Physical and chemical properties of soils irrigated with vinasses for the cultivation of sugarcane (*Saccharum* spp.) in the central region of Veracruz, Mexico

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ABSTRACT

Objective: To evaluate the physical and chemical properties of a soil irrigated with vinasse for two years (+V), compared with a soil without vinasse (−V) application.

Design/Methodology/Approach: The following parameters were evaluated for both agroecosystems: texture, pH, electrical conductivity (EC), organic matter (OM), phosphorus (P), potassium (K), nitrate $\left(N\text{-}NO_3^-\right)$, and total nitrogen (TN). The evaluation followed the standardized methods established in NOM-021-SEMARNAT-2000.

Results: There were no significant changes ($p>0.05$) in the soil's pH and electrical conductivity. However, the application of vinasse significantly increased ($p<0.05$) the concentrations of TN (1.52%), K (112.00 mg L^{-1}), and OM (4.52%) in relation to soils −V (0.78%, 25.60 mg L^{-1}, 7.40 mg L^{-1}, and 2.75%, respectively).

Study Limitations/Implications: There are few studies about the contributions and the physical and chemical effects of soil irrigation with vinasses in the State of Veracruz.

Findings/Conclusions: Even though vinasse had a positive effect on the physical and chemical characteristics of the soil, the mineral fertilization program must be reformulated to increase the K and P concentration in soils with silt loam texture. In addition, we recommend adjusting and normalizing the dose of N that vinasse can provide to complement conventional fertilizers.

Keywords: Soil fertility, Sugarcane, Vinasses.

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INTRODUCTION

Sugarcane has been cultivated in Mexico for over 450 years. At present, Mexico is the sixth world sugarcane producer, with an annual yield of 61 million tons. Fifteen Mexican states (261 municipalities) are involved in this activity. Together, they generate 11.6% of the primary sector value, equivalent to 0.4% of the gross domestic product (Sentíes-Herrera *et al.*, 2014; Pérez-Sánchez, 2017).

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The State of Veracruz has the greatest number of sugarcane mills (18 out of 50) and the largest cultivated area (284,000 ha) in Mexico (Pérez-Sánchez, 2017). It has the highest sugarcane production in the country. The four main cultivated varieties are CP 72-2086, MEX 68-P-23, MEX 69-290, and MEX 79-431, which contribute 42.82% to the national sucrose production and have an annual yield of approximately 110 ton ha^{-1} per variety (SAGARPA, 2016; SIAP, 2020; Vera-Espinosa *et al.*, 2016).

Some studies conducted in the central region of the state show that the La Gloria and San Nicolás sugar and alcohol mills produce nearly 33 million liters of bioethanol from sugarcane molasses distillate (Becerra-Pérez, 2009). It is estimated that for each liter of ethanol produced in the sugarcane agro-industry, 13 L of vinasse are generated (de Mello-Prado *et al.*, 2013), which results in an annual production of around 430 million L of this byproduct. Vinasse is a viscous liquid of acidic pH with a high electrical conductivity, a high chemical oxygen demand, and a high concentration of organic matter and nutrients, especially K, N, and P (España-Gamboa *et al.*, 2011).

The high volume of vinasses generated by the sugar industry has led to the research into various forms that the nutrients they contain can be used. In the central region of Veracruz, producers use vinasses to supplement conventional (inorganic) fertilization through irrigation. Although this practice favors crop yields, its implementation has not been welcomed by the general population. Blaming its unpleasant smell and occasional undesirable effects after its application, 68% of producers in Veracruz reject the use of vinasse on crops (Quiroz-Guerrero *et al.*, 2011). This social perception and its concomitant negative attitude could be related to the lack of a comprehensive management of vinasse as a byproduct of the sugar industry. They could also be the result of a lack of training and systematic research programs in the field, as well as of the lack of adequate assessments of the effects of vinasses on the soil's physical and chemical properties.

Consequently, the objective of this work was to determine the physical and chemical properties of a representative soil of the sugarcane agroecosystem in the central region of Veracruz (+V), comparing it with a control soil (−V). Reference properties are indicators of soil quality. Therefore, this study will lay the foundations for regional producers to establish, in the mid-term, adequate fertilization doses, subsequently optimizing the agronomic efficiency and effectiveness of N, P, and K in the production and quality of sugarcane.

MATERIALS AND METHODS

Description of the study area

The study was conducted in the municipality of Paso de Ovejas, Veracruz, Mexico (19° 08' and 19° 22' N; 96° 20' and 96° 38' W), located in the Microregion of Priority Attention (MAP) of the Colegio de Postgraduados Campus Veracruz (Figure 1). The municipality has 97 localities with a total area of 387.8 km^2, 263.3 km^2 of which are used for agriculture. Warm sub-humid climate predominates in the region (average humidity of 61%), with a temperature of 24-25 °C, and an average annual rainfall of 1,500 mm. Topographically, the altitude of region ranges from 10 to 400 m and is part of the sugarcane area of the State of Veracruz, with a cultivation area of 3,500.8 ha and an annual harvest of 357,076.5 tons (SIM, 2019).

Treatments and experimental design

Two similar plots located close together were selected for this study. Both have been cultivated with sugarcane for the last 30 years; one of them has a history of vinasse irrigation (+V) and the other one does not (−V) (Figure 1). The soil −V was treated twice a year with conventional fertilizers. The first application (NPK 20-10-20 fertilizer) was carried out after cutting. The second fertilization was applied with urea (46-00-00), forty days after the first fertilizer was applied. The vinasse-irrigated soil (+V) followed the same conventional fertilization arrangement as the soil −V; however, from 2018 onwards, vinasse was diluted in the irrigation water once a year, using the following method: five irrigations of 20 m^3 $plot^{-1}$ were carried out, with a one-hour interval between applications. Vinasse was applied after cutting and the conventional fertilizer was applied for the first time 20 days later. The sugarcane variety cultivated in the soil without vinasse (−V) was ColMex 95-27; meanwhile, the variety used in the soil with vinasse (+V) was CP 72-2086, an early maturing variety. The sampling, preparation, and analysis of the samples were conducted following NOM-021-SEMARNAT-2000 (SEMARNAT, 2000).

Determination of the physical and chemical parameters of soil samples

Physical and chemical parameters were determined for both soil samples. Phosphorus (P), potassium (K), and nitrate $\left(N\text{-}NO_3^-\right)$ were quantified by spectrophotometry using

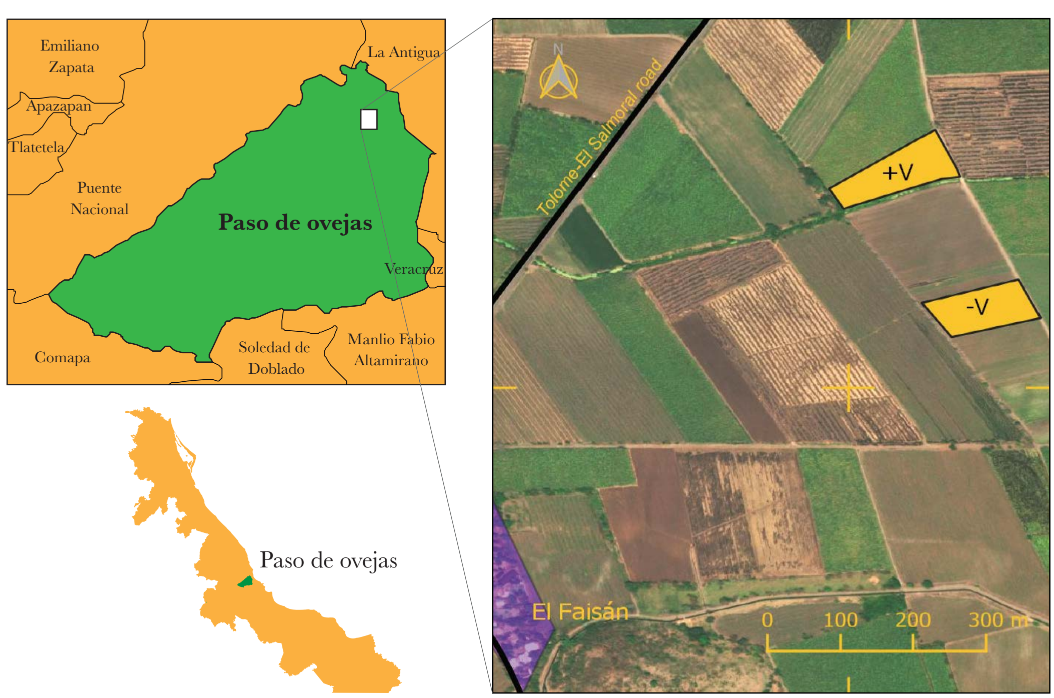

Figure 1. Location of the study plots, with (+V) and without vinasse application (−V), within the municipality of Paso de Ovejas, Veracruz, Mexico (QGIS 3.0).

a HI 83225 multi-nutrient analyzer (Hanna Instruments). According to the methods standardized in NOM-021-SEMARNAT-2000, the texture was determined using the Bouyoucos method; organic matter (OM) by wet combustion (Walkley and Black); and total nitrogen (TN) by the traditional Kjeldahl method. Potential hydrogen (pH) and electrical conductivity (EC) were measured using a potentiometer (Hanna Instruments) and a HI 2300 conductivity meter (Hanna Instruments), respectively.

Statistical analysis

An analysis of variance (ANOVA) was conducted for all assessed physical and chemical variables. A Tukey's test with a significance level of $p<0.05$ was carried out when significant differences were found between the means of both soils. Analyses were conducted using the InfoStat software.

RESULTS AND DISCUSSION

Table 1 presents the average values of the main physical and chemical properties determined in soils with (+V) and without (−V) a history of vinasse irrigation.

Applying vinasse did not modify the soil's physical properties. The analyzed soils had clay loam (−V) and silt loam (+V) textures. Although the use of soils with loam clay textures is recommended for the cultivation of sugarcane, producers in the central region of Veracruz have grown sugarcane efficiently in different soil types with no negative effects on production yields (Aguilar-Rivera, 2014). After the cultivation period, the sugarcane yield per hectare recorded for the cultivated varieties matched the potential mean values for the region (130 t ha^{-1} for ColMex 95-27 in soil −V and 105 ton ha^{-1} for early maturing CP 72-2086 in soil +V) (SAGARPA, 2016). Yield values are mentioned as a point of reference, since the relation between yields and the changes resulting from the application of vinasse was not measured.

The average pH of soils −V and +V remained in the neutral range (7.06-7.00, respectively), which indicates that the vinasse application combined with a conventional fertilization (commercial chemicals) during two consecutive years did not alter this

Table 1. Physical and chemical properties of sugarcane soils with (+V) and without a history of vinasse application (−V). Values belong to the mean ± standard error.

Parameter/Nutrient	Soil without vinasse irrigation (−V)	Soil with vinasse irrigation (+V)
pH (u. pH)	7.06 ± 0.03^{a}	7.00 ± 0.31^{a}
Electric conductivity (dS m^{-1})	0.435 ± 0.040^{a}	0.544 ± 0.085^{a}
Texture	Clay loam	Silty clay
Organic matter (%)	2.75 ± 0.10^{b}	4.52 ± 0.13^{a}
Phosphorus (P) (mg L^{-1})	5.20 ± 0.31^{a}	3.50 ± 0.14^{b}
Potassium (K) (mg L^{-1})	25.60 ± 6.73^{b}	112.00 ± 15.92^{a}
Nitrate $\left(N\text{-}NO_3^-\right)$ (mg L^{-1})	7.40 ± 1.24^{a}	1.75 ± 1.02^{b}
Total nitrogen (%)	0.78 ± 0.02^{b}	1.52 ± 0.05^{a}

Different letters in the same row indicate significant differences ($p<0.05$).

parameter. Similar trends regarding the pH's attenuation capacity were observed in other studies that applied 150, 300, and 450 m^3 vinasse ha^{-1} doses in sugarcane crops (Del Pino *et al.*, 2017). Likewise, Jiang *et al.* (2012) point out that no acidification was observed after three years of uninterrupted vinasse application in sugarcane crops. Nevertheless, the pH values in both studies were lower (5.1-5.4 and 4.89-4.93, respectively) than the results obtained in this work.

Although no pH variations were found in the soil +V, further research is needed to determine whether or not vinasses have a long-term effect on the pH of soils in the sugarcane agroecosystems of the central region of Veracruz. This would help to avoid soil acidification, since changes in the pH are more likely to become evident during longer application periods.

The differences between both soils regarding EC were not significant ($p>0.05$) (Table 1). The values found (0.435 dS m^{-1} in soil −V and 0.543 dS m^{-1} in soil +V) do not indicate salinity problems, since the saline effect is usually negligible when EC values are under 1 dS m^{-1} (NOM-021-SEMARNAT-2000). According to Soobadar (2014), for sugarcane yields to undergo a 10% decrease, EC values would have exceeded 1.7 dS m^{-1}.

In this study, the low EC was also reflected on the content of primary nutrients (*e.g.*, P and K). The P concentration fluctuated between 3.50 mg L^{-1} (+V) and 5.20 mg L^{-1} (−V); these levels are considered low for sugarcane cultivation. As was expected, the vinasse significantly increased ($p<0.05$) the concentration of K in relation to the control soil (−V). In spite of this, the values of K in soils +V (118 mg/L) fell below the requirements for the development of sugarcane in silty clay soils (156-295 mg L^{-1}). These results showed a deficiency in the P and K concentration that the plant can absorb (Del Pino *et al.*, 2017).

The sugarcane crop has a high nutrient demand, particularly of N (58.8-200 kg N ha^{-1}) P (33.3-172 kg P ha^{-1}), and K (86.4-417.5 kg K ha^{-1}) (Salgado *et al.*, 2006). The unavailability of these nutrients can cause a drop in sucrose contents (Salgado *et al.*, 2006; Guerrero-Peña *et al.*, 2017).

These results suggest that the mineral fertilization program should be reformulated to satisfy the P and K demand of the sugarcane soils in the central region of Veracruz, particularly during the second fertilization, when the applied fertilizer is based exclusively on urea (40N-00-00 composition).

Meanwhile, a positive effect was observed on the OM recovery when the soil was treated with vinasse. The concentration of OM in the soil +V was 4.52 mg L^{-1} (high level), a significantly higher value ($p<0.05$) than the control soil −V (2.75 mg L^{-1}, medium level). Some studies have shown that the uninterrupted application of low vinasse doses during periods of up to three years (as is the case of this study) can improve the soil's physical conditions —such as the compaction state (bulk density decreases while porosity increases)—, help to attenuate the soil's acidity (Jiang *et al.*, 2012, Sánchez-Lizárraga, 2018), and foster a greater nutrient mobilization (Neves *et al.*, 1983). As shown in Table 1, vinasse increased the percentage of OM and nutrients in the soil; both elements improve the crop's quality and fertility.

Regarding TN, vinasse is a byproduct with a low N content (0.1 g m^{-3}-0.73 g m^{-3}) (Carvalho *et al*., 2013; Silva *et al*., 2014); however, when a 100 m^3 ha^{-1} dose is added, the N content can reach 10-73 kg N ha^{-1} rates (Silva *et al*., 2015). Therefore, the contribution of vinasses, combined with conventional fertilization, reaches significant N levels. In this study, vinasse was a significant source of N ($p<0.05$), reaching levels well above those required by the crop. Therefore, an appropriate nitrogen fertilization program should be established in order to avoid the loss of this nutrient through volatilization, lixiviation, or denitrification processes.

The concentration of N in soils +V (1.52%) was two times higher than in soils −V (0.78%) that were treated only with conventional fertilizers. In spite of this contribution, the N released by vinasse seems to have been slow, probably due to the mineralization of different types of organic nitrogen (Del Pino *et al*., 2017). Alotaibi and Schoenau (2012) estimate that approximately 20% of the total N in vinasse is found as ammonium, a cation that, once absorbed, is immediately assimilated by sugarcane. However, the soil's neutral pH conditions suggest that part of the ammonium becomes ammonia. This transformation seems to indicate that volatilization could be the partial cause of the loss of ammonium in soil +V (CONADESUCA, 2008; Silva *et al*., 2015). This is directly related to the low nitrate concentration (1.75 mg L^{-1}) recorded in relation to the soil −V, where most N converted into nitrate (7.40 mg L^{-1}) through nitrification.

Finally, a residual effect from vinasse benefits the crop directly. It is a viable strategy to recycle nutrients and consequently reduce dependency on conventional fertilizers.

CONCLUSIONS

Vinasse combined with conventional fertilizers has several potential advantages for the soil's properties, such as an increase in the levels of K, TN, and OM. The application frequency did not cause salinity problems in soils with a silt loam texture. However, the fertilization scheme should be normalized to adjust the P and K concentration to the optimal levels for the cultivation of sugarcane. Applying 100 m^3 ha^{-1} doses of vinasse was a viable alternative for the supplementary conditioning and fertilization of the soil, since it provides a source rich in OM, water, and nutrients that meet the nutritional requirements of sugarcane at a low cost. Nevertheless, it is important to adjust the OM and TN levels in order to prevent their loss by volatilization, lixiviation, or denitrification processes which could contribute to the increase greenhouse gas emissions (particularly CO_2 and N_2O) or have a negative impact on superficial water and groundwater sources.

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