Effect of biosolids application on soil physical properties of a sugarcane crop

Efecto de aplicación de biosólidos sobre las propiedades físicas de un suelo cultivado con caña de azúcar

Waldemar Peñarete M.[1], Jorge Silva-Leal[2], Norberto Urrutia C.[1] Martha Daza T.[1],*
Patricia Torres-Lozada[2]

[1]Universidad del Valle, EIDENAR School, Faculty of Engineering, Area of Agricultural Engineering and Water Resources Area,
[2]Universidad del Valle, EIDENAR School, Faculty of Engineering, Area of Sanitary and Environmental Engineering
*****Corresponding author: waldemarp71@hotmail.com

Rec.: 08.08.12 Accep.:20.08.13

Abstract

The effects of the biosolids applications on physical properties (bulk density, porosity and soil structural stability) in a soil of sugarcane crop and crop yield were evaluated. The experiment was carried out in the Cañaveralejo wastewater treatment plant at Cali, Colombia using a randomized complete block experimental design, two replications and eight treatments: (soil without biosolids application and without mineral fertilization (To), and soil with mineral fertilization (FM), and six treatments with biosolids application to 100% and 200% of the dose required nitrogen by the crop as follows: BD100-BD200 dehydrated biosolids, BST100-BST200 thermally dried biosolids, and BA100-BA200 alkalinized biosolids. Results showed that significant differences were not found in soil physical properties and crop yield but trends to decrease the values of bulk density (1.33 Mg m^{-3} to 1.29 Mg m^{-3}) and microporosity (48.8% to 45.8%), and to increase the values of structural stability (1.8 mm to 3.1 mm) and macroporosity (2% to 5%) were identified, which favor the water-air relation in the soil.

Key words: Bulk density, crop yield, porosity, structural stability, vertic properties.

Resumen

Se evaluó el efecto de la aplicación de biosólidos resultantes de la Planta de Tratamiento de Aguas Residuales (PTAR) Cañaveralejo, Cali, Colombia, sobre las propiedades físicas (densidad aparente, porosidad y estabilidad estructural) de un suelo Vertic endoaquepts con características vérticas, sembrado con caña de azúcar, así como la influencia sobre el rendimiento del cultivo. Se utilizó un diseño experimental de bloques completos al azar con dos repeticiones y ocho tratamientos: dos testigos (suelo sin biosólido y sin fertilización mineral (To) y suelo con fertilización mineral (FM) y seis tratamientos con biosólidos aplicando 100% y 200% de la dosis de nitrógeno requerida por el cultivo así: BD100 y BD200 biosólidos deshidratados, BST100 y BST200 biosólidos deshidratados secados térmicamente y BA100 y BA200 biosólidos alcalinizados. Los resultados mostraron cambios ligeros en las propiedades físicas del suelo y en el rendimiento del cultivo. Se observó una tendencia en los tratamientos con biosólidos de disminuir la densidad aparente (de 1.33 Mg m^{-3} a 1.29 Mg m^{-3}) y la microporosidad (48.8% a 45.8%) y de aumentar la estabilidad estructural (1.8 mm a 3.1 mm) y la macroporosidad (2.0% a 5.0%).

Palabras clave: Densidad aparente, estabilidad estructural, porosidad, propiedades vérticas, rendimiento del cultivo.

Introduction

Within the framework of the policy of preserving the quality of water, Wastewater Treatment plants - WWTP have been built, which generate solid or semisolid byproducts (sludge and/or biosolids) depending on the type of treatment process and the state of digestion thereof (WEF, 1998). The application of biosolids in agriculture as amendments or fertilizer is a practice commonly used in developing countries, for their content of organic matter and nutrients such as nitrogen, phosphorus and potassium (European Commission, 2010). There are studies on the benefits of applying these products on soil physical properties, including: reduction of the bulk density (Tsadilas *et al.*, 2005), increased total porosity (Civeira and Flushing, 2006) and structural stability (Ojeda *et al.*, 2008).

Filizola *et al.* (2008) found negative effects as clay dispersion and damage to soil structure and Camilotti *et al.* (2006) observed no changes in the soil by the application of biosolids. Research in Colombia are primarily based on the use of biosolids as a source of organic matter (OM) and nutrients in the recovery of degraded soils (Torres *et al.*, 2007); however, there are few studies aimed at measuring the effect on the physical properties such as bulk density, structural stability and moisture retention (Ramirez and Perez, 2006). This study aimed to evaluate the application of biosolids on crop yield and some physical properties of a soil planted with sugarcane in Valle del Cauca, Colombia.

Materials and methods

Study site and establishment of the experiment

Sugarcane was grown on site at the WWTP-C, (3° 28' 17'' N, 76° 28' 52.8'' O, 967 masl), in a Vertic Endoaquepts soil in tropical dry forest agro-ecological zone with slope <1%, average temperature of 24 °C and annual rainfall between 1000 and 1500 mm (IGAC, 2006). An initial characterization of the chemical and physical soil properties was carried out: pH, organic carbon - OC, total Kjendahl nitrogen, $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, $N\text{-}NO_3^-$, total P, exchangeable bases (Ca_2^+, Mg_2^+, K^+ and Na^+), effective cation exchange capacity (ECEC) calculated from the sum of exchangeable bases, percentage of magnesium interchange (PMgI) calculated as the ratio of Mg available and the ECEC; physical properties such as bulk density, particle density, total porosity, macroporosity and microporosity, structural stability expressed by the average weighted diameter (DPM) and texture, following the protocols of the IGAC (2006b).

Biosolids came from the facilities of the WWTP-C, which operates with advanced primary treatment modality (TPA) and sludge treatment line consists of thickening, anaerobic digestion and mechanical dewatering in filter presses (BD); BD also subjected to additional processes of pathogen reduction (thermal drying at 60 °C for 13 h (BST) and alkaline treatment with 9% of dry weight quicklime (BTA) were evaluated (Silva *et al.*, 2013). Biosolids were characterized in terms of pH, humidity, OC, Total N, $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, $N\text{-}NO_3^-$, total P, K^+, Ca^{+2} and Mg^{+2}.

Crop fertilization was calculated based on the initial soil analysis, crop requirements, nitrogen contribution from biosolids and its mineralization rate (USDA, 2011). Mineral fertilization (FM) was performed 3 months after sowing; biosolid fertilization was made 1 month before the sowing, located at the bottom of the furrow. Soil preparation consisted of two passes of plow discs and furrowing for the experimental arrangement. The seed of sugarcane used was CC-8592 (Cenicaña-Colombia) variety, which was distributed within each furrow and covered with a layer of soil of about 10 cm. The irrigation was applied according to crop water requirements using the furrow application system with window pipes.

At the beginning of the trial and 4, 10 and 12 months after planting (m.a.p.) were measured: bulk density (DA) (cylinder), total porosity (PT), macroporosity (MP), microporosity (MIP) (porosimeter), the structural stability of the soil (modified Yoder method) and yield of the crop harvest in t/ha. To determine DA and porosities, two samples of undisturbed soil were taken using an auger and stainless steel cylinders of 5 cm^3, within the central 10 m of each furrow in the area of influence of the crop, at a depth of 12 cm for a total of six samples per treatment. For structural stability tests, a composed sample in each furrow was taken, for a total of three samples per treatment (IGAC, 2006b). Crop yield was determined by the total field weight of the cane in each furrow per treatment (20 m x 1.5 m) which was extrapolated to production/ha.

The experimental design used was a randomized complete blocks, with two replicates, each consisting of eight treatments and each treatment consisting of three furrows 20 m long x 1.5 m wide (Table 1).

Evaluation of descriptive statistics and analysis of variance with a subsampling component and a significance level of 95% ($P < 0.05$) for the variables was done. Differences between means were determined by Tukey's test at $P < 0.05$, with the statistical program R version 2.15.0.

Results and discussion

Soil and biosolids characterization

Soil characterization and biosolid The initial soil analysis appears in Table 2, which shows that the pH is alkaline, with high ECEC, moderate to high N, P and K content

Table 1. Description of treatments and doses used.

Treatment	Description	Biosolid (t/ha)
To	Control	0
FM[a]	Mineral fertilization	0
BD100	Dehydrated biosolid[b]	11.6
BD200	Dehydrated biosolid[c]	32.2
BST100	Thermally dried biosolid[b]	8.5
BST200	Thermally dried biosolid[c]	17.0
BA100	Alkalinized biosolid[b]	23.8
BA200	Alkalinized biosolid[c]	47.6

a. Conventional mineral fertilization with 180, 100 and 110 kg/ha of urea (46% N), triple superphosphate (46% P_2O_5) and potassium chloride (60% K_2O), respectively.
b. Biosolid with 100% of the nitrogen dose required by the sugarcane crop.
c. Biosolid with 200% of the nitrogen dose required by the of sugarcane crop.

Table 2. Physical-chemical properties of the soil at the beginning of the trial.

Characteristic	Value[a]	Characteristic	Value[a]
pH (units)	8.01	Na^+ (cmol(+)/kg)	0.43
		CICE (cmol(+)/kg	31.74
Organic-C (g/kg)	11.63	PMgI (%)	28.6
N-Total Kjendahl (mg/kg)	–	Particle density (Mg/m^3)	2.65
N-NH_4^+ (mg/kg)	8.1	Bulk density (Mg/m^3)	1.33
N-NO_2^- (mg/kg)	1.7	Porosity (%)	47.83*
N-NO_3^-(mg/kg)	4.4	Macroporosity (%)	6.55*
P-Total (mg/kg)	7.6	Microporosity (%)	40.62*
K^+ (cmol(+)/kg)	0.51	Structural stability-DPM (mm)	2.65
Ca^{+2} (cmol(+)/kg)	21.75	Sand, silt and clay (%)	29.8 – 16.8 – 54.4
Mg^{+2} (cmol(+)/kg)	9.05	Texture	Clayley

a. Average values of four repetitions.

and high exchangeable bases content, but with imbalance in Ca/Mg relations (2.4:1) less than ideal (3:1), and Mg/K (17.7: 1) greater than ideal (6-8) which can lead to antagonisms that affect the absorption of these nutrients by the plants and consequently crop yield of sugarcane (Castro and Gomez, 2010). In addition, the PMgI is greater than 25% in the change complex, which promotes the dispersion of the aggregates and affects soil structure.

Values of particle density, PT and DA comprised mostly by MIP (85% of the PT) are characteristic of this type of soil. However, this soil presented cracks that evidenced its vertic properties and presence of swelling clays; its texture is clayey, poorly drained, limited by periodic flooding, with a fluctuating water table according to the seasonal cycle (IGAC, 2006).

The characteristics of the biosolids used are seen in Table 3 and show that most of its components were within the parameters established for these types of materials (Potisek *et al.*, 2010). The contents of OM and nutrients, especially N and K, cause these materials to have great importance for agricultural use; despite this, high pH values can create restrictions for use in alkaline soils, since nutrients such as phosphorus and some microelements diminish their availability to plants, with increasing Ca concentration and pH (Castro and Gomez, 2010).

Effect of the aplication of biosolids on the physical properties

DA values found are included in Table 4 and are within the reported range for soil studies in the area (Carbonell, 2010); however, it should be noted that densities above 1.4 Mg/m^3 are considered high for fine textured soils (Finch, 2009).

Overall, these results are consistent with research conducted by Barbosa *et al.* (2007) and Dornelas *et al.* (2011) who, with higher applications (between 12 and 200 t/ha of biosolid) to those used in this study for up to five years, did not find significant changes in the physical properties of soils, including DA.

For treatments with BD100, BD200 and BA100, BA200 was found that the higher the dose of biosolids, the lower the values found, being this more evident in the fourth month after planting. This shows that the higher organic matter content in the soil, the lower the values of DA (Melo *et al.*, 2004) generating greater porosity and creating better conditions for the development of plant roots (Finch, 2009). For the treatments with BST the behavior

Table 3. Chemical characteristics of the applied biosolids.

Parameter	Dehydrated BD	Thermal Drying BST	Alkalinized BA
pH (units)	7.6	7.8	12.0
Organic carbon (g/kg)	243.1	257.4	218.2
N-Total Kjendahl (mg/kg)	25035	25700	17970
N-NH_4^+ (mg/kg)	1824.7	1130.7	133.08
N-NO_2^- (mg/kg)	0	0	0
N-NO_3^- (mg/kg)	33.8	17.8	34.5
P-Total (mg/kg)	14.5	14.3	9.7
K^+ (mg/kg)	950	960	720
Ca^{+2} (g/kg)	35.4	31.93	137.51
Mg^{+2} (g/kg)	5.47	5.66	5.19
Aplication rate (t/ha)	11.6	8.5	23.8
Mineralization rate (%)	33	45.7	23

Table 4. Bulk density average with biosolids application during the crop cycle of sugarcane.

Treatments	**Time since sowing (months)**					
	4		**10**		**12**	
	Av. (Mg/m$^{3)}$	**C.V. (%)**	**Av. (Mg/m^3)**	**C.V. (%)**	**Av. (Mg/m^3)**	**C.V. (%)**
To	1.24	6.6	1.26	3.5	1.36	6.7
FM	1.36	8.3	1.24	8.7	1.38	6.9
BD100	1.34	7.6	1.29	5.1	1.34	6.6
BD200	1.30	7.7	1.35	7.4	1.36	6.2
BST100	1.27	7.4	1.28	6.2	1.29	6.6
BST200	1.33	9.3	1.29	5.0	1.33	6.2
BA100	1.39	9.7	1.30	3.9	1.38	8.9
BA200	1.32	6.7	1.31	4.0	1.37	6.9
F =	16.179		15.047		0.886	
P =	0.159		0.194		0.527	
d.f.	7		7		7	

C.V. coefficient of variance.

was the opposite, finding the lowest values of DA in the lower dose treatment, which may be related to a high rate of mineralization and a low dose of biosolids applied (Uribe *et al.*, 2003). Furthermore, at 12 m.a.p. DA values increased in all treatments, including the control, with respect to the values of previous sampling times, possibly because these soils tend to naturally compact. Changes in the behavior of the DA versus weather conditions presented during the experimental phase showed that in the first months after planting and in the last two, precipitation was above evaporation (243 mm vs. 115 for the most critical month), which caused soil saturation that, due to its textural characteristics and presence of swelling clays 2:1, could generate increases in density. For the sampling 10 m.a.p., temperatures were higher, so the soil moisture and the DA decreased in all treatments.

Overall, treatment with mineral fertilizers (FM) presented higher values of DA than the biosolids treatments except at m.a.p. 10, when it was lower. This was possibly due to the presence of cracks that favored the increment in pore volume and the reduction in value of the DA (Torrente, 2007), indicating that cylinder sampling in expansive clayey soils is probably not most appropriate the method for determining DA (Pla, 2010).

The results obtained did not differ significantly (P> 0.05) between treatments for the three sampling times evaluated, indicating that differences in the obtained values are due to factors other than the treatments applied. According to Macedo *et al.* (2006) some changes in soil physical properties occur gradually over very long periods and are a function of climatic, soil and management factors, mainly.

In Figure 1 PT values are presented, which are within the acceptable range for this type of soil (approx. 50%) (Jaramillo, 2002). As with the DA no significant differences (P> 0.05) between treatments were found in the sampling months, indicating that the application of biosolids in the period of cultivation of sugarcane did not change the values of PT, as demonstrated by Melo *et al.* (2004), Macedo *et al.* (2006) and Dornelas *et al.* (2011).

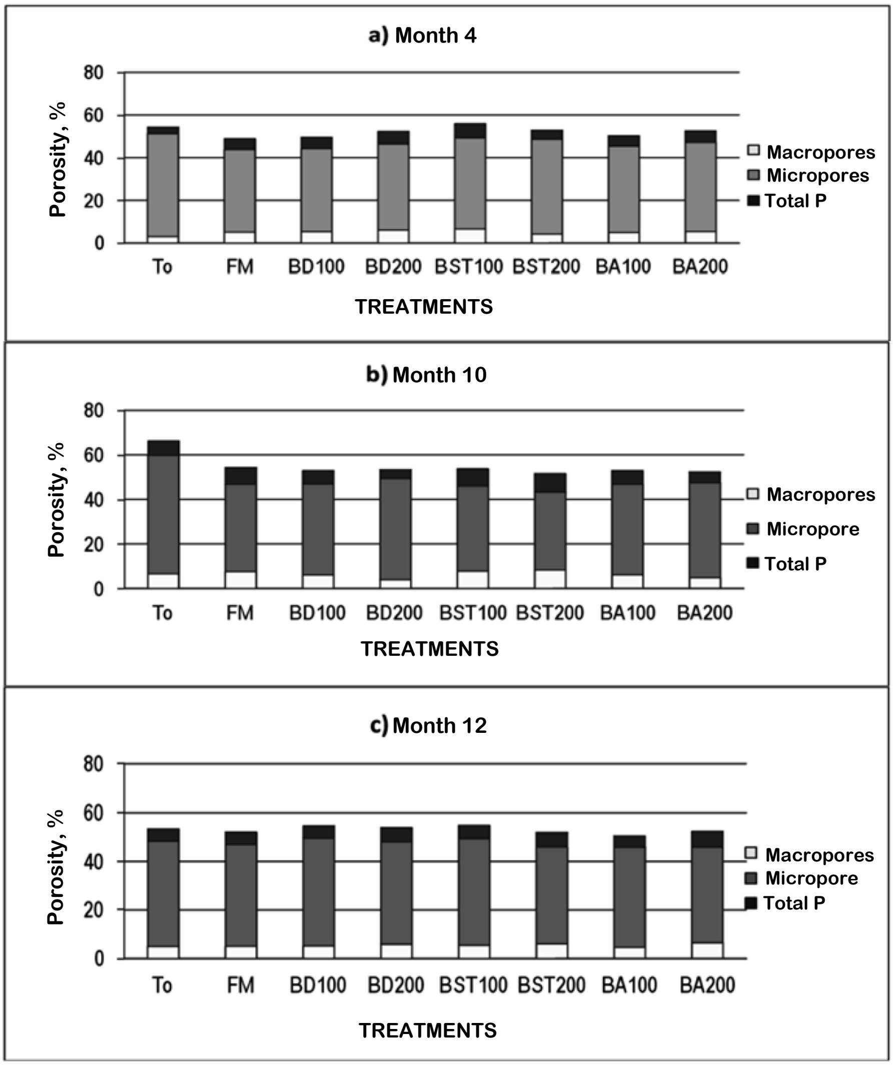


Figure 1. Behavior of soil porosity in each sampling period and treatment.

For the treatments with biosolids, PT values were similar, being BST100 which presented the higher value for all sampling periods, in concordance to the DA. The lowest values for PT occurred at BD100, BST200 and BA100 at 4, 10 and 12 m.a.p., respectively. The values of BD and BA showed no difference in soil PT when varying the application doses for sampling periods; while in the case of BST, the lowest dose favored the highest values of PT for all sampling times. In the case of mineral fertilization (FM), the PT was lower than that observed with biosolids 4 m.a.p., however, at 10 m.a.p. it presented the highest values coinciding with the values found for DA. This shows that application of OM improves the physical properties, including porosity, and promotes soil aggregation (Six *et al.*, 2004).

The values of macroporosity (MP) found were lower than 10% with coefficients of variation > 25%, probably due to the high spatial variability of the soil under study and sampling errors. According to Jaramillo (2002) MP values should be approximately 25%; values below 10% may indicate of soil compaction phenomena, revealing limitations for draining excess water and aeration of the crop. The control treatment showed lower MP values at 4 m.a.p., followed by mineral fertilizing and by the treatments with biosolids, being BD100 and

BD200 the ones that showed the highest values for all sampling periods.

This indicates that the addition of organic materials at early stages probably favored the formation of large aggregates (macrostructure) which determined the MP in this soil with vertic properties, which helps to generate more suitable conditions for germination and plant growth. However, in the other two sampling periods the BD100, BD200, BA100 and BA200 treatments reduced the MP in the soil, showing possible clay dispersion phenomena by the addition of dispersing elements to the soil such as Na^+ and Mg^{+2} contained in the biosolids, as demonstrated by Filizola *et al.* (2008). In BA100 and BA200 treatments is possible that the precipitation of calcium carbonate has initially presented around the pores, indicating cementation processes as demonstrated Glab and Gondek (2008).

MIP values found varied between 43% and 60% in all sampling periods, with no significant differences (P> 0.05) between treatments, with coefficients of variation lower than 20%, indicating the high capacity of moisture retention that these soils possess. Like the MP, the optimum values of MIP are around 25% and higher values indicate high moisture retention and low aeration (Jaramillo, 2002).

In the control treatment, for all sampling periods, higher MIP values were observed; while the addition of biosolids contributed to the decline of these values, which improves aeration and drainage conditions in the soil, with BST100 and BST200 treatments the ones with the lowest values. In treatments with biosolids, BST100 had the highest values 4 m.a.p.; while BD200 presented the highest values 10 m.a.p. However, at 12 ma.p., once most of the OM applied was mineralized, MIP values for all treatments were similar among them including the control and mineral fertilization. When comparing doses, BD and BA showed that increasing the dose increases the MIP, contrary to what happens with BST where the lowest dose the higher value was obtained.

The results of the variation of the values of the average weighted diameter (DPM), as a measure of structural stability (Table 5) allow this soil to be qualified as moderately stable (IGAC, 2006b). No significant differences (P> 0.05) were found among treatments; however, the lowest values of DPM were presented for To and FM treatments compared to the treatments with biosolids for all sampling periods, highlighting the role of the OM in the formation and increment of the size of the aggregates.

Among treatments with biosolids, BA100 and BA200 stand out as the ones

Table 5. Effect of biosolid application on the structural stability of the soil as particle

Treatments	**Time since sowing (months)**					
	4		**10**		**12**	
	Av. (mm)	**C.V. (%)**	**Av. (mm)**	**C.V. (%)**	**Av. (mm)**	**C.V. (%)**
To	1.62	15.0	2.30	33.5	3.21	7.2
FM	1.64	20.1	2.81	19.3	2.58	23.2
BD100	1.79	22.3	2.37	29.1	2.99	18.9
BD200	2.04	21.5	2.93	12.5	3.12	12.9
BST100	1.94	23.2	2.42	37.3	3.42	25.7
BST200	2.16	25.2	2.45	22.5	3.25	13.8
BA100	2.47	27.7	2.84	20.0	2.97	20.4
BA200	1.82	30.7	3.01	17.5	3.24	9.6
F value	1.875		1.307		1.345	
p value	0.100		0.273		0.256	
d.f.	7		7		7	

C.V. coefficient of variance.

that presented the highest DPM, showing the flocculant and stabilizing power of calcium. Higher doses of biosolids formed larger aggregates, showing a direct relationship between application of OM and DPM similar to that found by Six *et al.* (2004).

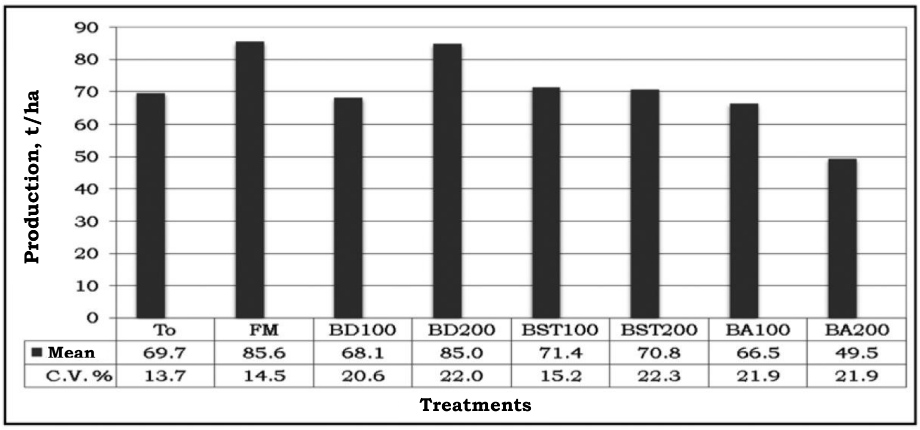
In general, the application of biosolids had no significant effect on the physical properties of the soil studied, whose characteristics did not allow structural changes with application rates used in the crop cycle; however, the application showed a tendency to decrease the DA, increase MP and DPM, improving soil physical conditions, being the treatment with heat-treated biosolid with 100% nitrogen dose the one that showed the best performance.

Crop yield

Figure 2 shows the yields obtained with different treatments (F = 2.2447, P> 0.05 - ns and 7 df) being similar to those found by Chiba *et al.* (2008). Yields ranged between 49.5 and 85.6 t/ha of sugarcane, results that were below average for the Valle del Cauca during the period 2010-2011 which were 114.6 and 122 t/ha of sugarcane, respectively (Cenicaña, 2011). These low yields are possibly due to the high rainfall at the time, by the presence of La Niña phenomenon, combined with cultural practices used as the location of the seed in the bottom of the furrow and not on the top (Ramirez, 2012) and to particular soil and variety (Victoria *et al.*, 2012) features.

The highest yield was reached with the mineral fertilization versus the other treatments, indicating that the conventional inorganic fertilization supplies the nutrient requirements of the crop (NPK) and that the application of organic fertilizers alone is not enough. The BA100 and BA200 treatments were the ones with lower yields, even below the control, probably due to, in addition to the above factors, the pH of soil under study is moderately alkaline, and when materials with high pH are added, can reduce the availability of essential elements, including phosphorus and the micronutrients Fe, Cu and Zn. Furthermore, excessive addition of Ca may create imbalances between cations and limit absorption of Mg and even K (Estrada, 2001).

Among treatments with biosolids, the BD200 was the one with the largest production, this being similar to that obtained by applying FM. When BD was applied, the highest yields were achieved with the highest doses of this treatment; whereas for BA and BST the response was inverse, that is, at lower doses greater performance, which coincided with the best physical conditions of the soil.



	To	FM	BD100	BD200	BST100	BST200	BA100	BA200
■ Mean	69.7	85.6	68.1	85.0	71.4	70.8	66.5	49.5
C.V. %	13.7	14.5	20.6	22.0	15.2	22.3	21.9	21.9

Figure 2. Effect of biosolids application on sugarcane crop yield.

Conclusions

- The application of biosolids did not produce significant differences in the physical properties of the soil tested or the crop yield; however, a tendency to increase macroporosity and structural stability and decrease the bulk density and microporosity in the soil was observed, with respect to the control treatments and mineral fertilization.
- The highest yield was achieved with mineral fertilization, which shows that sugarcane productivity depends, among other factors, on the overall soil fertility which includes not only the adequacy of the physical environment, but also a sufficient and adequate nutrient supply.

Acknowledgements

The authors thank Colciencias and Universidad del Valle for their financial support in the project 1106-489-25147, also thank the Municipal Companies of Cali EMCALI EICE ESP for allowing the completion of the research at the facilities of the Wastewater Treatment Plant Cañaveralejo-WWTP-C.

References

Barbosa, M. C.; Tavares Filho, J.; and Fonseca, I. C. 2007. Efeito do lodo de esgoto em propiedades físicas de um Latossolo Vermelho eutroférrico. Sem. Ciên. Agr. 28:65 - 70.

Camilotti, F.; Andrioli, I.; Marques, M.; Da Silva, A.; Tasso, L.; and De Nobile, F. 2006. Atributos físicos de um latossolo cultivado com cana-de-açúcar após aplicações de lodo de esgoto e vinhaça. Engenharia Agrícola, Jaboticabal 26(3):738 - 747.

Carbonell, J. 2010. Variabilidad espacial de la producción de caña de azúcar en el valle del río Cauca. Características físicas y químicas de los suelos y equipos de aplicación variable de fertilizantes. In: Memorias Curso de Nutrición y Fertilización de la Caña de Azúcar. Tecnicaña - Asociación de Técnicos Cultivadores de Caña, Cali. p. 197 - 207.

Castro, H. and Gómez, M. 2010. Fertilidad de suelos y Fertilizantes. In: Burbano, H and Mojica, F (eds.). Ciencia del Suelo. Principios básicos. Sociedad Colombiana de la Ciencia del Suelo. Bogotá, Colombia. p. 213 - 303.

Cenicaña (Centro de Investigación de la Caña de Azúcar de Colombia). 2011. Informe anual 2010. Cali. 105 p.

Chiba, M. K.; Mattiazzo, M. E.; and Oliveira, F. C. 2008. Cultivo de cana-de-açúcar em Argissolo tratado como lodo de esgoto. I: Disponibilidade de nitrogênio no solo e componentes de produção. Rev. Bras. Ciên. Solo. 32(2):532 – 643.

Civeira, G. and Lavado, R. 2006. Efecto del aporte de enmiendas orgánicas sobre propiedades físicas e hidrologicas de un suelo urbano degradado. Argentina. CI. Suelo 24(2):123 - 130.

Comisión Europea. Sewage sludge. European Commission, Brussels. Disponible en: http://ec.europa.eu/environment/waste/sludge/index.htm 2010.

Dornelas, M.; Vieira, M.; Araújo, L.; Pires, A. e Ferreira, H. 2011. Atributos físicos e químicos de área degradada tratada com lodo de esgoto. Jaguariúna, SP: Embrapa Meio Ambiente, Novembro. Circ. Tec. No. 21.

Estrada, G. 2001. Disponibilidad de calcio, magnesio y azufre. Su análisis en suelos y plantas y su interpretación. In: F. Silva (ed.). Los elementos secundarios (Ca, Mg, S) y el silicio en la Agricultura. Sociedad Colombiana de la Ciencia del suelo, Bogotá, p. 85 – 104.

Filizola, H. F.; De Souza, M. D.; Fereira, M.A. and Boeria, C. R. 2008. Aspectos físicos de um solo tratado com lodo de esgoto. Estabilidad de agregados e argila dispersa em agua. Em: Bettiol, W y Camargo, O.(eds.). Lodo de esgoto impactos ambientais na agricultura. Empresa Brasileira de Pesquisa Agropecuaria –Embrapra. 2ª. Edición. 349 p.

Glab, T and Gondek, K. 2008. Effect of organic amendments on morphometric properties of macropores in stagnic gleysol soil. Pol. J. environ. Stud.17(2):209 - 214.

IGAC (Instituto Geográfico Agustín Codazzi). 2006a. Estudio detallado de suelos y capacidad de uso de las tierras sembradas con caña de azúcar localizadas en el valle geográfico del río Cauca. CD-ROM.

IGAC (Instituto Geográfico Agustín Codazzi). 2006b. Métodos analíticos del laboratorio de suelos. Sexta Edición. Bogotá. Imprenta Nacional de Colombia. 674 p.

Jaramillo, D. 2002. Introducción a la ciencia del suelo. Universidad Nacional de Colombia, Facultad de Ciencias. 613 p.

Macedo, J. R.; Souza, M. D.; Reichardt, K.; and Bacchi, O. S. 2006. Atributos físicos e hídricos em solo tratado com lodo de esgoto. In: Bettiol, W. y Camargo, O. A (Eds.). Lodo de esgotoimpacto ambiental do uso agrícola. Jaguariúna, Embrapa Meio Ambiente. p. 193 - 205.

Melo, V. P.; Beutler, A. N.; Souza, Z. M.; Centurion, J. F. e Melo, W. J. 2004. Atributos físicos de Latossolos adubados durante cinco anos com biossólido. Pesqu. Agropecu. Bras. 39:67 - 72.

Ojeda, G.; Alcañiz J. M.; and Le Bissonnais, Y. 2008. Differences in aggregate stability due to various sewage sludge treatments on a Mediterranean calcareous soil. Ecosys Environ, 125:48 - 56.

Pinzón, A. 2009. Apuntes sobre física de suelos. Cargraphics S.A. Bogotá. 44 – 46 p.

Pla, I. 2010. Medición y evaluación de propiedades físicas de los suelos. Dificultades y errores más frecuentes. I-Propiedades mecánicas. Suelos Ecuatoriales 40 (2):75 - 93.

Potisek, M.; Figueroa, U.; González, G.; Jasso, R. and Orona, I. 2010. Aplicación de biosólidos al suelo y su efecto sobre contenido de materia orgánica y nutrimentos. Sociedad Mexicana de la Ciencia del Suelo, A. C Terra Latinoamericana 28(4):327 - 333.

Ramírez, C. 2012. Estudio de algunos factores que afectan la germinación de la caña de azúcar. Tesis de grado Ingeniería Agrícola Universidad del Valle. Cali, Colombia. 106 p.

Ramírez, R. and Pérez, M. 2006. Evaluación del potencial de los biosólidos procedentes del tratamiento de aguas residuales para uso agrícola y su efecto sobre el cultivo de rábano rojo (*Raphanus sativus* L.). Rev. Fac. Nal. Agr. Medellín. 59 (2):3543-3556.

Silva, J. A.; Torres, P.; and Cardoza, Y. 2013. Thermal drying and alkaline treatment of biosolids: Effects on nitrogen mineralization. Clean Soil, Air, Water 41(3):298 – 303.

Six, J.; Bossuyt, H.; Degryze, S.; e Denef, K. 2004. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil Tillage Res. 79:7 - 31.

Torrente, A. 2007. Importancia de las propiedades físicas del suelo en el uso eficiente del agua en la agricultura de alto rendimiento. Suelos Ecuatoriales 37(1):15 – 23.

Torres, P.; Silva, J.; and Escobar, J. C. 2007. Aplicación agrícola de lodos compostados de plantas de tratamiento de aguas residuales municipales. Livest. Article #184. Retrieved September 19, 2012, Res. Rur. Develop. 19(12). From http://www.lrrd.org/lrrd19/12/torr19184.htm

Tsadilas, C.; Mitsios, I.; and Golia, E. 2005. Influence of biosolids application on some soil physical properties. Soil Sci. Plant. Anal. 36:709 - 716.

Uribe, M. H.; Chavez, N. and Orozco, G. 2003. Uso de biosólidos como fertilizantes en cultivos forrajeros y algodón. En: Salazar, E.; Fortis, M.; Vazquez, A. A.; y Vazquez, V. C. (eds.). Agricultura orgánica. Facultad de Agricultura y Zootecnia de UJED Sociedad Mexicana de la Ciencia del Suelo. 271 p.

USDA (United State Department of Agriculture) . 2011. Natural resources conservation service. National Agronomy Manual. 4th. Ed. 190–V–NAM.

Victoria, J.; Amaya, A.; Rangel, H.; Viveros, C.; Cassalett, C., *et al.* 2002. Características agronómicas y de productividad de la variedad Cenicaña Colombia (CC) 8592. Cenicaña - Centro de Investigación de la Caña de Azúcar de Colombia. Serie Técnica no. 30. 79 p.

WEF - Water Environment Federation. 1998. Biosolids Composting. Special Publication. EE.UU. 187 p.