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Can sewage sludge increase soil fertility and replace inorganic fertilizers for pineapple production?

O lodo de esgoto pode aumentar a fertilidade do solo e substituir adubos minerais na produção de abacaxi?

Pueden los lodos de aguas residuales aumentar la fertilidad del suelo y reemplazar los fertilizantes minerales en la producción de piña?

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Abstract
Sewage sludge from treatment plants is an important source of N and organic matter for agriculture. The objective of this study was to analyze the effect of sewage sludge and mineral fertilization on the soil chemical properties and production of five pineapple cultivars. The study was conducted in 2 x 5 factorial scheme, consisting of two different fertilizers (sewage sludge and mineral fertilizers), combined with five pineapple cultivars (‘Pérola’, ‘Vitória’, ‘Smooth Cayenne’, ‘MD-2’, and ‘IAC Fantástico’). Sewage sludge fertilization favoured soil fertility by promoting a decrease in the pH and increase in the content of soil organic matter, phosphorus, calcium, iron, and zinc, compared to soil with mineral fertilization. In pineapple plants, sewage sludge fertilization provided statistically similar yields and physic chemical fruit characteristics compared to mineral fertilization. Among cultivars, the ‘Smooth Cayenne’ presented the highest yield (125 t ha^{-1}), followed by cultivars ‘MD-2’ and ‘IAC Fantástico’, with intermediate yields of 98 and 90 t ha^{-1}. Cultivars ‘Pérola’ and ‘Vitória’ presented lower yields. In this context, it was observed that sewage sludge can be used in pineapple cultivars, as an alternative source of nutrients to partial replaces inorganic fertilization.
Keywords: Biosolid; Final disposal; *Ananas comosus* var. *comosus*; Pineapple cultivars.

Resumo
O lodo de esgoto proveniente de estações de tratamento é importante fonte de N e matéria orgânica aos cultivos agrícolas. Objetivou-se analisar o efeito do lodo de esgoto e da adubação mineral nas propriedades químicas do solo e produção de cinco cultivares de abacaxizeiros. O estudo foi conduzido em esquema fatorial 2 x 5, composto por dois diferentes fertilizantes (lodo de esgoto e adubação mineral), combinados com cinco cultivares de abacaxizeiro ('Pérola', 'Vitória', 'Smooth Cayenne', 'MD-2' e 'IAC Fantástico'). A adubação com lodo de esgoto favoreceu a fertilidade do solo ao promover diminuição no pH e aumentar os teores de matéria orgânica, fósforo, cálcio, ferro e zinco, em comparação ao solo que recebeu somente a adubação mineral. Nos abacaxizeiros, a produção e características físico-químicas dos frutos foram estatisticamente semelhantes entre os tratamentos com lodo e

adubação mineral. Dentre as cultivares avaliadas, a 'Smooth Cayenne' apresentou a maior produtividade (125 t ha^{-1}), seguidas, respectivamente da 'MD-2' e 'IAC Fantástico', com rendimentos intermediários de 98 e 90 t ha^{-1}. As cultivares 'Pérola' e 'Vitória' apresentaram os menores rendimentos. Nesse contexto, observou-se que o lodo de esgoto pode ser utilizado como fonte alternativa de nutrientes para o cultivo de abacaxizeiros, em substituição parcial à fertilização mineral.
Palavras-chave: Biossólido; Disposição final; *Ananas comosus* var. *comosus*; Cultivares de abacaxizeiro.

Resumen
Los lodos de depuradora de las plantas de tratamiento son una fuente importante de N y materia orgánica para los cultivos agrícolas. El objetivo de este estudio fue analizar el efecto de los lodos de depuradora y la fertilización mineral sobre las propiedades químicas del suelo y el rendimiento de cinco cultivares de piña. El estudio se realizó en un esquema factorial 2 x 5, compuesto por dos fertilizantes diferentes (lodos de depuradora y fertilizante mineral), combinados con cinco cultivares de piña ('Pérola', 'Vitória', 'Smooth Cayenne', 'MD-2' y 'Fantastic IAC'). La fertilización con lodos de depuradora favoreció la fertilidad del suelo al promover una disminución del pH y aumentar los niveles de materia orgánica, fósforo, calcio, hierro y zinc, en comparación con el suelo que solo recibió fertilizante mineral. En piña, la producción y características fisicoquímicas de los frutos fueron estadísticamente similares entre los tratamientos con fangos y fertilización mineral. Entre los cultivares evaluados, 'Smooth Cayenne' presentó la mayor productividad (125 t ha^{-1}), seguido respectivamente por 'MD-2' y 'IAC Fantástico', con rendimientos intermedios de 98 y 90 t ha^{-1}. Los cultivares "Pérola" y "Vitória" mostraron los rendimientos más bajos. En este contexto, se observó que los lodos de depuradora pueden utilizarse como fuente alternativa de nutrientes para el cultivo de la piña, en sustitución parcial de la fertilización mineral.
Palabras clave: Biosólido; Disposición final; *Ananas comosus* var. *comosus*; Cultivares de piña.

1. Introduction

Sewage sludge is a material abundant in organic matter and essential elements to plants that can be used in agriculture (Berton & Nogueira, 2010; Nicolás et al., 2014; Qayyum et al., 2015; Li et al., 2020; Rehman & Qayyum, 2020). Considering the importance of this crop to Brazil and regions with semiarid climate, the use of sewage sludge in pineapple farming may contribute to a reduction in the use of mineral fertilizers, increase soil fertility and the production of pineapple cultivars.

Soils located in regions of tropical climate are poor in nitrogen, phosphorus, and exchangeable bases, and agronomic practices are required in order to improve their chemical conditions for the planting of species of economic interest. In this sense, the application of sewage sludge has increased soil fertility and productivity in various crops, such as corn, barley, sugarcane, rice, and wheat (Latare et al., 2014; Nascimento et al., 2015; McCray et al., 2017; Bastida et al., 2019; Mohamed et al., 2019).

The use of sewage sludge in agricultural promotes the plant nutrition through the greater availability of N (Latare et al., 2014; Ociepa et al., 2017; Melo et al., 2018; Mohamed et al., 2019), a corrective effect of soil acidity, in addition to providing other nutrients for plants. According to Bittencourt et al. (2017), the sludge applied to agricultural areas in the state of Paraná provided 90% of limestone (PRNT 75%), 69% of nitrogen, 83% of P_2O_5 and 35% of the K_2O demanded by agricultural and forestry crops.

However, for pineapple crops, the use of sludge as a source of nutrients can alter the fruit production and quality intended for the juice production industry or in natura consumption, requiring new scientific information. The objective of this study was to evaluate the effects of sewage sludge and mineral fertilization on the soil chemical properties and production attributes of five pineapple cultivars.

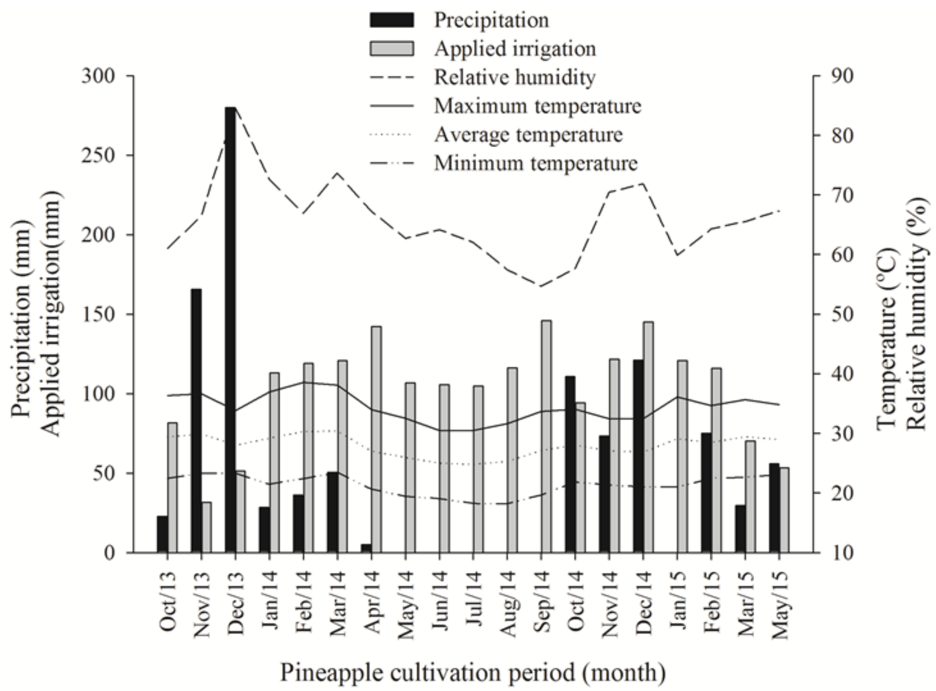
2. Methodology

The study was conducted in the experimental area of the Sewage Treatment Plant (ETE) of the Minas Gerais Sanitation Company (COPASA), in Janaúba-MG, located at 15º 43 '47.4 "S and 43º 19' 22.1" W, with an elevation of 516 m. According to the classification by Köppen (Alvares et al., 2013), the climate of the region is type "Aw" (tropical with dry winter). The monthly data on rainfall, irrigation water depth, relative humidity, and minimum, mean, and maximum temperature obtained by the meteorological station located at the experimental area are described in Figure 1.

The soil of the experimental area is as a Latossolo Vermelho eutrófíco according to the Brazilian Soil Classification System (Santos et al., 2018a). The treatments were arranged in a randomized block design with four replications, in a 2 x 5 factorial scheme, consisting of two different fertilizers - sewage sludge (SS) and mineral fertilization (MF) - and five pineapple cultivars (‘Pérola’, ‘Vitória’,‘Smooth Cayenne’,‘MD-2’, and‘IAC Fantástico’).

At planting, the pineapples received 3 g per plant of P2O5 in the form of single superphosphate (Cardoso et al., 2013). In the vegetative period, the plants of the treatments with mineral fertilization received 15 g per plant of N and K in the form of urea and potassium sulfate, respectively, in four plots, as proposed by Cardoso et al. (2013).

Figure 1. Precipitation, irrigation depths, relative humidity, maximum, mean and minimum monthly temperature obtained in the municipality of Janaúba, state of Minas Gerais, for the pineapple cultivation period.



Source: INMET (2020).

In the treatment with sewage sludge, the equivalent nitrogen dose (15 g per plant) was applied after the chemical characterization of the sludge (Table 1) and the calculation of the available N. The available N content was calculated by the sum of the N in the mineral form (N-NH_4^+ + N-NO_3^-), originally contained in the sewage sludge, with the 20% mineralized organic N fraction (MF), as proposed by Berton & Nogueira (2010). The total dose of sludge corresponded to 2.16 kg of SS per plant (15 g per plant of available N), divided into four interventions (according to mineral fertilization), comprising 60 days. A supplementary fertilization with 15 g of K_2O per plant in the form of potassium sulfate was also provided.

Table 1: Chemical characteristics of the sewage sludge used in the study.

pH	[1]CO	[2]N	[3]P	[3]K	[3]Ca	[3]Mg	[3]S	[3]Na	
H_2O	-- g kg^{-1} --								
5.4	180.0	33.0	7.6	3.2	13.0	2.3	11.8	0.1	
[3]Zn	[3]Fe	[3]Mn	[3]Cu	[3]B	[3]Cd	[3]Pb	[3]Cr	[3]Ni	C/N
-- mg kg^{-1} --									g g^{-1}
950.0	24293.0	152.0	14.0	5.8	5.2	69.1	143. 2	22.1	5.5

[1] Carbon, determined by the Walkley-Black method; [2]N - Kjeldahl method; [3]Total contents obtained by extraction in nitro-perchloric solution. Source: Authors.

The planting was performed in double rows, in a 0.90 x 0.40 x 0.20 m spacing (totaling 76,923 plants ha^{-1}), as recommended by Cardoso et al. (2013) for the 'Vitória' pineapple. The experimental units consisted of three double rows (six rows per plot) and ten plants in the row, totaling 60 plants per plot, out of which 12 useful plants were selected from the central rows for experimental evaluation.

The micro-sprinkler irrigation system was managed with a two-day irrigation shift, using the Irriplus® app, which determines the water demand of the pineapple (ETc) using the Hargreaves-Samani model (Mantovani et al., 2009) for the calculation of the ET0; the application was fed by meteorological data collected at a station located close to the experiment.

To evaluate possible changes in the soil chemical attributes, after fertilization, soil samples were collected in two growing seasons: before the treatments, representing the initial condition of the soil (IC), and after the last application, representing the final condition (FC) after harvesting the pineapples. In each plot, soil samples were collected (auger) at the 0-0.20; 0.20-0.40, and 0.40-0.60 m depths. Four subsamples were collected (0.1 m from the planting line) to form a composite sample. Afterward, the soil samples were air-dried, ground, and sieved with a 0.002 m mesh sieve, thus obtaining the air-dried fine soil (ADFS). The following characteristics were quantified in the ADFS: pH(H_2O), P, K, Ca, Mg, Zn, Fe, Mn, and Cu, according to the method described by Embrapa (2017); the total organic carbon was quantified by the wet oxidation method with external heating (Yeomans & Bremner, 1988).

The floral induction of the plants was performed 340 days after planting with 50 mL of a 1% Ethrel® solution added with calcium hydroxide (lime) at a dose of 0.35 g $L^{-}1$ water (Reinhardt, Souza, and Cabral, 2001). At that time, "D" leaf samples were collected to characterize the fresh mass (FMD).

The pineapple harvest (12 fruits per plot) was performed when the fruits presented more than 70% of the peel with a yellow color. The following characteristics were evaluated: fruit mass with crown (FMWC) and without crown (FMC); fruit length (FL), and fruit diameter (FD).

The sampled fruits were subjected to the postharvest analysis of the following characteristics (AOAC, 2016): titratable soluble solids (TSS) by refractometry, using an Atago digital refractometer, model N-1α, with results expressed in °Brix; titratable acidity (TA) by titration with sodium hydroxide (0.1mol L^{-1}), using 1% phenolphthalein as an indicator, with results expressed in mg of citric acid per 100 mL^{-1} of juice; pH, measured in anautomatic potentiometric titrator; fruit pulp color parameters: luminosity (PL) and Hue color angle (HA), which indicates the color of the pulp in spectrophotometry (model Color Flex EZ Spectrophotometer), with a direct reflectance reading of the L* (luminosity), a* (red or green tint) and b* coordinates (yellow or blue tint) of the Hunter Lab Universal Software system. The Hue angle (°H*) was calculated based on the values of L*, a*, and b*; peel firmness (SF) and pulp firmness (PF) were determined using a Fruit Pressure Tester FT 327 penetrometer, with results expressed in Newtons (N). For each replication, the mean of four measurements per fruit was used.

The data were subjected to analysis of variance by the F test ($p <0.05$) using the SISVAR® statistical software (Ferreira, 2019). The means were compared by the Scott-Knott test. We also checked for differences between treatments by applying the canonical discriminant analysis (CDA). With Wilks' Lambda test, we assessed the significance of the multivariate effects. The analyses of graphs, standardized canonical coefficients (SCC), and correlation coefficients (r), as well as the two coefficients related to the parallel discrimination rate (PDRC = SCC x r) (Baretta et al., 2005), provided information to determine which soil characteristic better discriminated between fertilizer treatments.

3. Results and Discussion

3.1 Changes in soil chemical properties

The chemical properties of the soil in the 0-0.20, 0.20-0.40, and 0.40-0.60 m layers were influenced ($p \leq 0.05$) by the types of fertilization at the end of the pineapple cultivation period (FC) and by the time of soil usage at the end of the cultivation, compared to the initial sampling (IC). The different pineapple cultivars did not interfere with soil properties.

The soil pH at the end of the cultivation cycle, in both treatments (MF and SS), showed a significant decrease of up to 0.40 m in depth compared to the soil pH at the beginning (IC) of pineapple cultivation (Table 2). Some factors may have contributed to this, such as the use of uncured sewage sludge with acidic pH (Table 1), sludge decomposition, and the application of the nitrogen fertilizer (urea) with an acidifying effect on the soil.

The fertilization with urea increases the NH_4^+ content in the soil and intensifies the nitrification process, releasing 2-4 moL of H^+ for each mole of NH_4^+ in the soil solution, causing a reduction in soil pH (Tong & Xu, 2012; Latifah et al., 2018). Sewage sludge decomposition throughout the cultivation time also favors soil acidification, as it contributes to the release of carbonic acid and non-metal oxides, such as SO_4^{2-} and NO_3^-, which can form acids with water (Ociepa et al., 2017). However, several studies have reported increases in soil pH after fertilization with sewage sludge (Bittencourt et al., 2012; Latifah et al., 2018), as a result of the use of alkalinizing agents, such as CaO or $Ca(OH)_2$, in the process of elimination of pathogens and residue stabilization. Therefore, the extent of pH changes depends on the texture and buffer capacity of the soil, as well as the type of sludge stabilization treatment.

Table 2. Chemical properties of the soil at the beginning (IC) and end (FC) of the cultivation period, and changes in the chemical attributes at the end of the growing period after fertilization with sewage sludge (SS) and mineral fertilizers (MF) in the 0-0.20; 0.20-0.40, and 0.40-0.60 m depth layers.

Properties	Colect	Soil layers					
		0 – 0.20 m		0.20 – 0.40 m		0.40 – 0.60 m	
		SS	MF	SS	MF	SS	MF
pH (H_2O)	Ci	5.63Aa	5.81Aa	5.37Aa	5.31Aa	5.10Aa	5.06Aa
	Cf	4.69Ab	4.70Ab	4.65Ab	4.70Ab	4.96Aa	5.06Aa
#Increment (%)		-16.60	-19.10	-13.40	-11.40	-2.70	-3.50
[1]TOC(g kg^{-1})	Ci	8.10Ab	9.70Ab	7.50Ab	6.70Ab	5.40Ab	5.20Ab
	Cf	26.40Aa	12.30Ba	12.40Aa	10.20Ba	7.20Aa	6.87Aa
#Incremento (%)		225.90	26.80	65.30	55.20	33.30	32.10
[2]P(mg dm^{-3})	Ci	2.67Ab	2.41Aa	1.40Ab	1.80Aa	0.30Aa	0.66Aa
	Cf	11.18Aa	2.16Ba	3.62Aa	2.26Ba	0.40Aa	0.85Aa
#Increment (%)		318.70	-10.30	158.50	25.50	33.30	28.70
[2]K (mg dm^{-3})	Ci	31.10Ab	20.40Ab	37.70Ab	20.90Ab	34.50Ab	23.20Ab
	Cf	240.00Aa	269.40Aa	211.20Aa	198.80Aa	140.90Aa	141.80Aa
#Increment (%)		671.60	956.60	721.70	698.30	475.10	511.20
[3]Ca(cmol$_c$ dm^{-3})	Ci	1.25Ab	1.41Aa	1.45Ab	1.47Aa	1.82Aa	1.80Aa
	Cf	2.28Aa	1.63Ba	2.11Aa	1.61Ba	1.93Aa	1.84Aa
#Increment (%)		68.80	33.50	50.70	13.80	13.90	-28.70
[3]Mg (cmol$_c$ dm^{-3})	Ci	1.19Aa	1.08Aa	1.21Aa	1.02Aa	0.98Aa	0.77Aa
	Cf	1.20Aa	1.30Aa	1.07Aa	1.01Aa	0.84Aa	0.92Aa
#Increment (%)		-1.60	-1.70	0.90	-0.90	-8.60	-27.90
[2]Fe (mg dm^{-3})	Ci	16.10Ab	14.00Aa	15.10Bb	14.20Ab	15.20Bb	13.80Ab
	Cf	125.70Aa	65.10Bb	89.90Aa	65.80Ba	69.70Ba	55.90Aa
#Increment (%)		680.80	365.00	495.30	363.30	358.50	305.00
[2]Cu (mg dm^{-3})	Ci	1.31Aa	1.08Aa	0.82Aa	1.10Aa	1.01Aa	0.98Aa
	Cf	1.19Aa	0.90Aa	0.77Aa	0.90Aa	0.87Aa	0.76Aa
#Increment (%)		-9.10	-16.60	-6.00	-18.10	-13.80	-22.40
[2]Zn (mg dm^{-3})	Ci	1.67Ab	1.27Aa	1.00Ab	0.75Aa	1.13Aa	1.72Aa
	Cf	6.80Aa	0.91Ba	3.53Aa	0.91Ba	1.17Aa	1.65Aa
#Increment (%)		307.10	-28.20	253.40	21.30	3.50	-4.00
[2]Mn (mg dm^{-3})	Ci	33.30Ab	31.70Ab	27.20Ab	26.00Ab	22.30Ab	38.40Ab
	Cf	65.20Aa	51.80Aa	51.80Aa	41.10Aa	51.00Aa	59.10Aa
#Increment (%)		95.70	63.40	90.40	58.00	128.60	53.90
[4]SB (cmol$_c$ dm^{-3})	Ci	2.52Ab	2.49Ab	2.78Ab	2.54Ab	2.87Aa	2.63Aa
	Cf	4.09Aa	3.62Aa	3.72Aa	3.13Aa	3.19Aa	3.21Aa
#Increment (%)		62.30	45.30	33.80	23.20	14.60	9.50
[5]CEC (cmol$_c$ dm^{-3})	Ci	3.93Ab	3.80Ab	4.30Ab	4.40Aa	4.61Aa	4.34Aa
	Cf	5.84Aa	5.18Ba	5.15Aa	4.54Ba	4.67Aa	4.57Aa
#Increment (%)		48.60	36.30	19.70	3.10	1.30	5.30
[6]V (%)	Ci	64.30Aa	65.80Aa	64.10Aa	57.40Aa	61.20Ab	60.30Ab
	Cf	70.80Aa	70.00Aa	72.20Aa	68.00Aa	69.90Aa	70.60Aa
#Increment (%)		10.10	6.38	12.64	18.47	14.21	17.08

Means followed by the same capital letter in the row and lowercase in the column do not differ from each other by the F-test at 0.05 of significance. [1]Total organic carbon (TOC) determined by titrating with ferrous sulfate; [2]Extractor: Mehlich1; [3]Extractor: KCl 1 mol L^{-1}; [4]Sum of bases (SB); [5]Cation exchange capacity (CEC); [6]Saturation by bases (V); #Increment: $\frac{(FC-IC)}{IC}x100$. Source: Authors.

The application of SS increased the total content of soil organic carbon (TOC) by 225, 65, and 33% at the 0-0.20; 0.20-0.40, and 0.40-0.60 m depths, respectively, at the end of the pineapple cultivation cycle (Table 2). These results corroborate those described by Nicolás et al. (2014), who observed increase rates between 100 and 120% after sludge fertilization in soils with low carbon content (<1 g kg^{-1}). In the MF treatment, an increase in the TOC content was also observed for all layers, although rating only 26, 55, and 32% at the 0-0.20; 0.20-0.40, and 0.40-0.60 m depths, respectively, compared to the initial growing period. These results can be attributed to the release and decomposition of plant residues of the pineapple root system, as well as to the deposition of weeds after performing the cultural treatments.

The fertilization with SS resulted in an increase of 318 and 158% in the P content in the soil in the 0-0.20 and 0.20-0.40 m depth layers, respectively (Table 2). Rehman & Qayyum (2020) and Qayyum et al. (2015) also reported an increase in thesoil phosphorus content in response to the addition of sludge, considering the high concentration of this element in the material, the reduction in the specific adsorption of phosphates present in the soil, and the increased bioavailability. The addition of organic compounds favors the formation of functional clusters with negative surface charges in the organic matter of tropical soils (Muraishi et al., 2011). This phenomenon facilitates the formation of organomineral bonds with the solid phase of the soil (oxides) and blocks the adsorption sites, increasing the solubility of the phosphate anion (Andrade et al., 2013).

The treatments with SS and MF provided an increase of the K content in all soil layers (Table 2). This increase occurred as a consequence of the potassium fertilization performed by topdressing during the pineapple cultivation. Similarly, there was an increase in the Ca content in the soil fertilized with SS in the 0-0.20 and 0.20-0.40 m layers, with values of 68 and 50%, respectively. The Mg content, on the other hand, was not influenced by the treatments.

The Fe and Zn contents were higher in the SS treatment in the 0-0.20 and 0.20-0.40 m depth layers. The increase was equivalent to 680 and 495% for the Fe content, and 307 and 253% for the Zn content, respectively (Table 2). These results were attributed to the presence of high levels of Fe and Zn in the SS (24,293 mg kg^{-1} of Fe and 950 mg kg^{-1} of Zn). Furthermore, the formation of organomineral complexes between metals and humic compounds of the SS favors the displacement of Fe and Zn in the soil profile (Hashemimajd & Somarin, 2011). It is worth noting that the concentration of Zn does not constitute a restrictive factor for the agricultural use of sludge since the Zn concentration obtained was below the limit of 2,800 mg kg^{-1} (Brazil 2006).The increase in the content of soil Zn, after the use of sewage sludge, has been often reported in the literature (Latare et al., 2014; Nascimento et al., 2015; Li et al., 2020).

The Cu content in the soil was not influenced by the treatments at any of the evaluated depths (Table 2). However, the soil Mn content increased in the treatments with SS and MF, after the end of the growing cycle, compared to the Mn contents found at the beginning of the cultivation, in all soil layers. The increase in the contents of exchangeable Mn, both in the soil fertilized with sludge and in the soil fertilized with mineral fertilizers, was attributed to the presence of this element in the sludge and the possible solubilization of native soil Mn as a result of the presence of a reducing environment created by the use of irrigation. The constant use of irrigation can favour the reduction of Mn^{3+} (manganite) to Mn^{2+}, increasing its content in the soil. (Carvalho Filho et al., 2011).

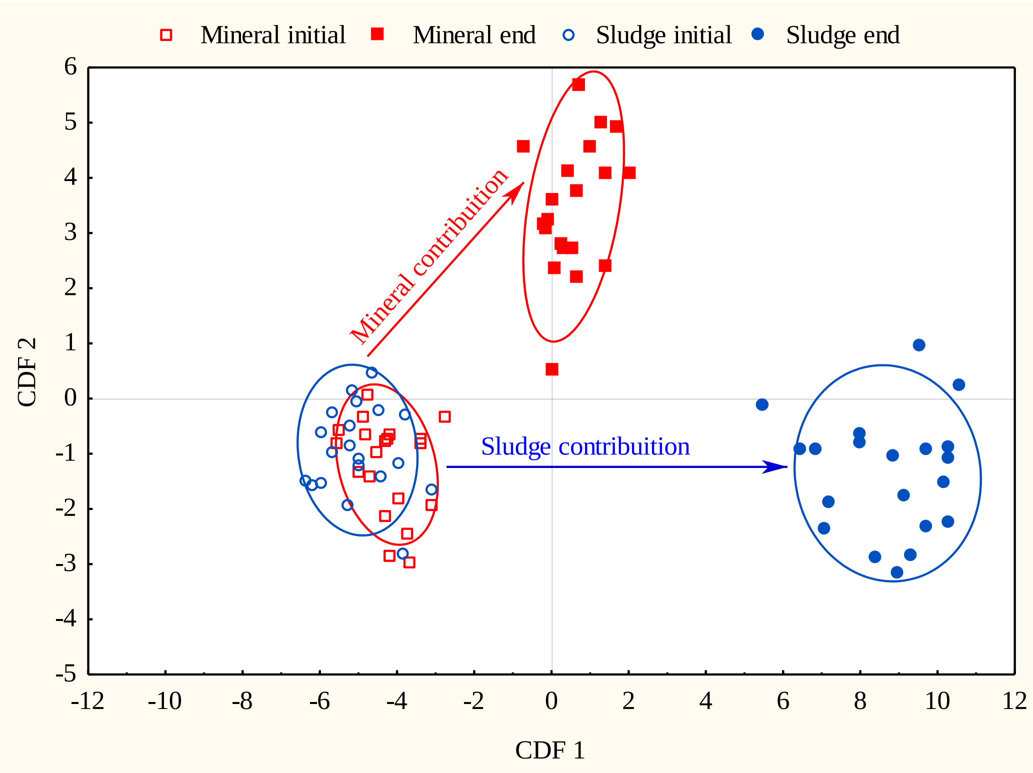
In the 0-0.20 and 0.20-0.40 m depth layers, there was an increase in the sum of bases, mainly determined by the addition of Ca and K in the treatment with SS and the addition of K in the treatment with MF (Table 2). In the 0-0.20 and 0.20-0.40 depth layers, the cation exchange capacity (CEC) increased similarly in the treatment with SS and the treatment with MF, although in a lower magnitude in the first.

The increase of the CEC after the slurry fertilization becomes extremely important for soils with low CEC and low organic matter contents, a prevailing condition in regions of tropical climate and semiarid regions, especially poor in organic matter. The increment of soil organic matter after sewage sludge fertilization provides positive effects on soil attributes and pineapple production (Maia et al., 2020), such as: a) increased soil aggregation, b) lower soil compaction, c) reduction of soil loss by erosive processes, d) increased soil water availability, e) increased microbiological activity (bacteria, fungi, and actinomycetes), f) promotion of nutrient transportation to the roots, g) greater growth and deepening of the root system in the soil profile, h) increased use efficiency of water and nutrients by plants, and i) higher chlorophyll content, shoot and fruit growth, etc.

Base saturation (V%) was not significantly influenced by the types of fertilization in the first layers (0-0.20 and 0.20-0.40 m depth). However, in the last layer, there was an increase in the base saturation of soils treated with the two types of fertilization, and this alteration was mainly attributed to the increase in the yield of the fertilizer (Table 2).

Multivariate analysis using canonical discriminants allowed to obtain the following observations for the soil chemical attributes in the 0-20 cm layer: The canonical discriminant function (CDF) 1 contributed with 87% of the discrimination between fertilization managements (Figure 2, Table 3). Sludge fertilization obtained the highest eigenvalues in comparison to mineral fertilization, and the chemical attributes that contributed the most to this discrimination were total organic carbon (TOC), total CTC, phosphorus, potassium, and iron. These attributes, presented in Table 3, had higher PDRC values and were always greater than 0.1, which is taken as the minimum for good discrimination (Azevedo Junior et al., 2019), indicating that sludge fertilization increases most of the chemical attributes of the soil over time in pineapple cultivation.

Figure 2. Standardized canonical coefficient (SCC) of the Canonical Discriminant Functions 1 (CDF 1) and 2 (CDF 2), discriminating sewage sludge and mineral fertilizationin the initial and last moments, considering every chemical soil attribute in the 0-0.20 m depth layer. Symbols represent the mean value of SCC for each soil sampling period and fertilization source (n= 21). Colored dots represent confidences ellipses (95%).



Source: Authors.

Table 3. Canonical correlation coefficient (*r*), standardized canonical coefficient (SCC), and parallel discrimination rate (PDRC) referring to soil chemical characteristics, within the first and second canonical discriminating function (CDF 1 and CDF 2), in sewage sludge and mineral fertilizationin initial and last moments. Bold values indicate greater component contribution to differences between treatments.

Characteristic	------------------CDF 1--------------------			------------------CDF 2--------------------		
	r	SCC 1	PDRC 1	*r*	SCC 2	PDRC 2
pH	0.249	0.239	0.060	-0.391	-0.590	**0.231**
TOC	-0.517	-0.760	**0.393**	-0.308	-0.135	0.042
P	-0.397	-0.539	**0.214**	-0.503	-0.566	**0.285**
K	-0.235	-0.466	**0.110**	0.465	0.407	**0.190**
Ca	-0.115	-0.080	0.009	-0.017	-0.275	0.005
Mg	-0.007	0.116	-0.001	-0.115	-0.176	0.020
Fe	-0.407	-0.359	**0.146**	0.070	0.037	0.003
Cu	0.003	0.366	0.001	-0.058	0.044	-0.003
Zn	-0.178	0.207	-0.037	-0.265	-0.435	**0.115**
Mn	-0.168	-0.021	0.003	0.068	0.016	0.001
SB	-0.268	0.238	-0.064	0.227	-0.451	-0.102
CEC	-0.224	-0.662	**0.148**	0.169	1.073	**0.182**
V	-0.033	-0.524	0.017	0.043	0.756	0.032
Eigenval		32.003			4.432	
Cum. Prop. (%)		87			99	

pH: pH in H_2O; TOC: Total organic carbon; SB: Sum of bases Σ(K, Ca, Mg); CEC: Cation exchange capacity Σ(K, Ca, Mg, H, Al); V: Base saturation Σ (K, Ca, Mg)/(CEC). Source: Authors.

For CDF 2 (with less contribution from discrimination), mineral fertilization causes a reduction in soil pH, P content, and an increase in K content in the soil (Figure 2, Table 3). These results indicated that the available forms of P supplied via mineral fertilization in tropical soils under pineapple cultivation are quickly drained into non-labile forms. However, for K, the current fertilization doses contributed to the increase of the availability of this nutrient in the soil at the end of cultivation, indicating the possibility of building fertility over the cultivation time.

3.2 Pineapple production

The production components of fruit weight with crown (FWWC), fruit weight without crown (FWC), 'D' leaf fresh matter (DFM), length (FL), and fruit diameter (FD) did not differ significantly after fertilization with different sources of fertilizers, indicating that sewage sludge fertilization provided yields equivalent to mineral fertilization. However, there were statistical differences ($p \leq 0.05$) among cultivars (Table 4). These differences were attributed to the distinct varietal characteristics of the studied pineapples.

The cultivar 'Smooth Cayenne' presented higher FWWC, FWC, DFM, FL, and FD (1625.0, 1483.0 g, 75.6 g, 17.3, and 13.0 cm, respectively). Cultivars 'MD-2' and 'IAC Fantástico' presented intermediate MFCC and MFSC, whereas cultivars 'Pérola' and 'Vitória' presented the lowest means related to fruit production (Table 4). Caetano, Ventura, and Balbino (2015) observed similar results when comparing the fruit weight of cultivars 'Smooth Cayenne', 'MD-2', 'Pérola', and 'Vitória'. The authors observed that cultivars 'Smooth Cayenne' and 'MD-2' showed FWWC of 1483.0 and 1380.0 g, respectively, values above those of cultivar 'Pérola', which presented a mean of 1266.0 g. The cultivar 'Vitória' presented the lowest fruit weight (1,194 g).

Table 4. Production characteristics (Fruit weight with crown-MFCC and without crown-MFSC, 'D' leaf fresh matter-DFM, length-FL and fruit diameter-FD) and Postharvest fruits characteristics (pulp firmness-PF, peel firmness-SF, titratable soluble solid-TSS, titratable acidity-AT, pH, ratio of the total soluble solid and titratable acid contents-TSS/TA, pulp luminosity-PL and Hue angle-HA in five pineapple cultivars (Smooth Cayenne, MD-2, ICA Fantástico, Pérola and Vitória).

	Production characteristics				
Cultivars	FWWC	FWC	DFM	FL	FD
	g			cm	
Smooth Cayenne	1625.0 a	1483.0 a	75.6 a	17.3 a	13.0 a
MD-2	1274.0 b	1144.0 b	68.6 b	14.8 c	12.4 a
IAC Fantástico	1167.0 b	1073.0 b	55.2 d	16.0 b	12.8 a
Pérola	1093.0 c	965.0 c	63.9 c	17.0 a	10.7 c
Vitória	1047.0 c	929.0 c	50.0 e	14.0 d	11.5 b
CV(%)	9.8	9.3	6.8	1.7	0.1

	Postharvest characteristics							
	PF	SF	TSS (°Brix)	TA	pH	TSS/TA	PL	HA
	Newton		°Brix	% Ac			L*	°H*
Smooth Cayenne	2452.0b	18775.0c	14.6a	0.8a	3.7b	19.7c	73.2b	87.2a
MD-2	3544.5a	28162.5a	12.8b	0.6b	4.1a	21.6c	70.9b	82.5b
IAC Fantástico	2473.5b	20831.0b	15.5a	0.5b	4.1a	31.2b	71.3b	82.6b
Pérola	1755.0c	17981.0c	14.4a	0.3c	4.2a	48.1a	75.7a	87.0a
Vitória	2815.5b	15945.0c	15.9a	0.3c	3.8b	44.7a	77.2a	87.0a
CV(%)	17.2	11.5	5.4	18.4	6.0	16.1	13.2	2.0

Means followed by the different letters in the column differ by Scoot-Knott test at 0.05 of probability. Coefficient of variation (CV%).
Source: Authors.

Cultivars 'Pérola' and 'Smooth Cayenne' presented longer fruits, whereas cultivars 'Smooth Cayenne', 'MD-2', and 'IAC Fantástico' presented fruits with larger diameter (Table 4), compared to cultivars 'Vitória' and 'Pérola'. However, Spironello et al. (2010) found no fruit length differences between cultivars 'Smooth Cayenne' and 'Pérola', with an average of 15 cm. In the present study, these cultivars exhibited fruits with a diameter equal to or greater than 17 cm (Table 4).

In the period of pineapple floral induction, the cultivar 'Smooth Cayenne' presented higher DFM (75.6 g), followed by cultivars MD-2, 'Pérola', 'IAC Fantástico', and 'Vitória' (68,6, 63, 9, 55.2, and 50 g MFD, respectively), indicating greater yield potential for the cultivar 'Smooth Cayenne' since plants with higher DFM produce larger fruits (Vileta et al., 2015; Santos et al., 2018b).

Soil fertilization with sewage sludge produced pineapple fruits with post-harvest characteristics similar to those of mineral fertilization, except for the cultivar 'IAC Fantástico', which presented a higher content of soluble solids (ºBrix) in the fertilization with SS. However, there was a statistical difference ($p \leq 0.05$) between cultivars for pulp and peel firmness, being greater in cultivars 'MD-2' and 'IAC Fantástico' (Table 4) and characterizing, according to Berilli et al. (2011), greater resistance to the industrial processing acceptance of these cultivars. Cultivars 'Smooth Cayenne', 'Vitória', and 'Pérola' showed lower pulp and peel firmness and did not differ statistically from each other.

Cultivars 'Vitória' and 'IAC Fantástico' presented a higher content of soluble solids (TSS). Cultivars 'Smooth Cayenne' and 'Pérola' had intermediate TSS content, and the cultivar 'MD-2'presented the lowest TSS content (Table 4). According to Berilli et al. (2011), the optimal values of soluble solids for pineapple are between 14 and 16 ºBrix for good quality fruits destined for in natura consumption. In this context, most of the cultivars used in the study showed good quality for fresh consumption, except the cultivar 'MD-2', whose fruits had approximately 12 ºBrix. This condition was considered minimal for acceptance by consumers. Fassinou Hotegni et al. (2016) report that the quality of the pineapple fruits is essential for their acceptance by consumers; the fruits need to reach minimum requirements - pulp TSS of at least 12 ºBrix and weight of at least 0.7 kg.

The titratable acidity (TA, in % citric acid) was higher in the cultivar 'Smooth Cayenne' when compared to the others. Cultivars 'Vitória' and 'Smooth Cayenne' presented the lowest pH values in relation to the others and, therefore, more acidic pulps (3.77 and 3.72, respectively). The pH obtained for the cultivar 'Smooth Cayenne' was higher than that found by Viana et al. (2013), which corresponded to 3.29 ± 0.02. For the cultivar'Vitória', Silva et al. (2012) found values with intervals from 3.5 to 3.8, similar results to those of the present study. Cultivars 'MD-2', 'IAC Fantástico', and 'Pérola'presented a pH range from 4.09 to 4.24 and did not differ statistically from each other (Table 4).

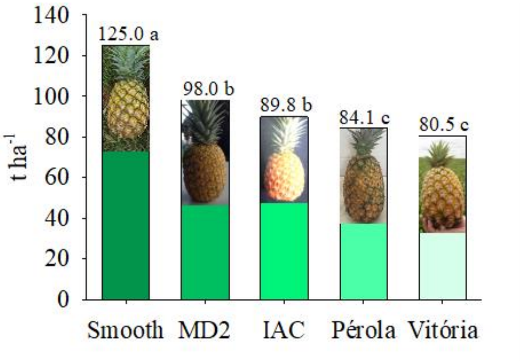
The ratio between soluble solids and titratable acidity (TSS/TA) was lower in cultivars 'Smooth Cayenne' and 'MD-2' (Table 4). This fact possibly occurred due to the higher acidity associated with the lower ºBrix observed in these cultivars. However, cultivars 'Pérola' and 'Vitória' presented the highest TSS/TA ratio. This characteristic is related to the sensation of sweetness, producing fruits with sweet pulp. These results are in agreement with those found by other authors (Silva et al., 2012; Viana et al., 2013; Berilli et al., 2014).

These results were related to the genetic characteristics of each cultivar, such as white pulp ('Pérola', 'Vitória') or yellow pulp ('IAC Fantástico' and 'MD2'), more acidic ('Smooth') or less acidic pulp ('Pérola'), more sweet ('Pérola' and 'Vitória') or less sweet pulp ('Smooth', 'MD2'), and greater peel and pulp firmness ('MD2'). The presence of fruits with greater peel and pulp firmness allows greater physical resistance to transportation and commercialization, which may increase the shelf-life of fruits until consumption or processing.

Fruit production was not influenced by the types of fertilization. This result suggests that sewage sludge was efficient in promoting the growth, development, and production of pineapple plants. However, a higher yield was obtained by the cultivar 'Smooth Cayenne', with 125.0 t ha^{-1}, statistically differing from cultivars 'MD-2' and I'AC Fantástico', which presented intermediate yields of 98.0 and 89.8 t ha^{-1}, respectively. Cultivars 'Pérola' and 'Vitória' presented the lowest yields of 84.1 and 80.5 t ha^{-1}, respectively (Figure 3).

Organic fertilization in pineapples has the potential to replace mineral fertilization (Darnaudery et al., 2018; Mahmud et al., 2018). Rothé et al. (2019) showed that organic fertilization is possible, even if applied only at planting (poultry feathers, blood meal, and composted manures), and that the average fruit weight was similar (organic fertilization= 762.6 g ± SE 19.0 and mineral fertilization = 807.4 g ± SE 17.7) to that of mineral fertilization with urea (200 kg ha^{-1} of N) and potassium sulfate (300 kg ha^{-1} K). Darnaudery et al. (2018) also showed that NPK fertilization could be replaced by organic fertilizers as well as by integrated fertilization. Pineapple growth was slower with organic fertilization (*Mucuna pruriens* green manure incorporated into the soil and foliar applications of sugarcane vinasse from a local distillery, rich in K - 14.44 g L^{-1}), with 199 days after planting vs. 149 days for integrated fertilization (M. pruriens green manure: 240.03 kg ha^{-1} N, 18.62 kg ha^{-1} P, and 136.11 kg ha^{-1} K, incorporated into the soil and a half-dose of NPK fertilizer) or conventional fertilization (NPK fertilizer at the recommended doses of 265.5 kg ha^{-1} N, 10.53 kg ha^{-1} P, and 445.71 kg ha^{-1} K), and fruit yield was lower, with 47.25 t ha^{-1} vs. 52.51 and 61.24 t ha^{-1}, probably because the organic fertilization provided an early increase in soil mineral N, whereas the N requirement is much higher at four months after planting.

Figure 3. Yield of pineapple cultivars after SS and MF fertilization (mean between fertilization with SS and MF). Means followed by the same letter do not differ by the Scott-Knott test at a significance level of 0.05.



Source: Authors.

The yield obtained in this study was higher and/or similar to those found in the literature. Cardoso et al. (2013) obtained a yield of 65 t ha^{-1} in a study conducted with the cultivar 'Vitória' at the same planting density (76,923 plants ha^{-1}). However, Guarçoni and Ventura (2011) obtained a yield of 66.25 t ha^{-1} when testing doses of N and K with the cultivar 'MD-2'at a planting density of 51,280 plants ha^{-1}. García et al. (2017), working with the cultivar 'Smooth Cayenne' at a density of 36,000 plants ha^{-1}, obtained a yield of 54.44 t ha^{-1}. These variations in yield are linked to several factors related to the genetic characteristics of the cultivars, climate, variations in planting densities, fertilization, irrigation, and other cultural practices adopted.

The results obtained indicate that the use of sewage sludge as a nitrogen source is equivalent to mineral fertilization in the production and nutrition of all pineapple cultivars, providing a positive effect on soil attributes, reducing the consumption of mineral fertilizers, contributing to production.

4. Conclusion

Sewage sludge can be used in pineapple crops as a source of nitrogen in replacement to mineral fertilization. The fertilization with sewage sludge promoted the reduction of pH and increased the levels of organic carbon, P, Ca, Fe, and Zn in the 0-0.4 m soil layer. Regardless of the fertilizer source, the cultivar 'Smooth Cayenne' obtained the maximum yield (125 t ha^{-1}), followed by pineapple cultivars 'MD-2' and 'IAC Fantástico', with intermediate yields (98 and 90 t ha^{-1}, respectively), and cultivars 'Pérola' and 'Vitória', with lower yields than the others (84 and 81 t ha^{-1}, respectively).

The organic fertilization with sewage sludge does not interfere with the physicochemical characteristics of the fruits compared to mineral fertilization.

The use of sewage sludge in agriculture can be made possible with the preparation of future studies that identify the mineralization rate of nutrients for cultivated plant species, enabling the recommendation of balanced doses of organic or organomineral fertilizers based on sludge, and the adoption of agricultural practices that contribute to environmental and economic sustainability of society and rural properties.

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