Research, Society and Development, v. 11, n. 10, e20111032275, 2022
(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v11i10.32275

Productivity and nutrition of castor bean fertilized with sewage sludge stabilized by different processes

Produção de mamoneira adubada com lodo de esgoto estabilizado por diferentes processos

Producción de higuerilla fertilizada con lodos de depuradora estabilizados por diferentes procesos

Received: 06/28/2022 | Reviewed: 07/09/2022 | Accept: 07/14/2022 | Published: 07/21/2022

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Abstract
The objective of this study was to evaluate production in castor bean crop treated with sewage sludge (SS) subjected to different stabilization processes. The experiment was conducted in a Cambisol, with a randomized block design, in subdivided plots, with four replications and six main treatments: without fertilization; fertilization with solarized, composted, vermicomposted, or limed SS; and mineral fertilizer. The secondary treatment was soil depth or plant part. Soil and plant attributes were evaluated by comparing the treatments using the Scott–Knott test ($P \leq 0.05$). The fertilization with limed SS resulted in a greater increase in soil fertility-related attributes than with the other fertilizers. The fertilizations increased the P, K, Ca, Mg, and S levels; pH; sum of bases; cation exchange capacity; and the percentage of exchangeable bases in the upper soil layer in comparison to that in the lower layer; however, in general, there was no influence on nutrient content in the plant. Regardless of the stabilization process, fertilization with SS generated castor bean seed yields ranging from 2.56 to 3.02 t ha-1, similar to that with mineral fertilization and higher than that of unfertilized soil.
Keywords: Biosolid; Oleaginous; Organic fertilization; Plant nutrition; *Ricinus communis* L.

Resumo
O objetivo deste trabalho foi avaliar a produção da mamoneira tratada com lodo de esgoto (LE) submetida a diferentes processos de estabilização. O experimento foi conduzido em Cambissolo, com delineamento em blocos casualizados, em parcelas subdivididas, com quatro repetições e seis tratamentos principais: sem adubação; adubação com LE solarizado, compostado, vermicompostado ou caleado; e fertilizantes minerais. O tratamento secundário foi a profundidade do solo ou parte da planta. Os atributos do solo e da planta foram avaliados comparando-se os

tratamentos pelo teste de Scott–Knott (P ≤ 0,05). A adubação com LE caleado promoveu maior aumento dos atributos relacionados à fertilidade do solo, quando comparado aos demais fertilizantes. As adubações aumentaram os teores de P, K, Ca, Mg e S; pH; soma de bases; Capacidade de troca de catiônica; e a porcentagem de bases trocáveis na camada superior do solo em relação à camada inferior; entretanto, em geral, não houve influência no teor de nutrientes na planta. Independentemente do processo de estabilização, a adubação com LE gerou produtividades de mamona que variaram de 2,56 a 3,02 t ha-1, semelhante à adubação mineral e superior à do solo não adubado.
Palavras-chave: Biossólido; Oleaginosa; Adubação orgânica; Nutrição de plantas; *Ricinus communis* L.

Resumen
El objetivo de este trabajo fue evaluar la producción de plantas de ricino tratadas con lodos de depuradora (LD) sometidas a diferentes procesos de estabilización. El experimento se realizó en Cambisol, con un diseño de bloques al azar, en parcelas divididas, con cuatro repeticiones y seis tratamientos principales: sin fertilización; fertilización con LD solarizado, compostado, vermicompostado o encalado; y fertilizantes minerales. El tratamiento secundario fue la profundidad del suelo o parte de la planta. Los atributos del suelo y de la planta se evaluaron comparando tratamientos mediante la prueba de Scott-Knott (P ≤ 0.05). La fertilización con LD encalado promovió un mayor aumento de los atributos relacionados con la fertilidad del suelo, cuando se comparó con otros fertilizantes. Las fertilizaciones incrementaron los niveles de P, K, Ca, Mg y S; pH; suma de bases; capacidad de intercambio catiónico; y el porcentaje de bases intercambiables en la capa superior del suelo con relación a la capa inferior; sin embargo, en general, no hubo influencia en el contenido de nutrientes de la planta. Independientemente del proceso de estabilización, la fertilización con LE generó rendimientos de higuerilla que oscilaron entre 2,56 y 3,02 t ha-1, similar a la fertilización mineral y superior a la del suelo sin fertilizar.
Palabras clave: Biosólido; Oleaginosa; Fertilización orgánica; Nutrición vegetal; *Ricinus communis* L.

1. Introduction

Currently, with the impact of increasing urbanization, several environmental problems are being experienced by many countries, including Brazil, related to the poor disposal and accumulation of waste from wastewater treatment plants (Fávaris et al., 2016). Owing to the large amount of sewage sludge produced, strategies for its recycling are required, and one of the possibilities is the use of these wastes in agriculture (Eid et al., 2018).

The use of sewage sludge as an organic fertilizer is the safest alternative among available means for the final disposal of this waste, with the advantages of reducing CO_2 caused by incineration and the addition of mineral fertilizers in cultivated areas (Pilnáček et al., 2019). This waste has been identified as a fertilizer as it is rich in organic matter and nutrients, leading to improvements in the physical, chemical, and biological properties of the soil, and acting as a nutritional source in crops (Sharma et al., 2017; Eid et al., 2018).

The use of sewage sludge in agriculture is the most ecological method of its disposal, as it promotes its recycling, and is regulated by the standards established by each country or region (Eid et al., 2017; Gonçalves et al., 2019). In addition, owing to the specific chemical characteristics of sewage sludge, it is necessary to identify the effects of its application on soil quality and crop yield in various edaphoclimatic situations (Barbosa et al., 2018).

Several studies have been conducted on sewage sludge in agriculture to evaluate its role in alleviating the negative impacts caused by its accumulation and, because of the potential of this residue, as an alternative source of fertilization, to fully or partially supply the nutritional needs of plant species of economic and social interest (Freitas et al., 2015; Fávaris et al., 2016). Studies involving fertilization with sewage sludge have been conducted in Brazil and the results were favourable for several crops in the response obtained to the application of this waste (Nascimento et al., 2015; Santos et al., 2019; Gonçalves et al., 2019).

The cultivation of castor bean (Ricinus communis L.) in Brazil mainly fulfils an energy requirement, which makes this oilseed an economically important crop. However, the crop displays low productivity in some production areas of the country, which may be owing to the low technological level employed, mainly because of the non-fertilization of soils. This can be attributed to the misleading idea that this species is undemanding in terms of fertilization or the lack of financial resources of producers to purchase mineral fertilizers (Diniz Neto et al., 2012; Simões et al., 2013).

According to the CONAMA Resolution nº 498 (Brasil, 2020) the castor bean is an appropriate crop for the use of sewage sludge, as the final product of the crop is not intended for human consumption. Thus, the use of sewage sludge as an organic fertilizer in the production of the castor bean can be a viable alternative from an economic and environmental point of view.

Accordingly, the objective of this study was to evaluate the chemical attributes of the soil and the nutrition and productivity of castor bean fertilized with sewage sludge subjected to different stabilization processes.

2. Methodology

The experiment was conducted from April 2010 to December 2010, at the Institute of Agricultural Sciences (ICA) of the Federal University of Minas Gerais (UFMG), located in Montes Claros - MG, latitude 16°40′57,6″ S, longitude 43°50′19.6″ W and altitude of 630 m, in a HAPLIC CAMBISOL with chemical and physical attributes as presented in Table 1.

Table 1. Chemical and physical attributes of the HAPLIC CAMBISOL used in the study.

Depth (cm)	**pH-H_2O**	**OM**	**P-SEP**	**P-Mehlich1**	**K**	**Ca**
		dag kg^{-1}	mg L^{-1}	-------- mg dm^{-3} --------		cmol$_c$ dm^{-3}
0-20	5.8	3.39	16.7	3.50	229.00	3.60
20-40	5.5	2.50	14.4	1.90	117.00	2.80
Depth (cm)	**Mg**	**Al**	**H+Al**	**SB**	**CEC$_t$**	**CEC$_T$**
	cmol$_c$ dm^{-3}	------------------------------- cmol$_c$ dm^{-3} -------------------------------				
0-20	1.50	0.20	3.62	5.69	5.89	9.31
20-40	0.80	0.76	3.62	3.90	4.66	7.52
Depth (cm)	**V**	**Sand**	**Silt**		**Clay**	
	%	--------------------------------- dag kg^{-1} ---------------------------------				
0-20	61.12	20	38		42	
20-40	51.86	26	36		38	

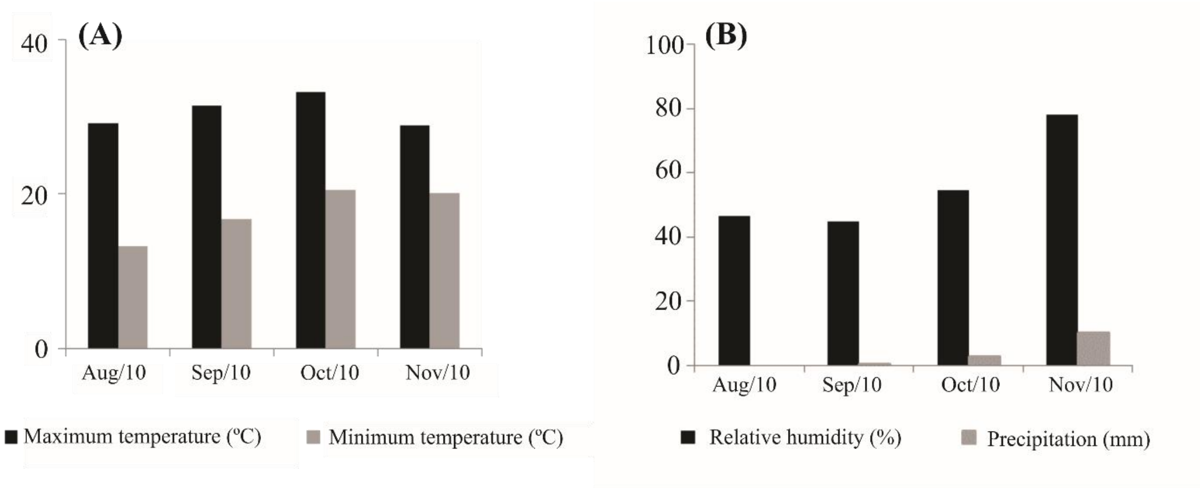
[1]Methodologies of Embrapa (1997); OM = organic matter; SEP = solution equilibrium P; SB = sum of bases; CEC$_t$ = cation exchange capacity at soil pH; CEC$_T$ = cation exchange capacity at pH 7.0; V = base saturation. Source: Authors.

The experimental design was that of randomized blocks, with four replicates, in a subdivided plot scheme, with fertilization being the primary factor and depth (in the case of soil), and leaf parts (in the case of plants), the secondary factor. Six treatments were used. One was chemical treatment (40 kg ha^{-1} N, 45 days after emergence; 90 kg ha^{-1} P_2O_5 and 30 kg ha^{-1} K_2O during planting) according to the Recommendations for the Use of Correctors and Fertilizers in Minas Gerais (CFSEMG, 1999), using urea, simple superphosphate, and potassium chloride as a source of N, P, and K, respectively. Four treatments were with sewage sludge stabilized by different processes, applied based on the levels of available N, calculated according to the CONAMA Resolution nº 498 (Brasil, 2020): solarized (4.09 t ha^{-1}), composted (24.84 t ha^{-1}), vermicomposted (12.78 t ha^{-1}) and limed (33.61 t ha^{-1}). The sixth treatment was without fertilization (control).

The BRS Energia bean cultivar (*Ricinus communis* L.) was used in the study. This cultivar has a height of approximately 1.40 m, a crop cycle between 120 and 150 days, green stem with wax, conical clusters with an average size of 60 cm, green waxy and indehiscent fruits, seeds containing on average 48% of oil, and a single harvest. The cultivation area should have an altitude greater than 300 m in relation to sea level and an average annual temperature between 20 °C and 30 °C, with an optimal temperature of around 23 °C. Annual rainfall should be at least 500 mm, with optimal rainfall between 650 and 800 mm (Gonçalves et al., 2005).

The cultivation area had an altitude of 647 m above sea level and presented, during the cultivation period, an average maximum temperature ranging from 28.85 °C to 33.16 °C, average minimum temperature ranging from 13.21 °C to 20.51 °C, and total rainfall of 390.8 mm (Figure 1).

Figure 1. Total precipitation (mm); average relative humidity (%); and maximum, minimum, and average temperatures in the period from August to November 2010.



Source: Authors.

The solarized sewage sludge was collected at the wastewater treatment plant (WWTP) of the municipality of Juramento - MG. The WWTP has a treatment line comprising preliminary treatment, UASB anaerobic reactor interconnected in series to an optional post-treatment pond and sewage treatment through solarization in a drying bed for a period of three months. The solarized sewage sludge was mixed with potato grass pruning (*Paspalum notatum*) to obtain a compost with a C:N ratio of 30:1. Temperature and humidity were monitored, and the compost cells were turned systematically.

The vermicompost was obtained by mixing a precomposted sewage sludge with grass pruning, used after the thermophilic phase, approximately 1 month after the beginning of the decomposition process, as a substrate for vermicomposting with California Red earthworms (*Eisenia foetida*). The limed sewage sludge was obtained by adding lime corresponding to 50% of the dry sludge mass. After mixing, the humidity was raised to 70%. The chemical characteristics of the materials containing sewage sludge are presented in Table 2.

Table 2. Chemical characteristics of sewage sludge stabilized using different processes.

Stabilization methods	**$N_{available}$[1]**	**P_2O_5**	**K_2O**	**Ca**	**Mg**	**S**
	kg t^{-1}	----------------------------------	----- dag kg^{-1}	-----	--------------------------	
Solarization	9.78	0.32 (13.09)	0.28 (11.45)	0.65 (26.59)	0.20 (8.18)	1.61 (65.84)
Composting	1.61	0.28 (69.55)	0.28 (69.55)	0.71 (176.36)	0.15 (37.26)	1.28 (317.95)
Vermicomposting	3.13	0.30 (38.34)	0.40 (51.12)	0.49 (62.62)	0.15 (19.17)	0.92 (117.57)
Lime	1.19	0.29 (97.47)	0.44 (147.88)	10.93 (3,673.57)	0.23 (77.30)	1.24 (416.76)

[1]Methodologies as described by Tedesco *et al*. (1995). The values in parentheses correspond to the quantities applied in kg ha^{-1}. The levels of N applied are based on the levels of available N (N_{avail}) (Brasil, 2020). Source: Authors.

The fertilizations with sewage sludge were performed only once, in the planting groove, with the addition performed at a depth of 0–20 cm. The experimental plots consisted of four rows of 3 m length, with 1 m spacing between them. The useful plots were the two central lines, disregarding 0.5 m from each end. The planting was performed in grooves, placing three seeds in each sowing site, at a distance of 0.5 m between plants. Fifteen days after emergence, pruning was performed, leaving only one plant. Manual weeding and sprinkler irrigation were followed.

At the beginning of the flowering of the crop, 45 days after emergence, the 4th leaf from the apex of the plant was collected for analysis of N, P, K, Ca, Mg, and S content (Tedesco et al., 1995; Malavolta et al., 1997). Seed yield was calculated with moisture corrected to 7%. After harvest, 150 days after emergence, eight soil subsamples per plot were collected between plants in the row at depths of 0–20 and 20–40 cm, to form composite samples for the determination of P, K, Ca, Mg, and S content and analyses of organic matter, pH, sum of bases (SB), effective cation exchange capacity (ECEC) (t), potential CEC (T), base saturation (V%), and H+Al (Teixeira et al., 2017).

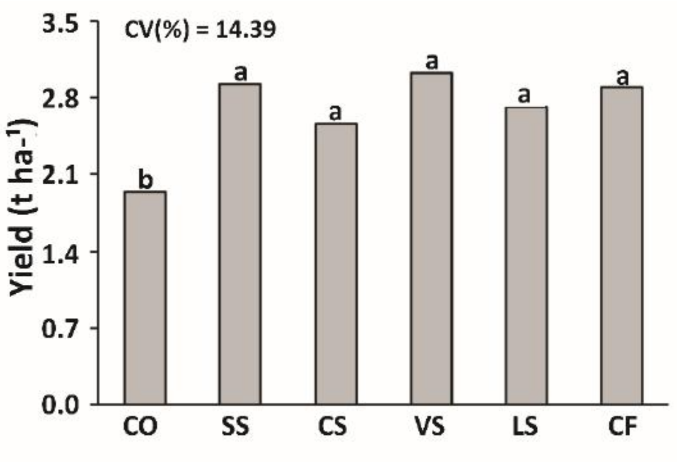
The data obtained were subjected to analysis of variance and the means of the treatments were compared by the Scott-Knott test at a 5% significance level.

3. Results

The application of sewage sludge in the soil resulted in a castor bean productivity equivalent to that observed with the application of mineral fertilization and higher than the productivity obtained in the plots without fertilization, regardless of the sludge stabilization process (Figure 2). It is noteworthy that the average yields observed with sewage sludge treatments ranged from 2.56 to 3.02 t ha^{-1}, surpassing the average productivity of the state of Minas Gerais in the same period, which was 1.05 t ha^{-1} (EMBRAPA, 2019).

Regarding soil P content (Table 3), the highest content was observed in the treatment with sewage sludge when compared to that in the other treatments. In addition, regardless of the treatments, the highest levels occurred in the 0–20 cm surface layer.

Figure 2. Productivity of the castor bean crop with the application of mineral fertilizer and sewage sludge treated with different processes.



Source: Authors.

CO - Control; SSS - Solarized sewage sludge; CS - Composted sewage sludge; VS - Vermicomposted sewage sludge; LS - Limed sewage sludge; CF - Chemical fertilization. Means followed by the same letter do not differ statistically from each other at a 5% significance level by the Scott–Knott test. Source: Authors

In this layer, the classification of P content in the soil ranged from "very low," in the treatment without fertilization, to "good" or "very good" in treatments with fertilizer (Alvarez et al., 1999). There were also increases in soil P content in treatments with sewage sludge and mineral fertilization compared to the initial content in the soil (Table 1), corroborating the results obtained by Bremm et al. (2012).

The K content in the soil did not vary with the treatments applied, and the highest values were found in the top layer of the soil (Table 3). In the treatments studied, including the control, the content of this element was classified as "very good" (Alvarez et al., 1999),

The application of limed sewage sludge led to an increase in soil Ca content, at the two depths evaluated, when compared to the other treatments (Table 3). In addition, Ca levels were higher in the surface layer for all treatments than the lower layer, except in the control.

Although the highest amount of Mg was applied with the sewage sludge, this treatment presented the lowest levels of the element in the soil, in the 0–20 cm layer, even lower than that in the control treatment. No differences were found in the 20–40 cm layer. However, the content of this element was concentrated more in the upper layer (0–20 cm) than in the lower layer (20–40 cm), except for the treatment with sewage sludge, in which the content of this element did not show differences between the layers.

Although the highest amount of Mg was applied with the sewage sludge, this treatment presented the lowest levels of the element in the soil, in the 0–20 cm layer, even lower than that in the control treatment. No differences were found in the 20–40 cm layer. However, the content of this element was concentrated more in the upper layer (0–20 cm) than in the lower layer (20–40 cm), except for the treatment with sewage sludge, in which the content of this element did not show differences between the layers.

Table 3. Chemical attributes of the soil after application of mineral fertilizer and sewage sludge treated with different processes.

Atributes[1]	**Depth (cm)**	**CO**	**SS**	**CS**	**VS**	**LS**	**CF**	**CV (%)**
Phosphorus	0-20	3.17 b	4.56 b	14.20 a	12.20 a	17.43 a	14.83 a	59.65
(mg dm^{-3})	20-40	2.70 a	3.80 a	4.33 a	3.05 a	4.97 a	2.57 a	44.76
Potassium	0-20	267.67 a	310.00 a	355.00 a	307.50 a	313.25 a	366.00 a	31.25
(mg dm^{-3})	20-40	183.67 a	242.50 a	147.25 a	280.50 a	334.75 a	265.00 a	41.06
Calcium	0-20	2.57 b	3.35 b	4.10 b	3.13 b	9.93 a	3.20 b	21.95
($cmol_c$ dm^{-3})	20-40	1.37 b	1.60 b	1.90 b	1.35 b	5.02 a	1.48 b	45.95
Magnesium	0-20	0.80 a	0.95 a	1.08 a	0.93 a	0.55 b	0.93 a	4.90
($cmol_c$ dm^{-3})	20-40	0.43 a	0.62 a	0.73 a	0.50 a	0.55 a	0.55 a	23.70
Sulphur	0-20	19.20 b	26.50 b	25.23 b	22.20 b	77.23 a	25.68 b	36.06
(mg dm^{-3})	20-40	13.80 a	22.50 a	23.40 a	22.60 a	37.90 a	21.40 a	39.19
Organic Matter	0-20	2.97 a	3.15 a	3.40 a	3.15 a	3.15 a	3.00 a	11.34
(dag kg^{-1})	20-40	2.07 a	2.03 a	2.07 a	2.05 a	2.18 a	2.03 a	8.01
pH in water	0-20	5.90 b	5.65 b	6.00 b	5.82 b	7.62 a	5.77 b	4.90
	20-40	5.40 a	5.50 a	5.70 a	5.60 a	6.40 a	5.40 a	9.45
Sum of bases	0-20	4.05 b	5.10 b	6.08 b	4.84 b	11.28 a	5.07 b	17.84
($cmol_c$ dm^{-3})	20-40	2.27 b	2.85 b	3.51 b	2.57 b	6.43 a	2.70 b	36.09
CEC_t	0-20	4.72 b	5.50 b	6.36 b	5.06 b	11.28 a	5.52 b	15.50
($cmol_c$ dm^{-3})	20-40	3.70 b	4.12 b	4.64 b	3.82 b	6.93 a	4.13 b	24.64
CEC_T	0-20	8.29 b	9.55 b	9.55 b	9.21 b	11.40 a	9.11 b	10.64
($cmol_c$ dm^{-3})	20-40	7.28 a	7.92 a	7.80 a	7.52 a	8.74 a	7.73 a	10.58
Bases saturation (%)	0-20	48.67 b	52.00 b	61.50 b	52.00 b	98.75 a	54.00 b	15.11
	20-40	31.00 b	34.50 b	43.50 b	33.50 b	69.50 a	34.75 b	27.19
Potencial acidity	0-20	4.24 a	4.46 a	3.47 a	4.37 a	0.13 b	4.04 a	27.20
($cmol_c$ dm^{-3})	20-40	5.01 a	5.08 a	4.29 a	4.95 a	2.31 b	5.03 a	21.51

[1]Embrapa methodologies (1997).CEC_t = cation exchange capacity at natural soil pH; CEC_T = cation exchange capacity at pH 7.0; V = base saturation; CO – Control; SS – Solarized sewage sludge; CS – Composted sewage sludge; VS – Vermicomposted sewage sludge; LS – Limed sewage sludge; CF – Chemical fertilization. For each variable, the means followed by the same lower case letter on the line do not differ from each other by the *Scott-Knott*test(p<5%). Source: Authors.

Although the highest amount of Mg was applied with the sewage sludge, this treatment presented the lowest levels of the element in the soil, in the 0–20 cm layer, even lower than that in the control treatment. No differences were found in the 20–40 cm layer. However, the content of this element was concentrated more in the upper layer (0–20 cm) than in the lower layer (20–40 cm), except for the treatment with sewage sludge, in which the content of this element did not show differences between the layers.

The S content in the soil was higher with the application of sewage sludge than in the other treatments (Table 3). This is owing to the higher contribution of this element in the sludge (Table 2).

The organic matter content did not vary between treatments, but was higher in the surface layer than in the other layers (Table 3).

The application of sewage sludge resulted in an increase in soil pH compared to that in other treatments (Table 3), reaching values classified agronomically as "very high" (Alvarez et al., 1999). In addition, the highest pH values were found in the soil surface layer in comparison to that in the sublayer.

The chemical composition of the materials containing sewage sludge (Table 2) and the respective doses applied indicate that a greater amount of K_2O (97.47 kg ha^{-1}), Ca (3,673.57 kg ha^{-1}), and Mg (77.30 kg ha^{-1}) was added to the soil treated with sewage sludge than the with the other treatments. Considering that the SB and V% are directly related to the presence of these elements in the soil, the higher levels of Ca, Mg, and K in the treatment with sewage sludge resulted in higher values of SB and V%. Moreover, a significant increase in these attributes occurred in the surface layer, from 0–20 cm (Table 3). In the other treatments, no statistical differences were observed.

In addition to SB and V%, the application of limed sewage sludge led to increases in ECEC(t) and CEC(T) when compared to other treatments (Table 3). In addition, the increases in these variables were higher in the soil surface layer than the deeper layer. In contrast, the treatments with solarized, composted, and vermicomposted sewage sludge, as well as the treatment with mineral fertilizer, led to statistically equivalent values of SB, V%, ECEC(t), and CEC(T) to those observed in the treatment without fertilization.

The (H+Al) was reduced in the soils treated with limed sewage sludge, which differed from the other treatments (Table 3). There was a greater reduction in the 20–40 cm layer than in the 0–20 cm layer.

The lowest N content in the castor bean was observed with the application of vermicomposted sewage sludge, in comparison to the other treatments (Table 4). However, regardless of the treatments, the highest levels of this nutrient were observed in the leaf limb, when compared to that in the petiole.

Regarding the levels of P, K, Ca, Mg, and S, there were no differences between treatments (Table 4). However, the content of K, Ca, and Mg was higher in the petiole than in the leaf limb, whereas P and S content was higher in leaf limb than in the petiole.

In general, there were no differences between the nutrient content found in soils fertilized with sewage sludge and mineral fertilization. Despite the greater supply of nutrients to the soil with the addition of organic residues and mineral fertilization, the levels of P, K, Ca, Mg, and S in the leaf tissue were below the levels considered appropriate for the crop, according to Malavolta et al. (1997). Only N levels in the leaf limb were adequate for the castor bean crop in all treatments. In the case of the control, the lower productivity of the plants with this treatment may have led to a higher concentration of N in the tissues, providing levels similar to those of treatments with fertilization.

The levels of P, K, Mg, S, and Ca in the leaf limb were below the levels considered adequate for the nutritional status of the castor bean as reported by Malavolta et al. (1997), although the content of these elements in the soil were classified in the range from "good" to "very good" with sewage sludge treatments (Alvarez et al., 1999).

Table 4. Nutrient content in leaf limb (LF) and petiole (PE) of castor bean in response to the application of mineral fertilizer and sewage sludge treated in different ways.

NUT[1]	CO	SS	CS	VS	LS	CF	CV	NA[2]
	---------------------------------- dag kg^{-1}					--------------------------------	%	-- dag kg^{-1} ---
Leaf								
N	4.48 b	4.70 a	4.72 a	4.19 b	4.80 a	4.68 a	5.70	4.00 – 5.00
P	0.23 a	0.25 a	0.27 a	0.27 a	0.27 a	0.28 a	11.86	0.30 – 0.40
K	1.56 a	1.69 a	1.62 a	1.77 a	1.73 a	1.65 a	7.55	3.00 – 4.00
Ca	0.87 a	0.69 a	0.73 a	0.75 a	0.84 a	0.75 a	14.72	1.50 – 2.50
Mg	0.17 a	0.13 a	0.14 a	0.14 a	0.14 a	0.13 a	13.39	0.25 – 0.35
S	0.24 a	0.20 a	0.22 a	0.30 a	0.26 a	0.26 a	20.13	0.30 – 0.40
Petiole								
N	1.58 b	1.54 b	1.52 b	1.30 c	1.80 a	1.46 b	8.30	-
P	0.14 a	0.12 a	0.16 a	0.18 a	0.17 a	0.17 a	14.83	-
K	3.63 a	3.26 a	3.27 a	3.18 a	3.56 a	3.39 a	7.75	-
Ca	1.45 a	1.31 a	1.23 a	1.40 a	1.62 a	1.43 a	10.94	-
Mg	0.44 a	0.35 a	0.35 a	0.36 a	0.38 a	0.37 a	12.95	-
S	0.18 b	0.19 b	0.19 b	0.19 b	0.23 a	0.19 b	7.69	-

C - Control; SSS - Solarized sewage sludge; CSS - Composted sewage sludge; VSS - Vermicomposted sewage sludge; LSS - Limed sewage sludge; CF - Chemical fertilization.; AL - Adequate level, according to Malavolta et al. (1997). For each variable, means followed by the same lowercase letter in the row and uppercase letter in the column do not differ statistically from each other by the Scott-Knott test, with 5% significance. Source: Authors.

4. Discussion

The yields obtained were also higher than those observed by Alves et al. (2015) and Barretos and Medeiros (2012), who obtained values ranging from 0.92 to 1.31 t ha^{-1} and 1.39 t ha^{-1}, respectively, for the same cultivar in regions with similar edaphoclimatic conditions.

Some studies have reported that the addition of sewage sludge to the soil increases the productivity of the castor bean crop, resulting in high dry matter and seed oil yield (Capuani et al., 2015; Maciel-Torres et al., 2017). Cavalcanti et al. (2015) reported that the productivity of castor bean fertilized with sewage sludge and potassium magnesium sulphate was similar to that found with NPK fertilization, indicating the potential of this residue as a substitute for mineral fertilization.

It is noteworthy that the average yields observed with sewage sludge treatments ranged from 2.56 to 3.02 t ha^{-1}, surpassing the average productivity of the state of Minas Gerais in the same period, which was 1.05 t ha^{-1} (EMBRAPA, 2019).

As shown in Table 2, the amounts of P2O5 and K2O applied for the sewage sludge exceeded the recommended amounts for the crop, which are 90 kg ha^{-1} of P2O5 and 30 kg ha^{-1} of K2O, in addition to the considerable supply of Ca, Mg, and S. For the treatment with composted and vermicomposted sewage, the quantities of K2O applied also exceeded the recommended amounts for the crop. However, even if there is no application of nutrients in total amounts required by the crop with sewage sludge treatments (except for limed sewage sludge), as already mentioned, these provided equal yields to each other and that with mineral fertilization and exceeded the yield of the control (Figure 2).

The positive influence of sewage sludge on soil P content has been highlighted in several studies (Costa et al., 2014; Bonini et al., 2015). pH values closer to 7, as observed in the treatment with sewage sludge, provide higher availability of P ($H_2PO_4^-$) in the soil solution. After 10 years of application of sewage sludge in tropical soil, Melo et al. (2018) claimed that the continuous application of sewage sludge increased the concentration of P in the soil, and was efficient in the complete replacement of phosphate fertilization. According to Martins et al. (2015) much of the sewage sludge P is in organic form and the increase in available P is owing to the mineralization of the P after 1 year of application.

The K content in the soil may be associated with the presence of muscovite in the source material, which is associated with metargilites/metassiltites belonging to the Serra de Santa Helena geological formation, likely explaining the levels of K ranging from medium to high in the soils of this formation. When assessing the application of sewage sludge in the cultivation of castor bean, Capuani et al. (2015) observed an increase in the availability of K in the soil. However, it should be noted that sewage sludge tends to be poor in K owing to the high solubility of this element, which results in it being retained in wastewater during sewage treatment.

The increase in Ca content in soils fertilized with limed sewage sludge was also observed by Nascimento et al. (2013) which was attributed to the addition of Ca during the stabilization process with lime (CaO). The behaviour of Mg in the soil was the opposite of that observed for Ca. The large amount of Ca in the limed sludge displaces Mg from the soil exchange complex, facilitating its leaching. This behaviour may have occurred owing to competition between these two elements for the adsorption sites in the soil (Malavolta, 2006). Capuani et al. (2015) applied sewage sludge with different combinations of limestone and studied the characteristics of the castor bean and chemical properties of the soil and observed the same inverse relationship between these nutrients. According to these authors, the combinations of Ca and Mg should be taken into account, resulting in a more appropriate balance of these elements in the soil.

Regardless of the treatment, the content of S were higher in the soil surface layer than in the deeper layers. Similarly, Lobo et al. (2012) observed that the application of sewage sludge increased soil S content in the surface layer (0–10 cm depth); however, it did not influence the content of this element in the subsurface layer (20–40 cm depth).

Although one of the benefits of sewage sludge is the increase in soil organic matter, in tropical regions such as Brazil, degradation of organic matter occurs very quickly (Alburquerque et al., 2015; Cavalcanti et al., 2015; Zuba Junio et al., 2015). Thus, its permanence in the soil is temporary, and therefore, in some studies its content was reported to not increase with the application of sewage sludge (Maio et al., 2011; Ribeirinho et al., 2012; Nascimento et al., 2014; Martins et al., 2015). The higher temperature and humidity prevalent in these regions accelerate the mineralization process of organic matter and little recalcitrant residue remains in the soil and will only influence soil attributes with systematic applications and at longer time frames (Bayer and Mielniczuk, 2008; Maio et al., 2011). In the present study, the period between the addition of sewage sludge to the soil and its sampling was enough for the degradation of organic matter, with little residue remaining in the soil.

The increase in pH owing to the application of alkalized sewage sludge was also observed by Nascimento et al. (2014), after adding lime (CaO) and hydrated lime $Ca(OH)_2$ during the stabilization process. According to Matos and Matos (2012), sewage sludge increases the pH of soils and can therefore be recommended as a corrector of soil acidity.

The increase in SB and V% with the application of limed sewage sludge was also observed by Nascimento et al. (2014) during the liming process. The addition of CaO in the stabilization of sewage sludge results in a material with high acidity correction capacity, leading to increased soil pH, precipitation of Al3+, and neutralization of H^+ ions, resulting in increased exposure of negative soil loads. Consistent with this process, Nascimento et al. (2014) found that a Haplic Cambisol treated with sewage sludge processed in different ways displayed high V%, ECEC(t), and CEC(T). Poggere et al. (2012), using alkalized sewage sludge, demonstrated that the attributes of soils that presented the best correlations with the sewage sludge were CEC(T), potential acidity (H+Al), and soil pH. The CEC(T) is important for soil fertility, as it indicates the total capacity of cation retention, which in general, will become available to plants (Xavier et al., 2014).

The reduction in (H+Al) in the treatment with sewage sludge is attributed to the increase in pH values associated with the increase in the content of exchangeable cations, leading to an increase in base saturation. These results demonstrate the corrective power of soil acidity by the limed sewage sludge. Consistent with these results, Barbosa et al. (2017) concluded that the application of alkalinized sewage sludge to the soil resulted in decreased (H+Al) and increased base saturation and effective cation exchange capacity, among other indicators.

In general, the effects of sewage sludge on soils have been recognized for some time, especially after successive applications, and the intensity varies, according to the origin of the residues, management, and doses used (Bueno et al., 2011). The benefits on the chemical and physical properties of soils are very evident and contribute to considerable increases in crop productivity (Alburquerque et al., 2015; Capuani et al., 2015; Cavalcanti et al., 2015; Áfaz et al., 2017; Maciel-Torres et al., 2017; Eid et al., 2018).

Considering these results, it was clear that sewage sludge is a good source of N for plants and that it can efficiently replace the N from mineral fertilization without harming the nutritional status of the crop. These results are consistent with those reported by Ribeirinho et al. (2012) and Alburquerque et al. (2015), who reported an increase in N content in the leaf limb of crops fertilized with sewage sludge. In contrast, the other nutrients from sewage sludge were insufficient to meet the plant’s demand, requiring complementation.

The application of sludge to the soil must be continuous to maintain organic matter levels because the decomposition of organic C added with sludge is rapid, presenting a very short soil residence time (Martins et al., 2015). Organic compounds such as sewage sludge can provide nutrients such as N, P, and K for plants, improving chemical attributes, besides providing greater recycling of nutrients in the soil by crops, than with mineral fertilization (Melo et al., 2011; Kray et al., 2011; Krob et al., 2011). Studies have shown that sewage sludge provides several benefits to agriculture, such as the incorporation of nutrients in various crops, resulting in improved plant development (Pedrosa et al., 2017; Martins et al., 2018). Furthermore, sewage sludge can be used as a complementary organic fertilizer, thus reducing the use of chemical fertilizers and, consequently, the cost of fertilization (Gonçalves Jr. et al., 2012).

Nevertheless, the use of sewage sludge as a source of organic matter and nutrients requires some care, especially regarding the content of heavy metals, toxic organic substances, and pathogens, which tend to accumulate in the soil after successive applications of this residue.

5. Conclusion

Fertilization with limed sewage sludge leads to increases in the soil Ca, P, and S content; pH; the sum of bases; the cation exchange capacity; and the percentage of base saturation as well as a reduction in Mg availability and potential acidity (H+Al), compared to that with the control, mineral fertilization, and other forms of sewage sludge.

Chemical and sewage sludge fertilizations promote a higher increase in the levels of P, K, Ca, Mg, and S in the upper soil layer, as well as that of pH, sum of bases, cation exchange capacity, and percentage of exchangeable bases, than in the lower soil layer. In contrast, the potential acidity (H+Al) is higher in the lower layer than in the upper layer of the soil.

Fertilization with vermicomposted sludge leads to lower levels of N in the plant, whereas mineral and sewage sludge fertilization, and the control, provide the same levels in the plant. However, the levels are suitable for all treatments.

The levels of P, K, Ca, Mg, and S in leaf tissue do not differ between treatments and are below the levels considered adequate for culture.

N, P, and S content is concentrated more in the leaf limb, whereas K, Ca, and Mg levels are more concentrated in the petiole of the castor bean.

Regardless of the stabilization process, fertilization with sewage sludge generates castor bean yields ranging from 2.56 to 3.02 t ha^{-1}, equivalent to that with mineral fertilization and higher than that with unfertilized soil.

Using sewage sludge as organic fertilizer can reduce costs in the production of castor beans and, at the same time, eliminate the nonsense of using fertilizers from non-renewable energy to produce bioenergy. The positive effect of using sewage sludge was demonstrated in the present study. However, research on oilseeds and fertilization with stabilized compost of sewage sludge still demands more information, especially regarding the knowledge of the doses of organic fertilization of the stabilized residue that promotes greater agronomic efficiency.

Acknowledgments

The authors express their sincere gratitude to FAPEMIG, CNPq and CAPES for the financial support that made this work possible.

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