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Chemical attributes of an ultisol cultivated with sugarcane after application of high doses of vinasse

Atributos químicos de um argissolo cultivado com cana-de-açúcar após aplicação de doses elevadas de vinhaça

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ABSTRACT - The use of high doses of vinasse in sugarcane crop can cause modifications in the chemical characteristics of the soil. The aim of this study was to evaluate the effect of the application of high doses of vinasse on the chemical characteristics of an Ultisol cultivated with sugarcane for 210 days. The treatments used were doses equivalent to 0 (D0), 150 (D150), 300 (D300), 600 (D600) and 1200 (D1200) m^3 ha^{-1} of vinasse plus a control treatment with mineral fertilization. The experimental design was completely randomized with six treatments and six repetitions. Exchangeable potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na) contents, organic matter, cation exchange capacity, sodium adsorption ratio, exchangeable sodium percentage, electrical conductivity and pH were analyzed at 90, 120, 150 and 210 days after planting (DAP), in addition to microbial basal respiration at 210 days at depths of 0-0.20 and 0.20-0.40 m. Soil pH increased with the use of vinasse within the proper range for sugarcane, varying from 6.2 to 6.4. The highest K and Na contents were found at D600 and D1200; the highest K and Na availability occurred at 120 DAP and 150 DAP, respectively, indicating competition between these nutrients for exchange sites. Organic matter content was proportionally high according to the vinasse dose applied. D600 and D1200 doses increased Na content in the soil, with greater magnitude at the 0-0.20 m depth.

Keywords: Fertigation. Excess nutrients. Antagonism. Environment.

RESUMO - O uso de doses elevadas de vinhaça no cultivo da cana-de-açúcar modifica os atributos químicos do solo. Objetivou-se com o presente trabalho avaliar o efeito da aplicação de doses elevadas de vinhaça sobre características químicas de um Argissolo Amarelo cultivado com cana-de-açúcar. Os tratamentos consistiram na aplicação de doses equivalentes a 0 (D0), 150 (D150), 300 (D300), 600 (D600) e 1200 (D1200) m^3 ha^{-1} de vinhaça e mais uma testemunha. O delineamento experimental adotado foi inteiramente casualizado, com seis tratamentos e seis repetições. Avaliou-se a concentração de potássio (K), cálcio (Ca), magnésio (Mg) e sódio (Na) trocável, matéria orgânica, Capacidade de Troca Catiônica, Razão de Adsorção de Sódio, Porcentagem de Sódio Trocável, Condutividade Elétrica e pH aos 90, 120, 150 e 210 dias após o plantio (DAP), além da respiração basal microbiana aos 210 dias. O experimento foi conduzido em vasos com capacidade de 100 L. O pH do solo aumentou com a aplicação da vinhaça dentro da faixa considerada como adequada para a cana-de-açúcar, variando de 6,2 a 6,4. O K e Na apresentaram maiores concentrações em D600 e D1200; as maiores disponibilidades de K e Na no solo ocorreram, respectivamente, aos 120 e 150 DAP, indicando competição entre os elementos pelos sítios de troca. O teor de matéria orgânica foi proporcionalmente elevado conforme a dose de vinhaça aplicada. As doses D600 e D1200 aumentam a concentração de Na no solo, com maior magnitude na profundidade 0 – 0,20 m.

Palavras-chave: Fertirrigação. Excesso de nutrientes. Antagonismo. Meio ambiente.

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INTRODUCTION

Vinasse, a residue obtained in ethanol processing, is generated at a proportion 10 to 15 times greater than the fuel production (CHRISTOFOLETTI et al., 2013). According to data from CONAB (2021), the estimate of the national ethanol production in the first survey of the 2021/2022 season is 27 billion liters. This number gives an idea about the amount of waste generated and the need to know its applications and limitations in agriculture.

One of the chemical characteristics of vinasse is the predominance of potassium (K) over the other mineral elements used in the fertilization of sugarcane, followed by sodium (Na), calcium (Ca) and magnesium (Mg) (PAZUCH et al., 2017). Therefore, K content has been usually considered when defining the dose to be applied to plants, given that high doses of K^+ cause saturation of the exchange sites, problems of intoxication or luxury consumption by the plant, or even interfere in the absorption of other nutrients such as calcium and magnesium, which may generate situations of induced deficiency of these nutrients (MALAVOLTA, 2006).

Due to the characteristic concentration of mineral salts in vinasse, researchers such as Fuess, Rodrigues and Garcia (2017) and Pessoa-de-Souza et al. (2020) have observed other aspects besides the high concentration of K in the residue. They addressed the polluting potential of vinasse applied to the soil due to the high electrical conductivity and the contents of organic matter and macro- and micronutrients, especially potassium, which causes this residue to be used as fertilizer. However, when applied at high concentrations, it may cause leaching of excess ions, generating problems such as contamination of surface or subsurface springs. Sanchez-Lizarraga et al. (2018) stated that the application of vinasse with a dilution below 50% is already able to alter the electrical conductivity, K^+, Na^+, Mg^{2+} and Ca^{2+} ions and the availability of phosphorus and nitrogen in the soil.

Francisco et al. (2016) showed that vinasse doses from 300 m^3 ha^{-1} caused increments in the electrical conductivity of the soil and in nitrate and potassium contents. However, to date, no study has been found showing that the soil has undergone change in its classification to saline or sodic when subjected to vinasse application.

The increase in the contents of nutrients in the soil through the application of a certain dose of vinasse is beneficial to plants if the nutritional input of the dose corresponds to the nutritional requirement of the crop being fertigated. Otherwise, excess nutrient can cause toxicity or induced nutrient deficiency due to interactions that occur with the imbalance in their proportion in the residue.

The objective of this study was to evaluate the effect of the application of high doses of vinasse on the chemical characteristics of an *Argissolo Amarelo* (Ultisol) cultivated with sugarcane for 210 days.

MATERIAL AND METHODS

The study was carried out in a protected environment, between May and October 2019, at the Experimental Laboratory of Fertigation and Salinity of the Agricultural Engineering Department (DEAGRI) of the Federal Rural University of Pernambuco - UFRPE (Figure 1), Recife – PE, Brazil (8° 01’ 05” S and 34° 56’ 48” W), with an altitude of 6.49 m.

Figure 1. Location of the Experimental Laboratory of Fertigation and Salinity of the Agricultural Engineering Department (DEAGRI) of the Federal Rural University of Pernambuco (UFRPE), Pernambuco, PE, Brazil.

The experimental units consisted of 100-dm^3 plastic pots, which were filled with a 0.10-m-thick layer of crushed stone n° 0, followed by a nonwoven geotextile (Bidim) and then a 0.55-m-thick layer of soil, corresponding to 76.69 L of soil, leaving a 0.10 m free between the upper edge of the pot and the soil volume surface. The soil was carefully placed in the pot so as to obtain a porosity of 46.15% and a density of 1.4 g cm^{-3}, as observed under field conditions.

The soil used was classified as *Argissolo Amarelo distrocoeso abrupto* (Ultisol) with sandy clay texture, according to the classification of Santos et al. (2018), and was collected in a region of coastal tablelands (7° 51’ 13” S and 35° 14’ 10” W) in the Zona da Mata sub-region of the state of Pernambuco.

The soil material was collected at a depth of up to 40 cm and characterized (SILVA, 2009) for its physical-chemical parameters (Table 1). In general, the chemical characteristics of the soil were favorable to sugarcane development, so no corrections were required.

The experimental design adopted was completely randomized, with six replicates for treatments that received vinasse and three replicates for the two treatments that did not receive vinasse, totaling thirty experimental units. The treatments corresponded to the application of five increasing doses of vinasse - 0 (D0), 150 (D150), 300 (D300), 600 (D600) and 1200 (D1200) m^3 ha^{-1}, with no complementation of fertilization with mineral fertilizers (Table 2). A control treatment that did not receive doses of vinasse was established, using mineral fertilization as source of nutrients for plants, according to the recommendation of fertilization for sugarcane (CAVALCANTI, 2008), making it possible to compare the effects of the residue with a plant fertilized only with mineral nutrients.

The vinasse used in the treatments came from the Petribu Mill (7° 52' 47.1" S and 35° 13' 49.3" W) and was collected from the outlet pipe connecting the distillery to the distribution pond. Samples of the vinasse used were sent to a laboratory for physical-chemical analysis (SILVA, 2009) and showed pH of 4.2 and EC of 0.15 dS m^{-1}. In addition, the following results were obtained, in mg L^{-1}: 1,032.5 of carbon; 12,300 of biochemical oxygen demand (BOD_5); 27,250 of chemical oxygen demand (COD); 22,368 of total solids; 1,053 of potassium; 888.3 of calcium; 395.3 of magnesium and 729.1 of sodium.

Vinasse application in the soil was performed only once, twenty days before planting, so the input of nutrients was estimated based on the applied dose and characteristics of the vinasse.

Table 1. Physical-chemical characteristics of the *Argissolo Amarelo distrocoeso abrupto* (Ultisol) before vinasse application.

Parameters	Result	
	0-0.20 m	0.20-0.40 m
pH	5.80	5.60
K ($cmol_c$ dm^{-3})	0.09	0.06
Ca ($cmol_c$ dm^{-3})	1.75	1.25
Mg ($cmol_c$ dm^{-3})	0.75	0.75
Na ($cmol_c$ dm^{-3})	0.08	0.07
Al ($cmol_c$ dm^{-3})	0.05	0.15
P (mg dm^{-3})	8.00	5.00
H + Al ($cmol_c$ dm^{-3})	3.13	3.46
CEC[1] ($cmol_c$ dm^{-3})	5.80	5.59
t[2] ($cmol_c$ dm^{-3})	2.72	2.28
EC_{se}[3] (dS m^{-1})	0.098	0.099
SB[4] ($cmol_c$ dm^{-3})	2.67	2.13
V[5] (%)	46.03	38.03
m[6] (%)	2.00	7.00
ESP[7]	1.38	1.25
SAR[8]	0.07	0.07
Total sand (%)	75.50	73.85
Clay (%)	19.80	21.84
Silt (%)	4.70	4.31
Textural classification	Sandy loam	Sandy loam

[1]Cation exchange capacity; [2]Effective CEC (determined by the sum of bases plus exchangeable aluminum); [3]Electrical conductivity of saturation extract; [4]Sum of bases; [5]Base saturation; [6]Aluminum saturation; [7]Exchangeable sodium percentage; [8]Sodium adsorption ratio.

Table 2. Quantities of potassium (K_2O), calcium (Ca^{2+}), magnesium (Mg^{2+}) and sodium (Na^+) applied, equivalent to kg ha^{-1}, according to each dose in the experimental plots.

Dose	K_2O	Ca^{2+}	Mg^{2+}	Na^+
m^3 ha^{-1}	------------------------------------kg ha^{-1}--			
0	0	0	0	0
150	189	133.24	59.29	109.36
300	378	266.49	118.59	218.73
600	756	532.98	237.18	437.46
1200	1512	1065.96	474.36	874.92

The fertilization applied in the control treatment (mineral fertilization) consisted of NPK (14-24-18) at a total dose of 500 kg ha^{-1}, using ammonium sulfate as source of N, single superphosphate as source of P_2O_5 and potassium chloride as source of K_2O, following the recommendation of Cavalcanti (2008), in a total of 9 g of NPK per pot, using 1.26 g of ammonium sulfate, 2.16 g of single superphosphate and 1.62 g of potassium chloride. All mineral fertilization was applied as basal, with no need for top-dressing fertilization.

The water was applied manually, with watering on alternate days, starting on the day of planting. The applied water depth, equal for all treatments, was estimated based on the soil water balance, i.e., the difference between the applied volume and drained volume + 10%.

In the planting of sugarcane, cultivar RB867515, four setts containing one bud each were placed at 0.20 m depth, and thinning was performed at 30 days after planting (DAP), leaving three plants per pot.

As for the cultural practices, weeds were routinely removed and no phytosanitary problems were found throughout the experiment.

At 90, 120, 150 and 210 days after planting (DAP), soil samples were collected at the depths of 0-0.20 and 0.20-0.40 m and analyzed for potassium (K^+), sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), electrical conductivity of the soil saturation extract (EC_{se}) and organic matter (OM), in addition to the measurement of soil pH and estimation of CEC (cation exchange capacity), by summing the sum of bases and the potential acidity, SAR (sodium adsorption ratio), calculated considering the contents of sodium, calcium and magnesium, and ESP (exchangeable sodium percentage).

These parameters were analyzed using the soil saturation extract, following the methodology of Silva (2009). SAR and ESP were estimated following the recommendation of Ayers and Westcot (1985). At 210 DAP, microbial basal respiration ($C-CO_2$) was analyzed following the methodology of Silva, Azevedo and De-Polli (2007).

With the Mauchly's test, the result allowed evaluating the variables measured over time using the arrangement in split plots. Orthogonal contrast analysis and regression analysis were performed to assess the effect of each variable between treatments.

Analysis of variance (ANOVA) was performed to check which of the parameters evaluated were significant at 5% or 1% probability level.

Orthogonal contrast analysis was performed to compare mineral fertilization with treatments that received vinasse (MF vs. Vinasse (D150 to D1200)), mineral fertilization with no application of vinasse (MF vs. D0), mineral fertilization with a dose of 300 m^3 ha^{-1} (MF vs. D300), mineral fertilization with a dose of 1200 m^3 ha^{-1} (MF vs. D1200), and no application of vinasse with the application of vinasse (D0 vs. Vinasse (D150 to D1200)). To perform the regression analysis between the means, equations that best fitted the behavior of the data were created. Mineral fertilization was not considered in the fits of the equations.

RESULTS AND DISCUSSION

Exchangeable K and Na, SAR, ESP and EC were influenced ($p<0.05$) by the treatments × time interaction. The treatments related to vinasse doses caused significant variation ($p<0.05$) in pH, exchangeable Ca^{+2} and Mg^{+2}, and organic matter content in the soil. CEC was modified ($p<0.05$) over time, with significant influence ($p>0.05$) of the treatments, when analyzed individually (Table 3).

Table 3. Summary of the Analysis of Variance (ANOVA) and orthogonal contrasts for pH, exchangeable potassium (K^+), sodium (Na^+), calcium (Ca^{+2}) and magnesium (Mg^{+2}), Cation Exchange Capacity (CEC), Organic Matter content (OM), Sodium Adsorption Ratio (SAR), Exchangeable Sodium Percentage (ESP) and Electrical Conductivity of the Saturation Extract (EC_{se}) in an *Argissolo Amarelo distrocoeso abrupto* (Ultisol), cultivated with sugarcane and exposed to high doses of vinasse.

SV	Mean square										
	DF	pH	K^+	Na^+	Ca^{2+}	Mg^{2+}	CEC	OM	SAR	ESP	EC_{se}
Treat.	5	11.28**[1]	20.37**	10.81**	7.97**	3.72**	1.77^{NS}	3.88**	11.13**	14.83**	8.93**
Treat. × Time	15	1.54^{NS}	2.23*	2.70**	1.16^{NS}	0.84^{NS}	0.99^{NS}	1.47^{NS}	3.11**	4.18**	2.07*
	CV	3.28	48.11	40.02	11.90	26.16	8.80	8.84	37.35	32.48	74.44

*Significant at 5% probability level; **Significant at 1% probability level; NS not significant at 5% probability level; SV: sources of variation; Treat.: treatment; Time: time; DF: degrees of freedom; CV: Coefficient of variation; [1]F value.

An analysis of the mean of pH over the study period with sugarcane showed its variation from 6.2 to 6.4, indicating that the acidic character of vinasse did not contribute to soil acidification (Figure 2A), as the time of exposure of the soil to the residue was not sufficient to change this parameter. Freitas et al. (2017), when comparatively evaluating soil quality using chemical and physical attributes under different use and management systems, reported that most macro- and micronutrients are chemically available for absorption by sugarcane roots when soil pH is at 6.2.

There was an increase in soil pH only under the application of the doses D150 and D300 (Figure 2A). Doses above D300 indicate stability in the change of soil pH even with the increase in the vinasse dose applied, forming a plateau with broken line. Francisco et al. (2016), however, observed an increase in soil pH after applying doses of up to 578 kg ha^{-1}.

When analyzing the contrast MF vs. Vinasse (D150 to D1200), it was found that the Ca^{+2} content was significantly influenced ($p<0.05$), and significance ($p<0.05$) was also observed in the analysis of the contrast MF vs. D0, for exchangeable Ca^{+2} and organic matter content. After analyzing the contrast D0 vs. Vinasse (D150 to D1200), significance ($p<0.05$) was observed for pH, exchangeable Ca^{+2} and organic matter content (Table 4).

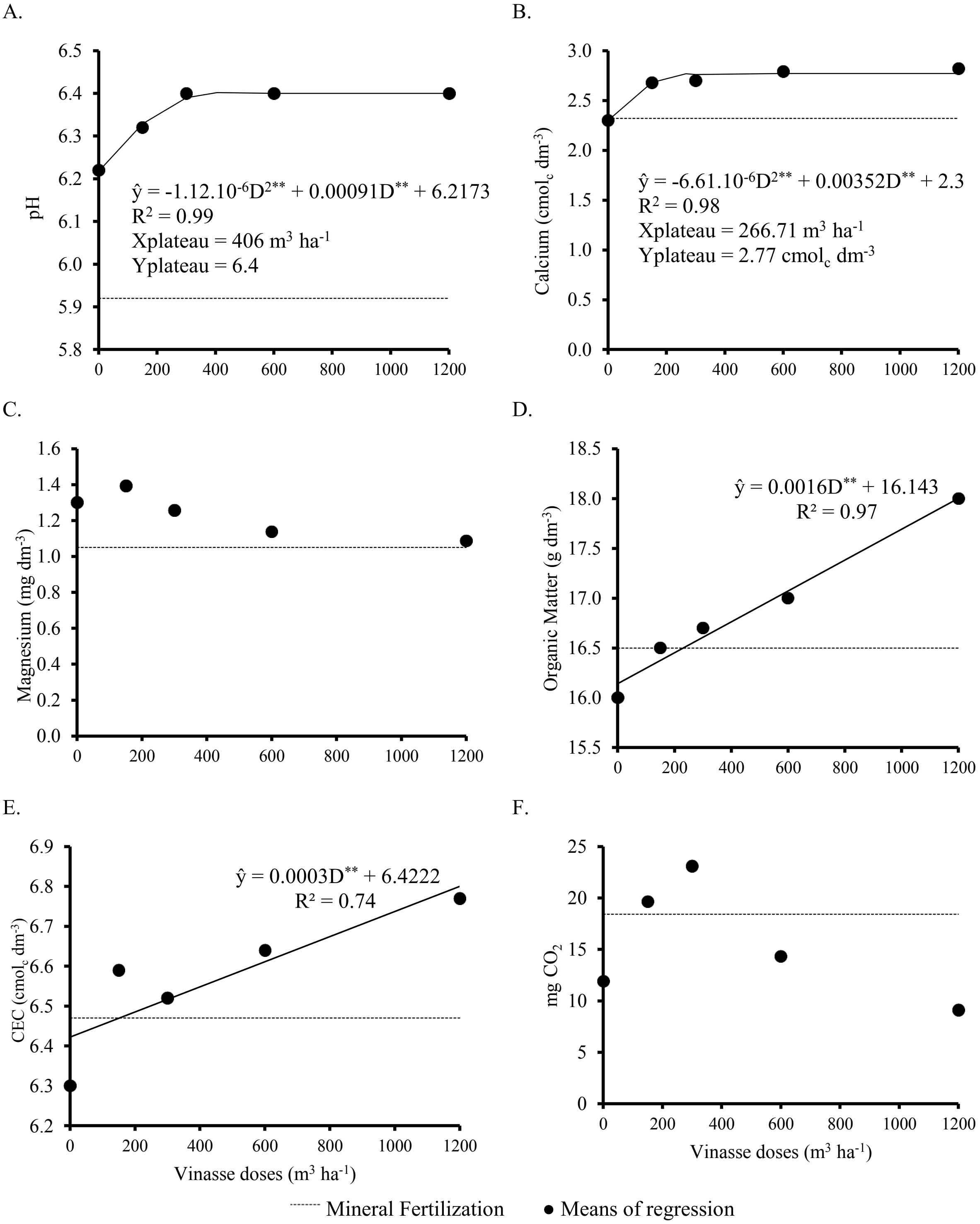


Figure 2. Mean values of pH (A), calcium (B), magnesium (C), organic matter (D), CEC (E) and microbial basal respiration (mg CO_2) (F) in an *Argissolo Amarelo distrocoeso abrupto* (Ultisol) cultivated with sugarcane and exposed to high doses of vinasse.

Table 4. Orthogonal contrasts for pH, exchangeable calcium (Ca^{+2}) and magnesium (Mg^{+2}), Cation Exchange Capacity (CEC), Organic Matter content (OM) and microbial basal respiration (mg CO_2) in an *Argissolo Amarelo distrocoeso abrupto* (Ultisol) with sandy clay texture, cultivated with sugarcane and exposed to high doses of vinasse.

Contrasts	Means					
	pH	Ca^{2+}	Mg^{2+}	CEC	OM	C-CO_2
		($cmol_c$ dm^{-3})	(mg dm^{-3})	($cmol_c$ dm^{-3})	(mg dm^{-3})	(mg CO_2)
MF	5.92	2.32	1.05	6.47	16.50	18.40
vs.	6.38	2.75	1.37	6.63	17.10	21.40
Vinasse (D150 to D1200)	NS	**	NS	NS	NS	NS
MF	5.92	2.32	1.05	6.47	16.50	18.40
vs.	6.22	2.30	1.40	6.30	16.00	11.90
D0	NS	**	NS	NS	*	NS
MF	5.92	2.32	1.05	6.47	16.50	18.40
vs.	6.40	2.70	1.40	6.52	16.70	29.89
D300	NS	**	NS	NS	NS	*
MF	5.92	2.32	1.05	6.47	16.50	18.40
vs.	6.35	2.82	1.29	6.77	18.00	19.39
D1200	**	NS	NS	NS	NS	NS
D0	6.22	2.30	1.40	6.30	16.00	11.90
vs.	6.38	2.75	1.37	6.63	17.10	21.40
Vinasse (D150 to D1200)	*	*	NS	NS	*	NS

*Significant at 5% probability level; **Significant at 1% probability level; NS not significant at 5% probability level.

For Ca^{+2}, it was observed that the soil showed a resistance to the increase in its content as the vinasse dose applied increased. Figure 1B shows that there was a plateau from the dose of 266.71 m^3 ha^{-1}, indicating a buffer capacity of the soil to this element, which affects the greater availability of this nutrient for plants. This behavior can be attributed to the interactions of Ca^{2+} with the K^+ and Na^+ ions present in the vinasse.

The magnesium applied via vinasse in the soil showed a higher content (1.23 mg dm^{-3}) than that found with mineral fertilization (1.05 mg dm^{-3}) (Figure 2C). However, there was no significant difference between the means in the contrasts, because in addition to being at a lower concentration in the vinasse compared to K^+, Na^+ and Ca^{2+}, it also has less interaction with the liquid and solid phases of the soil (CABRAL FILHO et al., 2018).

However, the high calcium concentration and low magnesium concentration is a trend that occurs in the chemical attributes of vinasse, since Nascimento et al. (2017) stated that applying up to 300 m^3 ha^{-1} of vinasse allowed an increase in calcium content in the soil, which was not observed for the magnesium content.

Magnesium, however, showed a significant difference as a function of the sampled soil depth, as presented in Table 5. Figure 3A shows that the magnesium content at the 0-0.20 m depth was higher than at 0.20-0.40 m. At the deeper depth, the maximum magnesium content was estimated at the dose of 571.43 m^3 ha^{-1}, corresponding to 1.25 mg dm^{-3}.

Table 5. Effect of treatments and treatment × depth interaction on pH, potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), Cation Exchange Capacity (CEC), Organic Matter (OM), Exchangeable Sodium Percentage (ESP) and Electrical Conductivity of the saturation extract (EC_{se}).

	F values								
	pH	K^+	Na^+	Ca^{2+}	Mg^{2+}	CEC	OM	ESP	EC_{se}
Treatments	2.62*	10.74**	9.52**	3.12*	2.79*	2.79*	7.13**	4.76**	3.61**
Treatments × Depth	0.97^{NS}	0.46^{NS}	0.53^{NS}	2.22^{NS}	5.78**	1.05^{NS}	3.52**	5.26**	1.87^{NS}

*Significant at 5% probability level; ** Significant at 1% probability level; NS Not significant at 5% probability level.

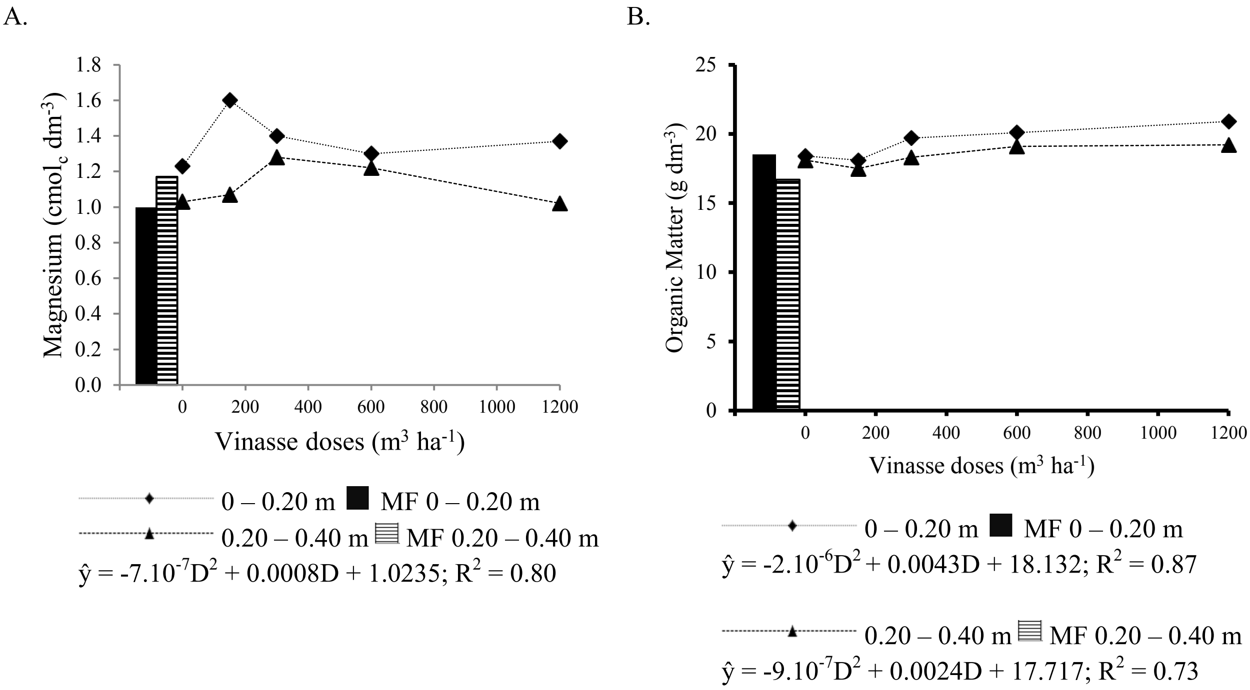


Figure 3. Effect of high doses of vinasse and mineral fertilization on magnesium and organic matter contents at depths of 0-0.20 and 0.20-0.40 m.

Through the orthogonal contrasts evaluated, Table 4, as well as Figure 2D, it can be affirmed that mineral fertilization and vinasse application were factors responsible for increasing the organic matter content in the soil compared to the absence of fertilization with the compound (D0). Yin et al. (2018) and Bento et al. (2019) also observed that vinasse and fertilizers composed of vinasse contributed to increasing organic matter content in the soil.

In relation to soil depth, the organic matter content at the 0-0.20 m depth was higher than at 0.20-0.40 m, because the highest concentration of organic matter is found in the most superficial layer of the soil (Figure 3B). At the 0-0.20 m depth, the maximum organic matter content was estimated at the dose of 1000 m^3 ha^{-1}, equivalent to 20.1 g dm^{-3}, and at the 0.20-0.40 m depth, the maximum was estimated at the dose of 1111.1 m^3 ha^{-1}, equivalent to 18.8 g dm^{-3}.

Through the CEC parameter (Figure 2E), an increase was observed in the contents of cations as the vinasse dose increased. The response similar to that observed for OM, according to Verdade (1956), is due to the organic fraction of the soil, which also contributes to the increase in cation exchange capacity, together with the mineral fraction of the soil.

Table 4 shows that the contrast MF vs. D300 was significant for microbial basal respiration (mg CO_2), indicating, with the aid of Figure 2F, that the difference is due to the mean observed at D300 (23.09 mg CO_2), which is higher than that found with mineral fertilization (18.41 mg CO_2). This result indicates that lower doses of vinasse enable microbial activity due to its lower concentration of salts. Moran-Salazar et al. (2016) stated that the organic compounds present in the vinasse, such as residual sugars, nutrients, melanoidins and polyphenols, are the ones that most affect the activity of microorganisms; however, the concentration of salts observed at the doses D600 and D1200 made the conditions in the soil unsuitable for better development of soil microorganisms.

Exchangeable potassium was influenced ($p<0.05$) by the treatment × time interaction (Table 3). After analysis, significance was observed for all contrasts and times of analysis (Table 6).

At 90 days after planting, difference was observed in the K content in the soil in the treatments that received vinasse when compared to mineral fertilization. In Figure 4A, the doses D300 and D1200 led to higher K content compared to MF, due to the concentration of K provided with these doses. At 120 days, K availability in the soil was maximal compared to the other sampling times, because, due to the growth of sugarcane, after this period, the plants absorbed the K available in the soil.

It was estimated that the dose of 1100 m^3 ha^{-1} was responsible for the highest K content in the soil, 1.29 $cmol_c$ dm^{-3}, because the soil used in this study was saturated with K^+ ions from this dose. The reduction of K between the doses D600 and D1200 was probably due to the leaching of the mineral, caused by the excess in the soil layers evaluated.

Table 6. Orthogonal contrasts for sodium ($cmol_c\ dm^{-3}$) and potassium ($cmol_c\ dm^{-3}$) at 90, 120, 150 and 210 days after planting of sugarcane as a function of mineral fertilization (MF) and vinasse doses ($m^3\ ha^{-1}$).

Contrasts	Means							
	------------------Sodium-------------				---------------Potassium---------------			
	90	120	150	210	90	120	150	210
MF	0.10	0.12	0.07	0.17	0.22	0.14	0.07	0.08
vs. Vinasse	0.32	0.16	0.18	0.32	0.26	0.62	0.42	0.42
(D150 to D1200)	NS	NS	*	NS	**	*	**	NS
MF	0.10	0.12	0.07	0.17	0.22	0.14	0.07	0.08
vs.	0.13	0.14	0.09	0.19	0.10	0.07	0.04	0.07
D0	**	NS	**	**	**	**	**	**
MF	0.10	0.12	0.07	0.17	0.22	0.14	0.07	0.08
vs.	0.33	0.17	0.13	0.23	0.24	0.67	0.38	0.32
D300	*	NS	NS	NS	**	**	**	NS
MF	0.10	0.12	0.07	0.17	0.22	0.14	0.07	0.08
vs.	0.35	0.14	0.24	0.43	0.33	0.65	0.58	0.59
D1200	NS	NS	NS	NS	**	NS	NS	NS
D0	0.13	0.14	0.07	0.19	0.10	0.07	0.04	0.07
vs. Vinasse	0.32	0.16	0.18	0.32	0.26	0.62	0.42	0.42
(D150 to D1200)	NS	NS	**	**	**	NS	**	**

*Significant at 5% probability level; **Significant at 1% probability level; NSNot significant at 5% probability level.

The K content of each treatment decreased after 120 days, due to consumption by sugarcane resulting from its development and to the possible leaching to greater depths of the pots, among other factors. Francisco et al. (2016), when evaluating the variation of K content in the soil, applying vinasse doses of up to 578 $m^3\ ha^{-1}$, found that there was a reduction in K content between 120 and 210 days after planting.

Yin et al. (2018) showed that the availability of K added to the soil through successive vinasse applications over 18 years contributed to a reduction in K content in the soil, possibly due to the consumption by sugarcane plants and mobility of the nutrient.

At 90 DAP, the Na content in the soil with D300 was higher than that obtained with MF; at 120 days, it can be observed in Figures 4A and 4B that, while the K content was high, the Na content was reduced, which may have occurred due to the competition for exchange sites between these two minerals, resulting from their similarity in some chemical properties (MALAVOLTA, 2006).

At 150 DAP, Na availability with the vinasse doses was higher than that obtained with MF, while there was a trend of increase from D300 because, due to the competition between K and Na, the high Na content at 150 DAP occurred only because of the low K content at this time (Figure 4B). Melo et al. (2016) observed that the Na content in the soil increased when 200 $m^3\ ha^{-1}$ of vinasse were applied.

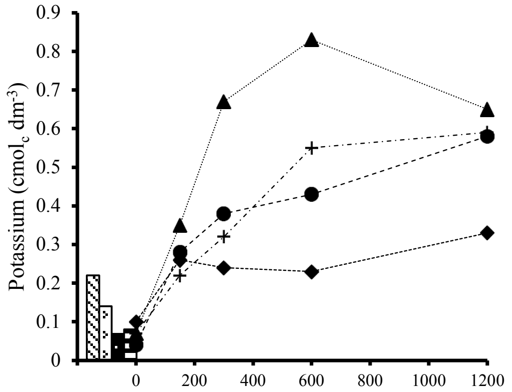
At 90 DAP, it was estimated that the highest Na content in the soil was obtained with the dose of 833.3 $m^3\ ha^{-1}$, corresponding to 0.37 $cmol_c\ dm^{-3}$; at 210 DAP, the maximum Na content in the soil was found with the dose of 1000 $m^3\ ha^{-1}$, equal to 0.43 $cmol_c\ dm^{-3}$.

As observed with K, the absence of increase in Na content at D1200 compared to D600 indicates that there was leaching of the mineral to deeper layers in the pot.

In the analysis of ESP, the behavior found was similar to that of sodium, implying that vinasse contributed not only to the increase in sodium content, but also to the adsorption of this mineral and to its saturation rate in the soil solution, since the contents of calcium and magnesium were low. Fuess, Garcia and Zaiat (2018) state that the sodium concentration present in vinasse can contribute to sodification when high doses of the residue are used.

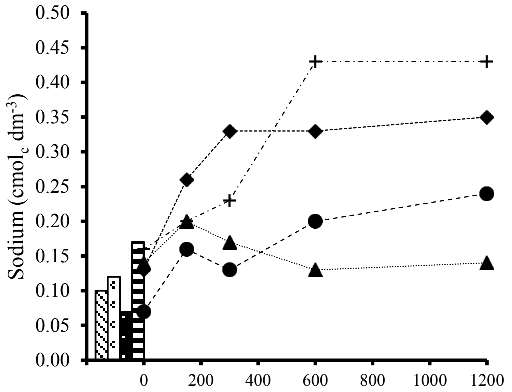
At 150 DAP, the ESP showed a significant difference between MF and vinasse (D150 to D1200) (Table 7), indicating that doses above D150 were sufficient to raise the ESP to an average higher than that obtained with MF (Figure 4C). Among the vinasse doses, the effect was significant at 150 and 210 DAP, when an increase in ESP was observed up to D600. The ESP increased in the soil as a function of both vinasse doses (above D300) and time (after 150 DAP).

A.



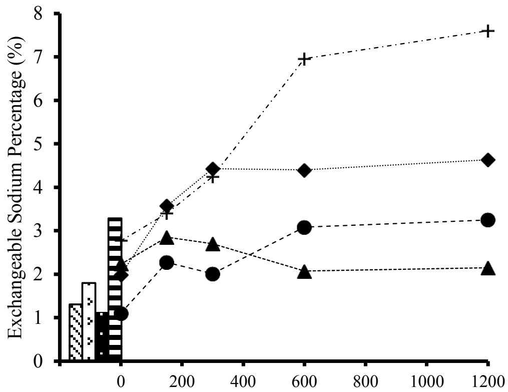
$\hat{y}^{90} = -10^{-7}D^2 + 0.0003D + 0.1526; R^2 = 0.64$
$\hat{y}^{120} = -10^{-6}D^2 + 0.0022D + 0.0802; R^2 = 0.98$
$\hat{y}^{150} = -4.10^{-7}D^2 + 0.0009D + 0.0949; R^2 = 0.92$
$\hat{y}^{210} = -6.10^{-7}D^2 + 0.0011D + 0.0617; R^2 = 0.99$

B.



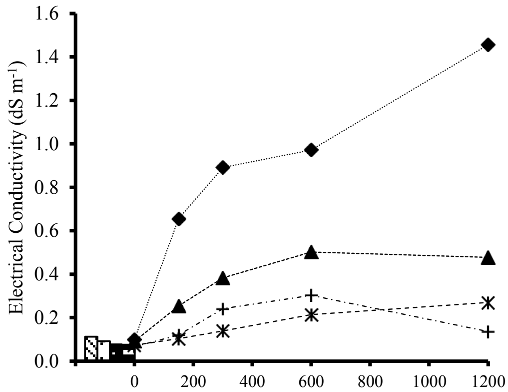
$\hat{y}^{90} = -3.10^{-7}D^2 + 0.0005D + 0.1605; R^2 = 0.86$
$\hat{y}^{150} = -10^{-7}D^2 + 0.0003D + 0.0866; R^2 = 0.87$
$\hat{y}^{210} = -3.10^{-7}D^2 + 0.0006D + 0.1314; R^2 = 0.91$

C.



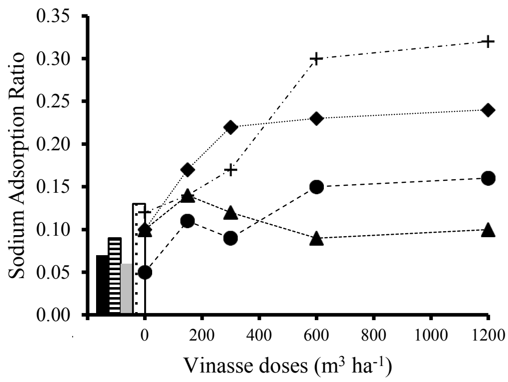
$\hat{y}^{90} = -4.10^{-6}D^2 + 0.0066D + 2.3643; R^2 = 0.85$
$\hat{y}^{150} = -2.10^{-6}D^2 + 0.0042D + 1.2583; R^2 = 0.90$
$\hat{y}^{210} = -4.10^{-6}D^2 + 0.0091D + 2.3936; R^2 = 0.96$

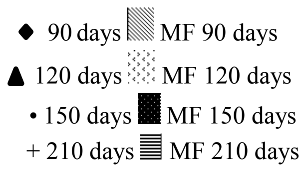
D.



$\hat{y}^{90} = -8.10^{-7}D^2 + 0.0002D + 0.2393; R^2 = 0.92$
$\hat{y}^{120} = -6.10^{-7}D^2 + 0.011D + 0.1015; R^2 = 0.99$
$\hat{y}^{150} = -1.10^{-7}D^2 + 0.0003D + 0.0673; R^2 = 0.99$
$\hat{y}^{210} = -6.10^{-7}D^2 + 0.0008D + 0.0507; R^2 = 0.96$

E.





$\hat{y}^{90} = -2.10^{-7}D^2 + 0.0003D + 0.1134; R^2 = 0.92$
$\hat{y}^{150} = -1.10^{-7}D^2 + 0.0002D + 0.0578; R^2 = 0.87$
$\hat{y}^{210} = -2.10^{-7}D^2 + 0.0004D + 0.0997; R^2 = 0.93$

Figure 4. Variation of potassium (A), sodium (B), ESP (C), EC_{se} (D) and SAR (E) over four periods as a function of doses of vinasse and mineral fertilization (MF).

Table 7. Orthogonal contrasts performed for the exchangeable sodium percentage (ESP) and electrical conductivity (EC_{se}) (dS m^{-1}) at 90, 120, 150 and 210 days after the beginning of sugarcane cultivation, as a function of mineral fertilization (MF) and vinasse doses (m^3 ha^{-1}).

Contrasts	Means							
	ESP				EC_{se}			
	90	120	150	210	90	120	150	210
MF vs. Vinasse (D150 to D1200)	1.31	1.80	1.13	3.29	0.11	0.092	0.08	0.07
	4.26	2.44	2.65	5.55	0. 99	0.40	0.18	0.19
	NS	NS	*	NS	NS	NS	NS	NS
MF vs. D0	1.31	1.80	1.13	3.29	0.11	0.09	0.08	0.07
	1.99	2.23	1.10	2.77	0.09	0.09	0.07	0.06
	**	NS	**	**	**	*	**	NS
MF vs. D300	1.31	1.80	1.13	3.29	0.11	0.09	0.08	0.07
	4.43	2.70	2.01	4.24	0.89	0.38	0.13	0.24
	*	NS	NS	NS	*	NS	NS	NS
MF vs. D1200	1.31	1.80	1.13	3.29	0.11	0.09	0.08	0.07
	4.63	2.15	3.25	7.60	1.45	0.47	0.26	0.13
	NS	NS	NS	NS	NS	NS	NS	NS
D0 vs. Vinasse (D150 to D1200)	1.99	2.23	1.10	2.77	0.09	0.09	0.07	0.06
	4.26	2.44	2.65	5.55	0.99	0.40	0.18	0.19
	NS	NS	**	**	**	NS	**	NS

[*]Significant at 5% probability level; [**]Significant at 1% probability level; [NS]Not significant at 5% probability level.

When evaluating the ESP in the first 0.40 m of the soil in the pot, it was noticed through Figure 5 that the exchangeable Na activity was higher at the most superficial depth; the doses responsible for the highest values of ESP at the depths of 0-0.20 and 0.20-0.40 m, respectively, were estimated at 1,137.5 and 930 m^3 ha^{-1}, with values of 7.57 and 6.03%. As the soil used in the study did not have an initially high sodium content, the amount incorporated through vinasse was sufficient to increase the content of this element and the parameters related to it (Figure 5).

At 90, 120 and 150 DAP, the difference in EC_{se} between the means of MF and D0 and between the means of D0 and vinasse (D150 to D1200) was significant (Table 7), indicating that the change in this parameter was caused by the vinasse doses applied. At 90 DAP, when the concentration of salts in the soil was higher, MF differed only from D300, and vinasse was responsible for the increase in EC_{se} (Figure 2D). Kheir and Kamara (2019) also observed an increase in the electrical conductivity of the soil treated with vinasse, attributing it to the presence of monovalent cations, especially sodium.

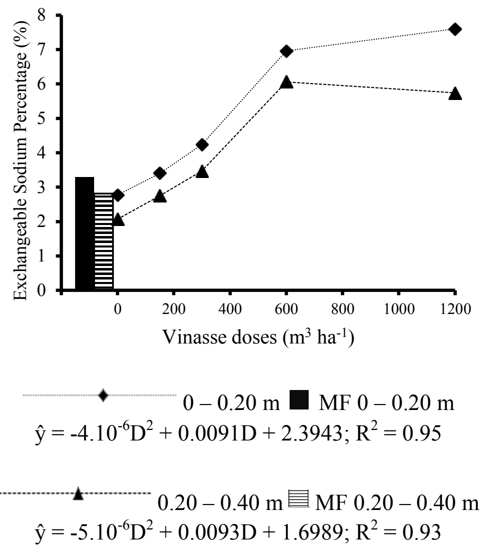


Figure 5. Evaluation of ESP at the depths of 0-0.20 and 0.20-0.40 m as a function of doses of vinasse and mineral fertilization (MF).

Regarding the effect of vinasse doses on EC_{se}, Figure 4D, there was a trend of increase according to the dose applied. Francisco et al. (2016) also observed that the electrical conductivity of the soil increased according to the volume of vinasse applied up to the dose of 576 m^3 ha^{-1}.

However, the decrease in the concentration of salts in the soil over time also reduces EC_{se} in an intensity corresponding to each dose, showing a trend of statistical equality between treatments.

When evaluating SAR, at 150 and 210 DAP, it was observed that vinasse was responsible for the higher sodium adsorption in the soil (Table 8), since the K content decreased at this time, reducing competition with sodium and allowing greater adsorption of this mineral on the exchange sites.

Table 8. Orthogonal contrasts performed for the sodium adsorption ratio (SAR) at 90, 120, 150 and 210 days after the beginning of sugarcane cultivation, as a function of mineral fertilization (MF) and vinasse doses (m^3 ha^{-1}).

	Means			
Contrasts	90	120	150	210
MF	0.07	0.09	0.06	0.13
vs.	0.21	0.11	0.13	0.23
Vinasse (D150 to D1200)	NS	NS	*	NS
MF	0.07	0.09	0.06	0.13
vs.	0.10	0.10	0.03	0.11
D0	*	NS	**	**
MF	0.07	0.09	0.06	0.13
vs.	0.22	0.12	0.09	0.17
D300	*	NS	NS	NS
MF	0.07	0.09	0.06	0.13
vs.	0.24	0.10	0.16	0.32
D1200	NS	NS	NS	NS
D0	0.10	0.10	0.03	0.11
vs.	0.21	0.11	0.13	0.23
Vinasse (D150 to D1200)	NS	NS	**	**

*Significant at 5% probability level; **Significant at 1% probability level; NSNot significant at 5% probability level.

The vinasse dose that promoted maximum SAR value at 90 DAP was estimated at 750 m^3 ha^{-1}, equivalent to 0.22; at 150 and 210 DAP, the dose that promoted maximum SAR value was estimated at 1000 m^3 ha^{-1}, with respective values of 0.16 and 0.30 (Figure 4E). The mean values of SAR corroborate Fuess, Rodrigues and Garcia (2017), who stated that vinasse usually does not cause sodification in the soil, hence being below the reference value cited by the authors of 15. However, Kheir and Kamara (2019) attribute the increase in SAR to the presence of sodium in the vinasse.

In general, it was observed that the consumption of nutrients by sugarcane as a function of vinasse application possibly caused a reduction in the contents of nutrients in the soil over the 210 DAP, with maximum K availability occurring at 120 DAP.

CONCLUSIONS

Vinasse doses of 300, 600 and 1200 m^3 ha^{-1} contributed to the increase of soil pH, but within a range tolerated by sugarcane, varying from 6.2 to 6.4.

The highest amount of exchangeable potassium and sodium in the soil was found in the period between 120 and 150 days, respectively, with the application of the doses of 600 and 1200 m^3 ha^{-1}.

Vinasse application in the soil increased the organic matter content proportionally to the increase in the dose.

Vinasse doses of 600 and 1200 m^3 ha^{-1} were not beneficial to the soil, as they cause higher sodium activity, especially at the 0-0.20 m depth.

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