Colegio de Postgraduados

Effects of filter cake application on soil chemical properties in sugarcane agroecosystems

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ABSTRACT

Objective: To evaluate the effects of filter cake application on the chemical properties of a Fluvisol under a sugarcane agroecosystem.

Design/methodology/approach: A targeted soil survey was conducted at a surface depth of 0-30 cm in a Fluvisol cultivated with the sugarcane variety CP 72-2086, in order to identify areas with and without filter cake irregularly distributed at different depths and soil compartments. The soil chemical properties evaluated included pH, electrical conductivity (EC), organic carbon (OC), organic matter (OM), total nitrogen (TN), the C/N ratio, and available phosphorus (P).

Results: The incorporation of filter cake after eight years in a sugarcane-cultivated Fluvisol resulted in statistically significant differences in pH, organic carbon, and organic matter. In addition, filter cake application promoted low to medium levels of available phosphorus, mainly in the rhizosphere and in two filter cake thickness treatments.

Limitations on study/implications: The chemical composition of filter cake varies according to sugar mill processing conditions, clarification reagents, storage practices, and composting procedures, which may lead to variability in the results reported across studies.

Findings/conclusions: The results indicate that filter cake positively influences key soil chemical properties such as pH, organic matter, organic carbon, and available phosphorus, particularly in the rhizosphere, thereby enhancing the long-term sustainability of sugarcane soils.

Keywords: *Saccharum* spp., sustainability, soil amendment, soil fertility, agricultural residues

Citation: Magaña-Aquino, M., Rivera-Cruz, M. C., Gómez-Merino, F. C., Obrador-Olán, J. J., & Trujillo-Narcía, A. (2025). Effects of filter cake application on soil chemical properties in sugarcane agroecosystems. *Agro Productividad*. https://doi.org/10.32854/3tzbf719

Academic Editor: Jorge Cadena Iñiguez
Associate Editor: Dra. Lucero del Mar Ruiz Posadas
Guest Editor: Juan Francisco Aguirre Medina

Received: August 7, 2025.
Accepted: November 12, 2025.
Published on-line: January XX, 2026.

Agro Productividad, 18(12). December. 2025. pp: 145-154.

INTRODUCTION

Mexico is a major sugarcane-producing country, operating 47 sugar mills during the 2024/2025 harvest season (CONADESUCA, 2025). In 2024, sugarcane cultivation covered a national area of 843,048.28 ha, of which 4.93 % (41,590 ha) was located in the state of Tabasco (SIAP, 2025). Fluvisols cultivated with sugarcane in this region have been subjected to intensive anthropogenic activities for more than 50 years (Ayuso, 2023). In

2024, the national area devoted to sugarcane cultivation increased by 1.11 times relative to the baseline year 2010 (SIAP, 2025). In parallel with this expansion of cultivated area, there has been a corresponding increase in the demand for and application of synthetic chemical fertilizers, leading to a decline in natural soil fertility, environmental contamination, and rising production costs.

These negative effects can be mitigated through the use of filter cake, an agroindustrial by-product which, when composted, functions as an organic fertilizer and soil amendment due to its high content of organic carbon, nitrogen, and other essential nutrients (Dotaniya *et al.*, 2016; López-González *et al.*, 2017; Salman *et al.*, 2023). Filter cake is a highly effective soil amendment that may contain varying proportions of waxes, plant fibers, sucrose, organic carbon, macronutrients, micronutrients, colloids, coagulants, and albuminoids, among other components (López, 1981; Salgado *et al.*, 2001; Kumar *et al.*, 2017). Interest in evaluating the effects of filter cake on agricultural soils has increased, as it represents a sustainable and cost-effective strategy to enhance soil fertility, reduce environmental pollution, and lower storage and disposal costs. The application of filter cake in agricultural systems has been shown to increase soil pH and improve soil reserves of organic carbon, nitrogen, phosphorus, and potassium (Arreola-Enríquez *et al.*, 2004; Basak *et al.*, 2021; Dotaniya *et al.*, 2025). Moreover, the impact of filter cake on the physical, chemical, and biological properties of the rhizosphere is of particular interest for understanding its role as an agricultural soil amendment (Solomon *et al.*, 2024). Accordingly, this study addresses the following research question: Has the incorporation of filter cake after eight years promoted improvements in the chemical properties of a Fluvisol cultivated with sugarcane? Answering this question contributes to addressing both national and local demands related to food security and agricultural sustainability.

MATERIALS AND METHODS

The study was conducted in a field plot located in the Ejido Rubén Jaramillo Lazo, municipality of H. Cárdenas, Tabasco, Mexico, at geographic coordinates 18° 09’ 06” N latitude and 93° 37’ 03” W longitude, and an elevation of 13 m above sea level. The climate of the study area is classified as warm humid, characterized by abundant rainfall during summer and autumn, with an estimated mean annual precipitation of 2,550 mm and temperatures ranging from 27 to 36 °C (INEGI, 2021).

For approximately 50 years, the agricultural soil has been managed under a conventional agronomic system involving the use of heavy agricultural machinery, synthetic chemical fertilizers, herbicides, and crop residue burning. However, in February 2015, the ejido farmers irregularly applied approximately 1 t ha^{-1} of dry filter cake on the soil surface, sourced from the Santa Rosalía sugar mill.

In February 2024, an *in situ* assessment of filter cake thickness (FCT) was carried out in the Fluvisol. The number of sugarcane rows was counted within a one-hectare area, and starting from the third row in an east-west direction, a targeted soil survey was conducted at 10 m intervals, considering a depth range of 0 to 30 cm. The objective was to identify sampling points containing sugarcane roots within the rhizosphere (RZ) and at least two soil layers (C1 and C2) differing in color according to the Munsell Soil Color Charts (USDA, 2017), as well as in filter cake thickness (Figure 1A, B, and C).

The experimental design consisted of a 3×3 factorial arrangement with four replications (n=4), comprising three filter cake thicknesses in the soil and three soil compartments within the 0-30 cm depth interval. The FCT included three levels: FCT1 without filter cake, with a thickness of 0-11 cm (Figure 1A); FCT2 with filter cake, 0-17 cm thick (Figure 1B); and FCT3 with filter cake, 0-24 cm thick (Figure 1C). The soil compartment factor included three levels: RZ, non-root soil layer 1 (C1), and non-root soil layer 2 (C2). The combination of both factors resulted in a total of nine treatments, which are described in Table 1.

In total, 48 soil samples were collected, each weighing 100 g. The samples were placed in individually labeled polyethylene bags and transported to the Agricultural and Environmental Microbiology Laboratory at the Colegio de Postgraduados, Tabasco Campus, for processing and analysis.

For the analysis of chemical parameters, soil samples were air-dried at room temperature under shaded conditions for five days. Soil pH (hydrogen potential) and electrical

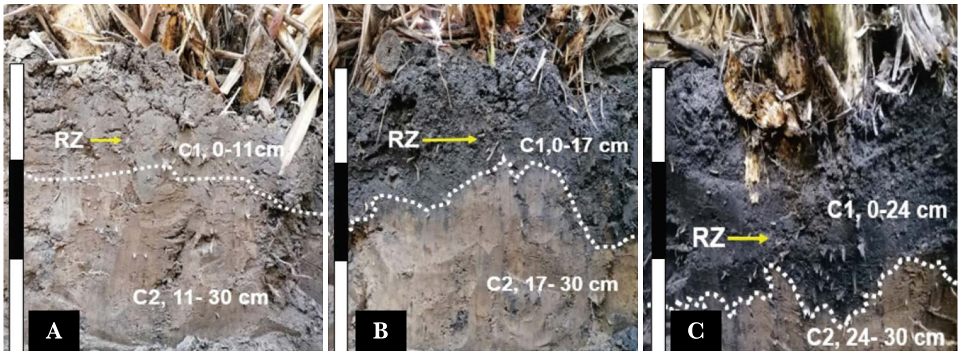

Figure 1. Fluvisol soil with filter cake thickness and surface soil compartments (0-30 cm) under sugarcane (*Saccharum* spp.) var. CP 72-2086. A) FCT1: soil layer without filter cake (0-11 cm, grayish brown); B) FCT2: soil layer with filter cake (0-17 cm, dark brown); and C) FCT3: soil layer with filter cake (0-24 cm, very dark brown). RZ: rhizosphere; C1: non-root soil layer 1; C2: non-root soil layer 2.

Table 1. *In situ* experimental treatments (with and without filter cake) and their corresponding soil compartments.

T	Code	Description
1	FCT1+RZ	Thickness 1 without filter cake (0-11 cm) + Rhizosphere
2	FCT1+C	Thickness 1 without filter cake (0-11 cm) + Non-root soil layer (0-11 cm)
3	FCT1+C2	Thickness 1 without filter cake (0-11 cm) + Non-root soil layer (11-30 cm)
4	FCT2+RZ	Thickness 2 with filter cake (0-17 cm) + Rhizosphere
5	FCT2+C1	Thickness 2 with filter cake (0-17 cm) + Non-root soil layer (0-17 cm)
6	FCT2+C	Thickness 2 with filter cake (0-17 cm) + Non-root soil layer (17-30 cm)
7	FCT3+RZ	Thickness 3 with filter cake (0-24 cm) + Rhizosphere
8	FCT3+C1	Thickness 3 with filter cake (0-24 cm) + Non-root soil layer (0-24 cm)
9	FCT3+C2	Thickness 3 with filter cake (0-24 cm) + Non-root soil layer (24-30 cm)

T: Treatment. FCT: Filter cake thickness. RZ: Rhizosphere. C1: Non-root soil layer 1. C2: Non-root soil layer 2.

conductivity (EC) were determined after shaking the samples in a soil-to-water suspension at a 1:2 ratio, following the methodology described by Jackson (1964), using a portable pH meter and electrical conductivity meter (HANNA Instruments, model HI 9811-5).

Soil organic matter (OM) and organic carbon (OC) content were quantified according to the procedure described by Nelson and Sommers (1982). Total nitrogen (TN) was determined using the micro-Kjeldahl method after digestion with sulfuric acid (H_2SO_4) (Bremner, 1965). Available phosphorus (P) was analyzed using the Olsen method (Olsen and Sommers, 1982), employing a 0.5 M sodium bicarbonate extracting solution adjusted to pH 8.5, and quantified by UV-visible spectrophotometry (GENESYS 10S UV-VIS spectrophotometer) at a wavelength of 882 nm.

Data obtained for each treatment were subjected to analysis of variance (ANOVA), and mean comparisons were performed using Duncan's multiple range test at a significance level of $p \leq 0.05$, using SAS statistical software (version 9.1.3; SAS Institute Inc., 2005).

RESULTS AND DISCUSSION

The results of this study indicate highly significant differences in soil pH (Duncan's test, $p \leq 0.05$; Table 2), particularly in treatments 8, 7, and 6, compared with treatments without filter cake (FCT1; treatments 1, 2, and 3). In addition, an increase in pH was observed in the C2 non-root soil layer with surface-applied filter cake (treatments 6 and 9) relative to the C2 layer without filter cake. This behavior can be attributed to an increase in hydroxyl ions in treatments with filter cake, resulting in a shift in soil reaction from acidic to moderately acidic conditions, according to the NOM-021-RECNAT-2000 classification (SEMARNAT, 2002).

These results are consistent with those reported by Bordin *et al.* (2024) in Brazil, who evaluated combinations of 10 t ha^{-1} of filter cake and 100 m^3 ha^{-1} of vinasse incorporated into soils cultivated with sunflower. In that study, soil pH increased from 5 to 6, which was considered beneficial due to the associated reduction in aluminum

Table 2. Changes in soil pH, electrical conductivity, and organic matter as affected by filter cake thickness and soil compartment.

T	Thickness / Compartment	pH	EC (dS m^{-1})	OM (%)
1	FCT1+RZ	4.7e	0.25b	6.1c
2	FCT1+C1	4.7d	0.23c	5.6cd
3	FCT1+C2	4.8d	0.15ef	4.2e
4	FCT2+RZ	5.8c	0.30a	8.2b
5	FCT2+C1	5.9c	0.18d	7.5b
6	FCT2+C2	6.1b	0.17de	5.0d
7	FCT3+RZ	6.1b	0.17de	9.4a
8	FCT3+C1	6.2a	0.14f	9.1a
9	FCT3+C2	6.0b	0.16ef	5.4 cd

T: Treatment. FCT1: No filter cake, soil thickness 0-11 cm. FCT2: With filter cake, soil thickness 0-17 cm. FCT3: With filter cake, soil thickness 0-24 cm. EC: Electrical conductivity. OM: Organic matter. Values followed by the same letter within a column do not differ significantly according to Duncan's multiple range test ($p \leq 0.05$, n=4).

concentration in the soil. The observed pH increases in the C2 layer of treatments 6 and 9 may be explained by the role of this layer as a reservoir for leached materials originating from the C1 layer containing filter cake. The downward movement and removal of suspended materials across one or more soil layers have been previously documented by Weil and Brady (2017) and is influenced by physical, environmental, and anthropogenic factors.

The variability of this property has a substantial impact on crop performance, as a soil pH of 6.5 is considered optimal for sugarcane development (FAO, 2025). Although sugarcane is tolerant of low pH conditions, prolonged soil acidity may impose several limitations, including poor crop growth, nutrient deficiencies, reduced soil biological activity, and increased aluminum toxicity (Al^{3+}) due to its greater solubility at pH values below 5. Under such conditions, phosphate species ($H_2PO_4^-$, HPO_4^{2-}), sulfates (SO_4^{2-}), and molybdates (MoO_4^{2-}) are retained by aluminum oxides and hydroxides, thereby limiting their availability to plants (Weil and Brady, 2017; Barrow and Hartemink, 2023; Zhu *et al.*, 2025). Consequently, reversing or preventing excessively acidic pH conditions in soils cultivated with sugarcane is of considerable agronomic interest.

The highest EC values were observed in treatment 4, followed by treatments 1 and 2, which correspond to soils without filter cake application. In contrast, treatment 8 (FCT3+C1) exhibited the lowest EC value (0.14 dS m^{-1}) (Table 2). The EC values recorded across all nine treatments indicate that salinity was not a limiting or detrimental factor in this study (SEMARNAT, 2002). Therefore, although filter cake application as an organic amendment may contribute soluble salts and nutrients that gradually increase soil EC, this increase was not sufficient to classify the soil as "very saline."

Regarding soil organic matter (OM) and organic carbon (OC), treatments 8, 7, and 4 exhibited a positive effect of filter cake application, showing highly significant differences (Duncan's test, $p \leq 0.05$; Tables 2 and 3) compared with treatments without filter cake (1, 2, and 3). For agricultural soils, these values indicate a very high OC content according to the agronomic classification proposed by Rodríguez and Rodríguez (2015). This reflects an increase in the soil organic reservoir, which undergoes degradation and mineralization processes, thereby supplying essential elements such as nitrogen, phosphorus, and sulfur to the soil solution in accordance with plant root system demand. This effect is primarily associated with the properties of filter cake, as it is a by-product rich in organic matter (Zhou *et al.*, 2022; Pino-Ortega and Batista-Nieto, 2025).

Llanes-Hernández *et al.* (2025) reported that the combined application of filter cake, chemical fertilizers, and grazing in sugarcane-cultivated soils for more than 30 years, followed by crop rotations including vegetables, grains, and tubers, maintained high organic matter levels ranging from 3.23 to 3.78% when compared with uncultivated soils. Such soil enrichment supports and promotes overall improvements in physical and chemical soil properties, thereby contributing to enhanced agricultural ecosystem productivity. Similarly, in rice and wheat cropping systems in India, Basak *et al.* (2021) observed a 25% increase in organic carbon following filter cake incorporation, accompanied by higher crop yields.

The organic carbon results for treatments 7 and 4 reveal an interesting pattern under the influence of filter cake and soil compartment position, with increases of 54% and 34% in the rhizosphere, respectively, compared with treatment 1 without filter cake (FCT1+RZ). Accordingly, organic carbon content exhibited an inverse relationship with soil depth, decreasing as depth increased. This pattern can be explained by the greater activity of soil carbon sequestration and biogeochemical cycling processes in surface soil horizons (Trumbore, 2009). Consequently, the rhizosphere, as the shallowest compartment and the zone closest to plant roots, utilizes filter cake as a readily available organic input that enhances and maximizes soil functions through interactions with root exudates, biological activity, and other soil factors, thereby creating a dynamic and favorable environment for plant development.

Total nitrogen (TN) contents (Table 3) were agronomically classified as high across six treatments, with values ranging from 0.15% to 0.21%. This was especially notable in the rhizosphere (RZ), the C1 and C2 compartments of FCT1 and FCT2, and the RZ compartment of FCT3, all falling within the 0.15-0.25% range established by NOM-021-RECNAT-2000 (SEMARNAT, 2002). These values indicate a high TN content in the soil. However, in the C1 and C2 compartments of FCT1 and FCT3, TN levels decreased to a medium classification.

Filter cake incorporation did not have a significant effect on total nitrogen (TN) content in the FCT1, FCT2, and FCT3 treatments (Duncan's test, $p \leq 0.05$; Table 3). This behavior contrasts with the findings reported by Rivera-Cruz *et al.* (2010), who observed a 1.1-fold increase in TN following filter cake application in an acidic soil cultivated with sour orange. Similarly, Septyani (2019) reported that the addition of 17 t ha^{-1} of filter cake combined with 25% cattle manure in oil palm-cultivated soils increased TN content by 3.5 times compared with soils without filter cake.

The lack of a significant TN response observed in this study may be attributed to nitrogen immobilization processes driven by soil microbial activity stimulated in the rhizosphere and its interactions, as filter cake typically exhibits a high C/N ratio

Table 3. Organic carbon, total nitrogen, C/N ratio, and available phosphorus in soil compartments influenced by filter cake application.

T	Filter cake thickness / Compartment	OC (%)	TN (%)	C/N	P (mg kg^{-1})
1	FCT1+RZ	3.5c	0.19a	18.4cd	3.7d
2	FCT1+C1	3.2cd	0.18a	18.3cd	3.3d
3	FCT1+C2	2.4e	0.15b	17.3d	1.8e
4	FCT2+RZ	4.7b	0.21a	23.5bc	10.0a
5	FCT2+C1	4.4b	0.19a	23.6bc	9.0b
6	FCT2+C2	2.9d	0.18a	16.6d	2.5e
7	FCT3+RZ	5.4a	0.19a	29.1b	7.6c
8	FCT3+C1	5.2a	0.14b	38.8a	3.8d
9	FCT3+C2	3.1cd	0.13b	25.4b	0.6f

T: Treatment. FCT1: No filter cake, soil thickness 0-11 cm. FCT2: With filter cake, soil thickness 0-17 cm. FCT3: With filter cake, soil thickness 0-24 cm. OC: Organic carbon. TN: Total nitrogen. C/N: Carbon-to-nitrogen ratio. Values followed by the same letter within a column do not differ significantly according to Duncan's multiple range test ($p \leq 0.05$, $n=4$).

(Pérez-Méndez *et al.*, 2011). Over time, nitrogen associated with organic amendments undergoes mineralization and becomes available for plant uptake. However, in the present study, filter cake was incorporated eight years prior to sampling, with no subsequent applications. As a result, most of the nitrogen initially supplied by the filter cake may have already been mineralized or depleted, causing the soil to revert to conditions similar to those of soils without filter cake. This occurs despite the currently high TN values, which may be influenced by sugarcane management practices and natural nitrogen cycling processes. This interpretation is supported by the findings of Breza and Grandy (2025), who demonstrated that nitrogen mineralization and immobilization rates depend on the stoichiometry, quantity, and quality of the applied organic substrate.

The C/N ratio (Table 3) exhibited highly significant differences among treatments (Duncan's test, $p \leq 0.05$). The highest C/N ratio (38.8) was observed in FCT3+C1 (treatment 8), indicating that TN is largely stored within the organic matter of the filter cake and is either temporarily unavailable for plant uptake or immobilized due to microbial competition. This nitrogen pool is expected to be gradually mineralized, considering that the optimal C/N ratio for organic amendments to decompose without causing nitrogen immobilization ranges between 24:1 and 30:1 (Weil and Brady, 2017).

Treatments 4, 5, and 6 within FCT2 exhibited C/N ratios ranging from 16.6 to 23.5, while treatments 1, 2, and 3 within FCT1 (Table 3) showed lower C/N values ranging from 17.3 to 18.4, below the optimal range. From an agronomic perspective, these lower C/N ratios are favorable, as they indicate active release of plant-available nitrogen, reduce nutrient immobilization, and promote plant growth through enhanced nitrogen uptake.

With respect to soil phosphorus (P) (Table 3), highly significant differences among treatments were observed as a result of filter cake application (Duncan's test, $p \leq 0.05$). According to NOM-021-RECNAT-2000 (SEMARNAT, 2002), treatments 4, 5, and 7, corresponding to FCT2+RZ, FCT2+C1, and FCT3+RZ, respectively, exhibited P concentrations of 10.0, 9.0, and 7.6 mg kg^{-1}, which are classified as low to medium when compared with treatments 1, 2, and 3 representing soils without filter cake (Table 2). A decreasing trend in P concentration with increasing soil depth was also observed, with the rhizosphere showing the highest values.

These findings are consistent with those reported by Arruda *et al.* (2019), who demonstrated that filter cake application improved the uptake and availability of labile inorganic phosphorus in the rhizosphere and altered the structure of microbial and fungal communities, positioning filter cake as a practical and viable alternative to conventional chemical fertilizers. Furthermore, the decomposition of filter cake organic matter generates competition for phosphorus adsorption sites, reducing phosphorus fixation and increasing its availability to plants, rather than allowing it to remain immobilized in the soil (de Aquino *et al.*, 2021).

Treatments grouped under FCT3 (Figure 1C; Table 3) showed a slight decrease in soil P concentrations compared with FCT2 (Figure 1B; Table 3). This reduction may be associated with increased soil alkalinity in the layer where filter cake was applied (0-24 cm), as higher pH levels can negatively affect phosphorus concentration and availability. This effect occurs because increases in soil pH strongly influence phosphorus reaction mechanisms and fixation processes, depending on soil type (Penn and Camberato, 2019).

CONCLUSIONS

This study demonstrates that the incorporation of filter cake into Fluvisol soils, even eight years after its initial application, leads to significant and sustained improvements in several soil chemical properties under sugarcane (*Saccharum* spp.) cultivation. The key findings indicate that filter cake applied at two thickness levels effectively reverses soil acidity by increasing pH from acidic to moderately acidic conditions, while also enhancing organic matter and organic carbon contents, particularly in the rhizosphere. In addition, an increase in soil phosphorus availability was observed in response to filter cake application at a thickness of 0-17 cm (FCT2), with values ranging from low to medium.

The effect of filter cake was most pronounced in the rhizosphere, followed by the upper non-root soil layer (C1), where interactions between plant roots and biological activity maximize organic functions and nutrient retention.

In summary, filter cake acts as a valuable organic soil amendment that promotes soil health and sustainability in sugarcane agroecosystems by mitigating the negative effects of intensive management and chemical fertilization. These findings highlight key strategies for the repurposing of agroindustrial by-products to enhance agroecosystem sustainability from both economic and environmental perspectives. However, the application of such by-products should be evaluated on a site-specific basis to determine their potential to complement or partially replace chemical fertilizers within a sustainable agronomic management framework.

FUNDING

This study was financially supported by funds of Colegio de Postgraduados. The first author thanks the Secretariat of Science, Humanities, Technology and Innovation of Mexico (SECIHTI) for the M. Sc. scholarship granted.

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