soil management in sugarcane reform

Overall, the results demonstrate that using *Crotalaria spectabilis* as a cover crop during sugarcane field reform in a sandy Ultisol increased OC and reactive humic fractions (HA and FA), reaching levels similar to those in the native forest reference. These changes were associated with improved K and Ca availability and with measurable shifts in soil pH and P dynamics. Therefore, incorporating high-biomass cover crops into reform operations represents a promising strategy to enhance organic matter pools and improve chemical reactivity in sandy soils, supporting more sustainable sugarcane production systems (Murphy, 2015; Yost & Hartemink, 2019; Nascimento et al., 2023).

In practical terms, these findings have direct implications for decision-making in sugarcane production systems established on sandy soils, which are inherently vulnerable to nutrient losses and rapid organic matter turnover. The results indicate that the choice of cover crop during the reform period is not merely a transitional practice, but a strategic management decision capable of influencing soil chemical quality beyond the immediate reform phase. The use of *Crotalaria spectabilis* proved to be particularly effective in enhancing reactive organic matter fractions and key nutrient availability, suggesting that producers operating on sandy soils may benefit from prioritizing high-biomass, nitrogen-fixing cover crops over conventional bare-soil reform or low-residue systems. From a management perspective, this approach can contribute to greater nutrient retention, reduced dependency on corrective fertilization inputs, and improved resilience of the soil system to climatic stresses, such as high temperatures and irregular rainfall. Consequently, incorporating *Crotalaria spectabilis* into sugarcane field reform may represent a cost-effective and environmentally sound strategy to improve soil functionality, sustain productivity, and support long-term sustainability of sugarcane cultivation in sandy environments.

Conclusions

Cover crop management during sugarcane field reform significantly affects soil organic fractions and chemical attributes in sandy soils. The use of *Crotalaria spectabilis* proved to be the most effective strategy, increasing organic carbon and reactive humic fractions and improving nutrient availability compared with conventional and soybean-based systems, with results comparable to those observed under native forest.

These findings highlight the importance of selecting high-biomass cover crops during the reform period as a key management decision to enhance soil quality, optimize nutrient dynamics, and support more sustainable sugarcane production in sandy environments.

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