Australian Journal of Crop Science
AJCS

Aust J Crop Sci. 18(10):686-692 (2024) | ISSN:1835-2707
https://doi.org/10.21475/ajcs.24.18.10.p83

Effects of gypsum, limestone and organic fertilizers on the properties of a Vertisol and sugarcane yield

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Submitted:* *03/01/2023

Revised:* *31/03/2024

Accepted:* *04/04/2024

Abstract: The accelerated degradation of soils demands urgent study of recovery alternatives for their properties with sustainability criteria. This study was carried out to evaluate the effect of amendment agents on vertisol and their relationship with sugarcane yield. Organic fertilizer (sugarcane filter cake-SFC), natural minerals (gypsum-limestone) and chemical fertilization (nitrogen-phosphorus-potassium-NPK) were applied as treatments. The experiment was carried out in a complete randomized block design with ten treatments and four replicates. The following physical and chemical properties were evaluated: pH in water, pH in KCl, and organic matter, assimilable P_2O_5 and K_2O, degree of soil aggregation, water-stable aggregates, permeability and plastic limit. The sugarcane yield components such as cane yield-CY (t ha^{-1}) and sucrose yield-SY (t ha^{-1}) were evaluated. Amendments of organo-mineral fertilizers with a chemical composition rich in calcium cause, in an acidic vertisol, produce significant increases in the pH, organic matter and assimilable phosphorus, as well as in the structure and their stability. The study of the relationships between physical and chemical properties and sugarcane yield showed high values of R^2 (51 - 72%) and a coefficient of determination of 0.68-0.94, which shows a high degree of significance and the extent to which the indicators of the properties studied increase the yields (CY 104-141t ha^{-1}, SY 18-25 t ha^{-1}).

Keywords: recover soil; organic fertilizer; sustainability; yield; Vertisol
Abbreviations: OM_Organic matter; SWSA_Soil water stable-aggregates; PL_Plastic limit; SF_Structure factor; CY_Cane yield; SP_Soil permeability; SY_Sucrose yield; SFC_Sugarcane filter cake.

Introduction

The global area under Vertisols is estimated to be approximately 308 M ha. In the tropics, they occupy 60% of the total área. In the study of Vertisols, there are numerous investigations on their genesis, classification and management, but few studies address the integration of amendments with organic fertilizers and natural minerals and their relationship with crop yields (Pal et al., 2012; Hernandez et al., 2014; Azinwi et al., 2018; Bennett et al., 2019; Villazón-Gómez 2021; Wang et al., 2021; Hamadjida, et al., 2022; Wang et al., 2022 Nyaombo and Majule 2022; Mganga et al., 2023; Zhang et al., 2023). In the studies with organo-mineral fertilizers, the mixture of organic fertilizers with industrial mineral fertilizers has predominated (Osumah et al., 2011; Eifediyi et al., 2013; Ojo et al., 2014; Dania et al., 2014). However, the works in which natural minerals are used, such as gypsum, limestone, zeolite, phosphate limestone and phosphorite with organic fertilizers, involve greater sustainability in the agroecosystem (Cairo and Reyes, 2017; Cairo, 2018; Cairo and Diaz, 2020; Cairo and Diaz, 2022). On the other hand, in acid Vertisols, there are greater possibilities of obtaining answers in the improvement of soil structure and this can be achieved with the use of calcium-rich organo-mineral fertilizers. There are very favorable precedents in the use of minerals rich in calcium and magnesium in soils with physical limitations and high natural fertility, such as Vertisols, which can be of great practical and economic interest (Cairo et al., 2017a; Cairo and Reyes, 2017; Cairo, 2018). The quality of Vertisols is very limited due to structural degradation problems, acidification processes due to improper fertilizer use, and compaction due to the continuous use of mechanization in sugarcane (Hernández et al., 2014; Cairo et al., 2017a). These soils are extremely plastic and poorly drained, with high water absorption capacity and poor water-air distribution. In consequense, as the substrate deepens, the air is smaller, so the roots of the cane only develop to a depth of 25 cm, resulting in less growth and yield of the crops (Vidal et al., 2006; Hernández et al., 2014). Specifically, vertisols in Cuba occupy an area of 695,000 ha (Hernández et al., 2014). Despite their agrophysical limitations, they can be used with good productive results, adapting improvement measures with organo-mineral fertilizers. Thus, the objective of the research was to evaluate

Table 1. Effects of treatments on soil structure.

Treatment	PL (%)*	SF (%)	P (Log 10k)	SWSA (%)
1- Control without application	26.96 i	52.37 i	1.60 f	50.59 c
2- NPK 100 - 60 - 200 kg ha^{-1}	28.33 h	51.54 j	1.77 e	53.88 c
3- SFC 50 t ha^{-1}	34.16 g	76.16 a	2.16 abc	60.96 ab
4- SFC 50 t ha^{-1} + $CaCO_3$ 10 t ha^{-1}	41.18 a	73.08 b	2.11 cd	61.56 ab
5- SFC 50 t ha^{-1} + gypsum 16 t ha^{-1}	39.74 b	70.78 c	2.20 abc	62.07 ab
6- SFC 50 t ha^{-1} + $CaCO_3$ 10 t ha^{-1} + K_2O 200 kg ha^{-1}	36.73 e	66.54 f	2.24 ab	62.49 ab
7- $CaCO_3$ 10 t ha^{-1}	36.68 e	69.07 e	2.30 a	63.60 a
8- $CaCO_3$ 10 t ha^{-1} + NPK 100 - 60 - 200 kg ha^{-1}	39.74 b	69.86 d	2.04 d	58.79 b
9- Gypsum 16 t ha^{-1}	37.21 d	60.47 h	2.24 ab	62.53 ab
10- Gypsum 16 t ha^{-1} + NPK 100 - 60 - 200 kg ha^{-1}	35.21 f	61.16 g	2.27ab	63.09 a
Standard Error (±)	0.017	0.019	0.036	0.889

SFC: sugarcane filter cake; PL: plastic limit; SF: structure factor; P: permeability; SWSA: soil water-stable aggregates. *Letters in the columns differ for P < 0.05 by Tukey HSD.

Table 2. Effects of treatments on some soil fertility indicators.

Treatment	pH (H_2O)	pH (KCl)	OM (%)	P_2O_5 mg $100g^{-1}$	K_2O mg $100g^{-1}$
1- Control without application	6.02 f	4.63 e	1.93 ef	6.05 g	13.80 i
2- NPK 100 - 60 - 200 kg ha^{-1}	6.02 f	4.58 e	1.90 f	6.10 g	14.10 g
3- SFC 50 t ha^{-1}	6.73 d	5.43 f	2.52 d	11.53 d	13.87 h
4- SFC 50 t ha^{-1} + $CaCO_3$ 10 t ha^{-1}	6.90 b	5.60 d	2.86 c	15.20 c	15.95 a
5- SFC 50 t ha^{-1} + Gypsum 16 t ha^{-1}	6.78 cd	5.48 ef	3.17 a	16.73 b	14.80 d
6- SFC 50 t ha^{-1} + $CaCO_3$ 10 t ha^{-1} + K_2O 200 kg ha^{-1}	6.98 a	6.23 a	3.01 b	17.08 a	14.49 e
7- $CaCO_3$ 10 t ha^{-1}	6.80 cd	5.70 c	1.96 e	4.13 h	14.40 f
8- $CaCO_3$ 10 t ha^{-1} + NPK 100 - 60 - 200 kg ha^{-1}	6.83 bc	5.95 b	1.97 e	6.08 g	12.92 j
9- Gypsum 16 t ha^{-1}	6.48 e	5.53 de	1.77 g	6.53 f	14.90 c
10- Gypsum 16 t ha^{-1} + NPK 100 - 60 - 200 kg ha^{-1}	6.50 e	5.48 ef	1.92 ef	6.62 e	15.82 b
Standard error (±)	0.017	0.017	0.011	0.013	0.015

Sugarcane filter cake: SFC; organic matter: OM. *Letters in the columns differ for P < 0.05 by Tukey HSD.

the effect of amendment agents on vertisol and their relationship with sugarcane yield.

Results and Discussion

Effect of amendment agents on soil structure

Table 1 and Figure 1 show the effects of the treatments on indicators of soil structure. All amendments significantly increase the lower limit of plasticity, stable aggregates, structure factor, and log 10K permeability. The organo-mineral combinations, sugarcane filter cake + gypsum, and sugarcane filter cake + calcium carbonate, reached the highest and most stable values in the structural indicators studied. Figure 1 showed the residual effect of the treatments along the time when the log 10K permeability is taken as a reference, which remains at values greater than 2.00 in the excellent category after 4 months of treatments application. The characteristics of the curve indicated a projection for the maintenance of the residual effect at times after those studied. On the other hand, studies by Cairo and Reyes, (2017); Cairo, (2018) agree that indicators such as the structure factor and permeability are determinants to control the state of improvement of plastic soils. Research on the structure and stability of the structure in vertisols has mainly referred to their genesis and degradation by crop production (Bennett et al., 2019; Villazón-Gómez, 2021; Kraemer et al., 2021; Hamadjida et al., 2022; Mganga et al., 2023; Zhang et al., 2023) but limited studies have been directed to the improvement of their structure with organo-mineral fertilizers. Cairo and Reyes, (2017) pointed out the importance of using natural minerals such as zeolite, limestone and gypsum. Cai et al., 2022 obtained results in the improvement of the structure of vertisol in an experiment under controlled conditions using biochar, chicken manure and compost. Nyasapoh et al., (2022) have demonstrated in Vertisol the effectiveness of biochar in improving its physical properties, the efficiency of water use and increasing crop yield. On the other hand, Niaz et al., (2023) used four organic amendments to improve the structure of sodic Vertisols. They showed results similar to those obtained in this investigation. Evaluating the residual effect of organo-mineral fertilizers in the soil can be a great practical feasibility to optimize their use under sustainable agriculture conditions.

Effects of amendment agents on soil fertility indicators

The effect of the treatments on the chemical indicators is based on the presence of calcium and other bases in the chemical composition of the organo-mineral substrates, which results in increases in pH, organic matter and assimilable phosphorus (Table 2). The organo-mineral combinations showed similar responses in chemical properties and structural ones, where the presence of calcium and organic matter guarantees a physical-chemical balance (Cairo et al., 2021). The use of organic fertilizers not only provides essential nutrients but also improves the water retention capacity, aeration, exchange capacity and solubility of essential nutrients, thus increasing their availability. This, in turn, activates soil microorganisms and promotes the decomposition of crop residues, thus maintaining proper C: N ratios and soil pH values (Kumar and Chand, 2013; Chintala et al., 2014). Table 2 reflects the statistical significance of the control and NPK treatments in relation to the combinations of organic fertilizer with natural minerals. Treatment 6 showed values of pH (in H_2O) 6.98, and P_2O_5 of 17.08 mg $100g^{-1}$ much higher than those of treatment 1 control with pH (in H_2O) 6.02 and P_2O_5 of 6.05 mg $100g^{-1}$. These results coincide with those found in Table 3 when the maximum and minimum values of all the properties studied, including yield, are compared. Other investigations carried out on vertisols from the same region do not obtain answers on chemical properties such as those achieved in this work, closely associated with low levels of pH and the organo-

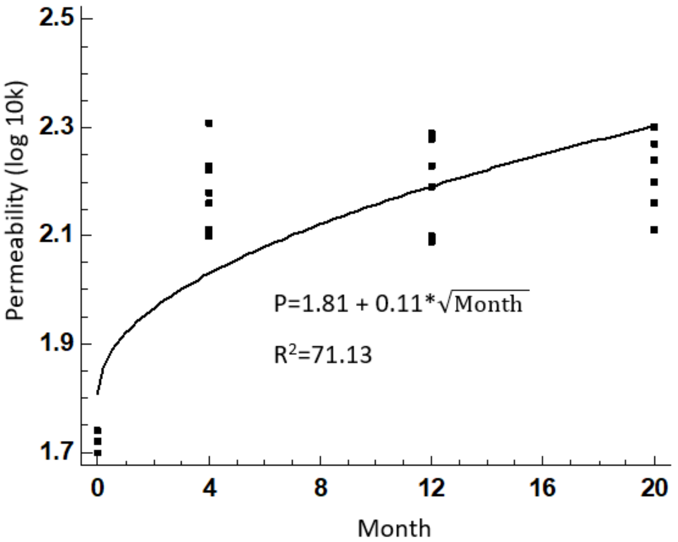

Figure 1. Residual effect of treatments on soil permeability as a function of time at a depth of 0-20 cm.

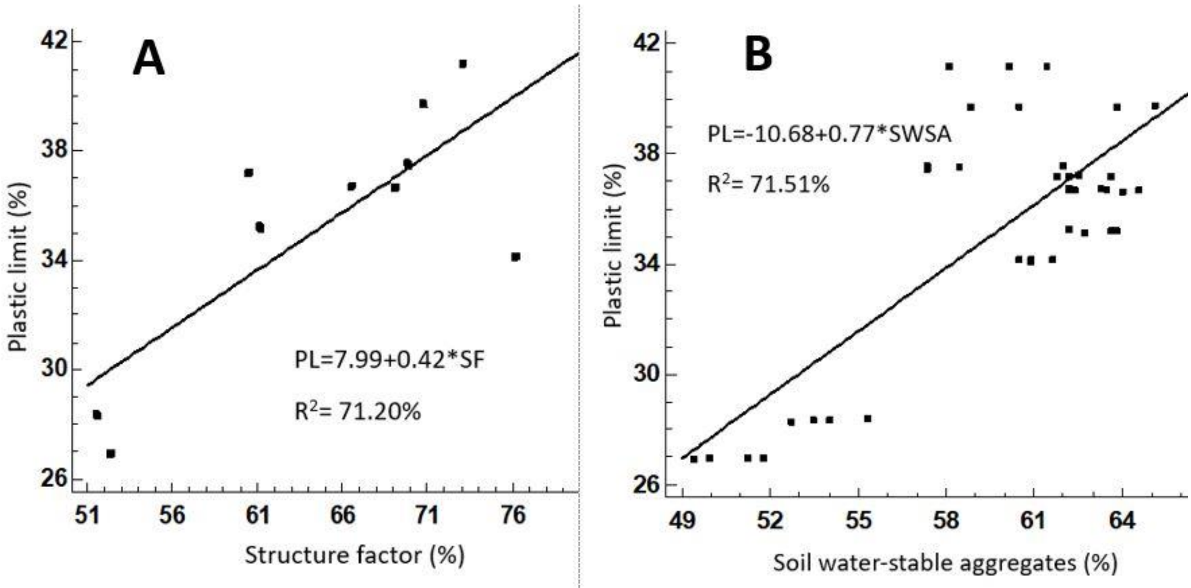

Figure 2. Relationship between plastic limit - PL with structure factor - SF (A) and soil water-stable aggregates-SWSA (B).

mineral substrates used (Cairo et al., 2017a; Cairo et al., 2017b; Cairo and Reyes, 2017; Cairo et al., 2021).

Relations between soil properties and yield

Table 3 shows trends in these properties after statistical analysis, as well as sensitivity to change in category. Ghaemi et al., (2014); Niaz et al., (2023) state that the use of the main components can contribute to the evaluation of soil quality and the sustainable management of agricultural systems. Of a total of 11 indicators studied, eight reached between 80 and 100 significant correlations. All properties have shown a change in category and high sensitivity in a direction proportional to the increase in yields (Rodriguez, 2010). The indicators studied showed a high coefficient of determination up to values greater than 0.90 and occupied positions in the first and second components. Figures 2 to 6 have reflected in detail the relationships between soil properties and yield. Figure 2 has highlighted the close relationships between soil structure and plasticity. For a structure factor of 74 % and 64 % stable aggregates, a humidity for the lower limit of plasticity of 38 % is reached (values of R^2 71%). This aspect is of great agronomic value for the management of vertisols. Niaz et al., (2023) using gypsum and organic fertilizers in sodic Vertisol found improvements in structural indicators. Under the conditions of the experiment, very close relationships between the chemical properties have also been obtained. Figure 3 showed these results with the establishment of a positive correlation between organic matter and assimilable phosphorus (R^2 98%). Three indicators, two physical and one chemical, summarize the relationships between soil properties and yield. A positive and highly significant relationship was shown between structural indicators, water stable aggregates (%) and permeability (log 10k) with cane yield and sucrose yield Figures 4 and 5. The 65 % of water stable aggregates and permeability (log 10k) 2.20 under study conditions represented 23 t of sucrose yield and 130 t ha of cane yield. Figure 6 indicates that as the pH in KCl increases, the yield of cane and sugar increases. The yields under study conditions with the application of organo-mineral fertilizers increase by up to 47% in tons of sucrose yield. Cabrera, (2001); Vidal et al., (2006); Cairo et al., (2017b) and Cairo, (2018) demonstrated the close relationship between soil properties and sugarcane and sugar yield in Vertisols using subsolation drainage-slit methods and organo-mineral fertilizers. The results indicated that the combined application of organic fertilizers and natural minerals transforms the absorbent complex, increases the pH,

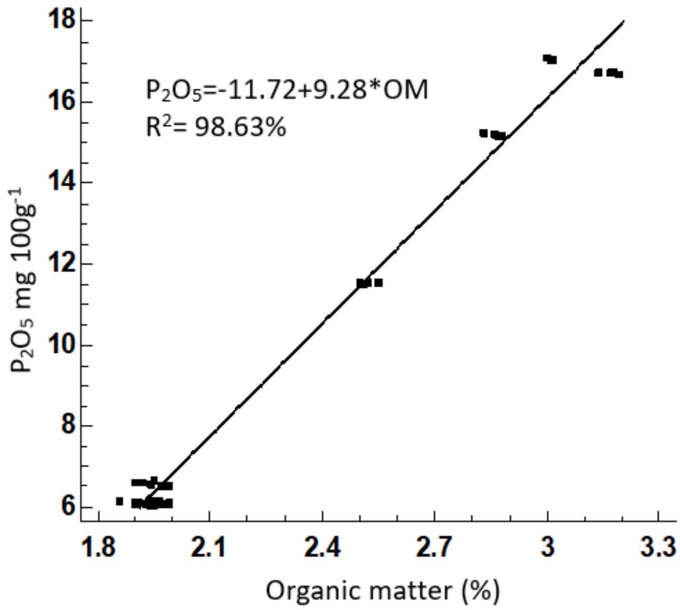

Figure 3. Relationship between P_2O_5 and organic matter-OM.

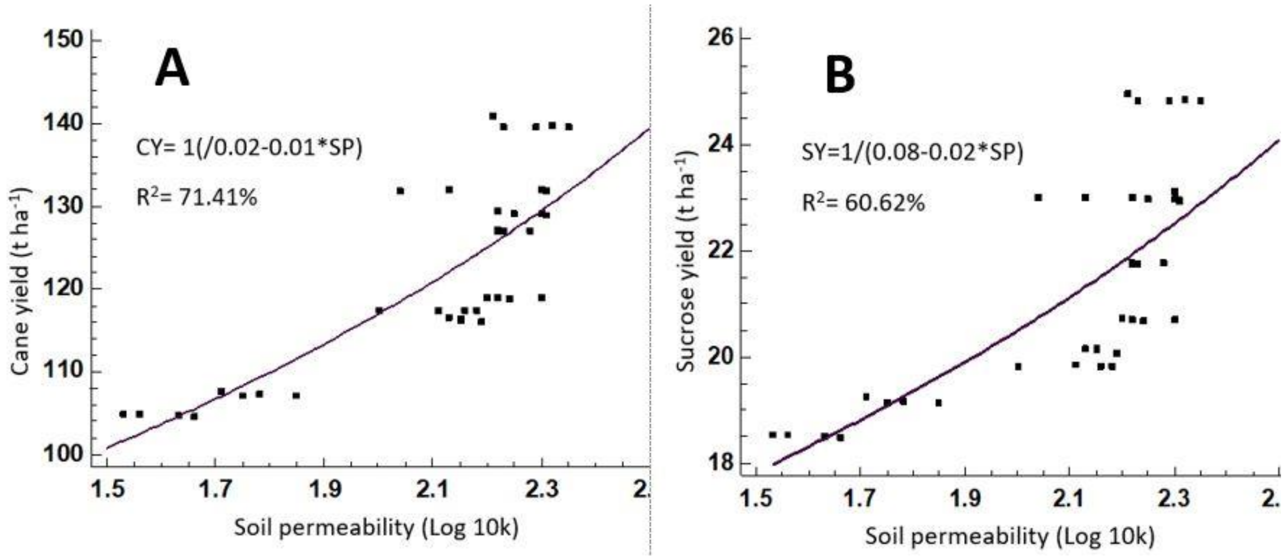

Figure 4. Relationships between soil permeability and sugarcane yield indicators (A)-(B).

facilitates aggregate formation and increases the availability of nutrients that stimulate the cane yield and sucrose yield.

Materials and Methods

Study sites

The research was carried out at the Sugar Cane Experimental Station located in the municipality of Sagua la Grande, province of Villa Clara (22°50′30.12″N; 80°0′47.61″W). The soils studied are classified as vertisols. (Soil Survey Staff, 1999). Vertisols are very clayey, and occupy an area with plain relief, but plastic, under an intense water regime.

Experimental description

The experiment was carried out in a randomized complete block design with four replicates. The individual plot size was 10 × 9.6 m. The sugarcane variety Ja 60-5 was planted in furrows at 1.60 m row spacing. Gypsum, limestone and organic fertilizers were applied in bands on the furrow. We also evaluated the total number of stems per plot and their weight to determine sugarcane yield and sucrose yield. The experimental design was considered with the criteria of offering a sugarcane fertilization and soil improvement system. Additionally, we took into account the type of soil and its physical-chemical characteristics, as well as organic fertilizers and natural minerals appropriate for these conditions. Tables 4 and 5 describe the treatments used and the chemical composition of the calcium carbonate filter cake and gypsum.

Analysis of soil properties

After establishing the experiment, sampling was carried out in each treatment at a depth of 0-20 cm to evaluate the soil structure at 4, 12 and 20 months. The last sampling included the chemical analysis of soils (120 samples). The chemical and physical properties were determined by the following methods: plant available phosphorus (P_2O_5) and potassium (K_2O) extracted with sulphuric acid (0.1 N) as described by Oniani, (1964). The P_2O_5 was colorimetrically determined and K_2O by flame photometry. Organic matter was determined by the colorimetric method of Walkley and Black, (1934) and pH (in water and KCl) by pH-meter in 1:2.5 soil water suspensions. Permeability was analyzed according to Henin et al., (1958) and the structure factor (SF) or the degree of soil aggregation, which indicates the percentage of clay that acts as cement in the formation of soil aggregates

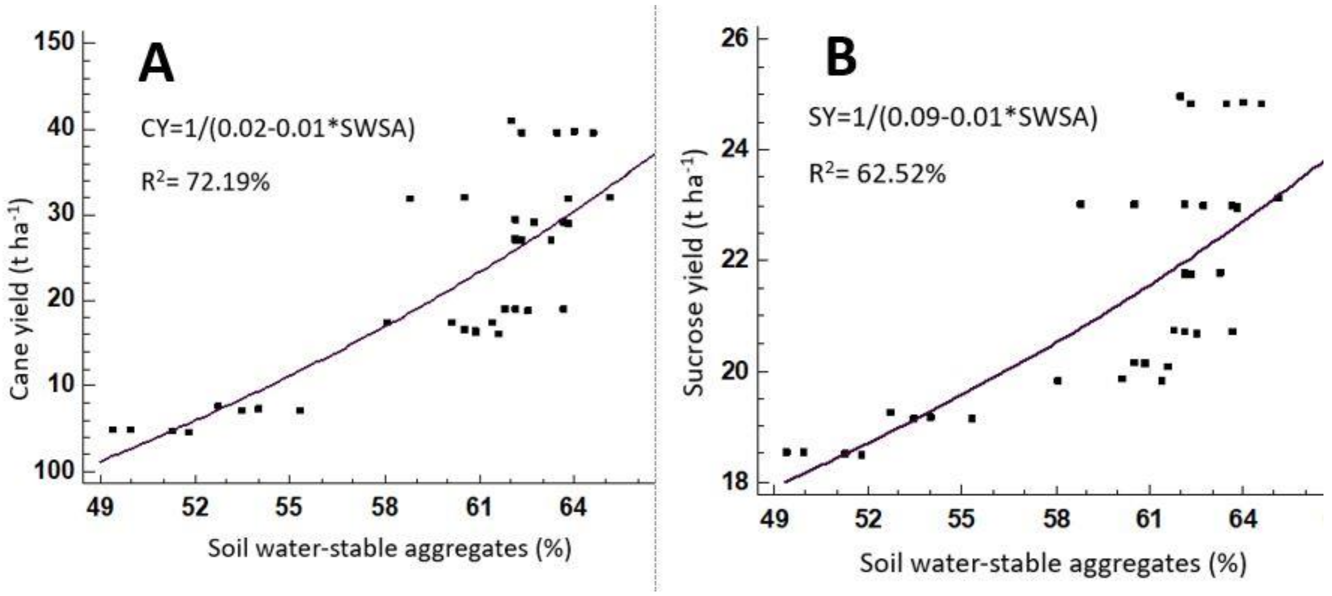

Figure 5. Relationships between soil water-stable agregates- SWSA and sugarcane yield indicators (A)–B).

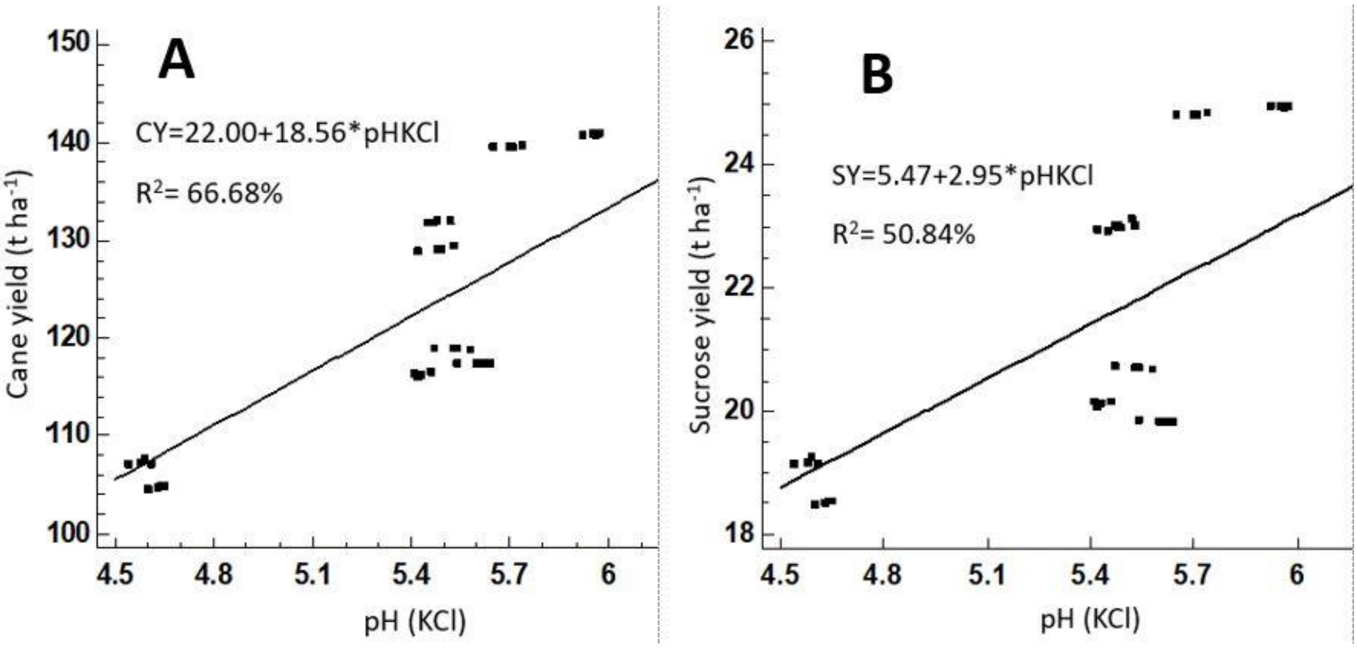

Figure 6. Relationships between pH and sugarcane yield indicators (A)–(B).

Table 3. Matrix of correlations and main components of the properties studied.

Properties	Significant correlations/Total correlations (%)	Range Degree of sensitivity		Principal Component
PL (%)	100	26.92	41.20	0.81 (1)
SF (%)	90	51.49 Regular	76.25 Excellent	0.73 (1)
P (Log 10k)	90	1.53 Regular	2.46 Excellent	0.82 (1)
SWSA (%)	90	49.38 Regular	66.61 Good	0.82 (1)
pH (H_2O)	80	6.00 Medium Acid	6.99 Neutral	0.68 (2)
pH (KCl)	80	4.54 Medium Acid	6.28 Neutral	0.89 (1)
OM (%)	70	1.74 Low	3.19 Medium	0.94 (2)
P_2O_5 mg100g^{-1}	80	4.10 Low	17.12 Very High	0.92 (2)
K_2O mg100g^{-1}	80	12.90 Medium	15.98 High	0.88 (3)
CY (t ha^{-1})	60	104.54	141.02	0.94 (1)
SY (t ha^{-1})	60	18.47	21.60	0.89 (1)

PL: plastic limit; SF: structure factor; SP: soil permeability; SWSA: soil water-stable aggregates; OM: organic matter; CY: cane yield (t ha^{-1}); SY: sucrose yield (t ha^{-1}).

Table 4. Treatment description.

Treatment
1- Control without application
2- NPK 100 - 60 - 200 kg ha^{-1}
3- Sugarcane filter cake 50 t ha^{-1}
4- Sugarcane filter cake 50 t ha^{-1} + $CaCO_3$ 10 t ha^{-1}
5- Sugarcane filter cake 50 t ha^{-1} + gypsum 16 t ha^{-1}
6- Sugarcane filter cake 50 t ha^{-1} + $CaCO_3$ 10 t ha^{-1} + K_2O 200 kg ha^{-1}
7- $CaCO_3$ 10 t ha^{-1}
8- $CaCO_3$ 10 t ha^{-1} + NPK 100 - 60 - 200 kg ha^{-1}
9- Gypsum 16 t ha^{-1}
10- Gypsum 16 t ha^{-1} + NPK 100 - 60 - 200 kg ha^{-1}

NPK: nitrogen, phosphorus, potassium.

Table 5. Chemical composition of the materials used in the experiments.

Parameter	Organic fertilizer of sugarcane filter cake	Parameter	Natural mineral	
			Gypsum	Limestone
N (%)	3.1	CaO (%)	26.00	
P (%)	1.9	MgO (%)	1.29	1.80
K (%)	1.2	SiO_2 (%)	5.87	
Ca (%)	1.4	S (%)	13.0	
OM (%)	41.0	Humidity (%)	0.6	0.5
C/N	8.2	$CaCO_3$ (%)		91.0
		$Ca(OH)_2$ (%)		5.0

as described by Vageler and Alten, (1931). Water-stable aggregates were determined using the methodology of Henin et al., (1958) and the plastic limit by the Atterberg rolls method, which is defined as the moisture content where the thread breaks apart at a diameter of 3 mm (Atterberg, 1911).

Statistical analysis

For statistical processing, the professional software package STATGRAPHICS Centurion XVI and IBM SPSS Statistics 25 were used. Simple classification ANOVA was applied with the TUKEY HSD mean comparison test, as well as linear regression techniques.

Conclusions

The use of gypsum, calcium carbonate, organic fertilizer and their combinations causes significant increases in the pH, organic matter and assimilable phosphorus, as well as in the structure and its stability. The study of the relationships between the physical and chemical properties and the cane yield showed high values of R^2 (51 - 72%) and a coefficient of determination of 0.68-0.94, which shows a high degree of significance and to the extent that the indicators of the properties studied increase the yields (CY in 104-141t ha^{-1} and SY in 18-25 t ha^{-1}). It was possible to demonstrate that the physical properties of the soil under these conditions are those that reached the closest relationships with the yield of cane and sugar. Evaluating the residual effect of organo-mineral fertilizers in the soil can be a great practical feasibility to optimize their use under sustainable agriculture conditions.

Disclosure statement

The author(s) did not report any potential conflict of interest.

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