Agronomía Colombiana
ISSN: 0120-9965
ISSN: 2357-3732
Universidad Nacional de Colombia, Facultad de Agronomía

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Agronomía Colombiana, vol. 38, no. 2, 2020, May-August, pp. 242-252
Universidad Nacional de Colombia, Facultad de Agronomía

DOI: https://doi.org/10.15446/agron.colomb.v38n2.81842

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Impacto de lodos secos y biocarbón de lodos sobre la altura y materia seca de *Solanum lycopersicum* L.

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ABSTRACT

The generation of sludge as anthropic waste is a fundamental pollution problem. However, its conversion to biochar can be an alternative to conventional fertilization for its management and use in agriculture. In this research, we evaluated the effect of the application of different doses of dry sludge (DS) and biochar of pyrolyzed sludge (PS) on the height and dry matter of a tomato (*Solanum lycopersicum* L.) crop and the nutrient content in the substrate. The biochar was made by rapid pyrolysis, and the substrate and the dry matter of plants were analyzed by different physical and chemical methods. An evaluation of 11 treatments was carried out in allometric measurements of plants and foliar dry matter, in three replicates with two materials (DS and PS) added to the substrate at different levels. The plant height and dry weight were evaluated using an incomplete factorial design in a completely randomized arrangement by performing statistical analysis of multivariate variance. An increase in plant height and dry weight was observed when the doses of DS and PS were increased; however, there were no statistical differences between the two materials. The amount of carbon, organic matter, and Ca concentrations in the dry leaf weight were increased with the addition of DS and PS. Likewise, the use of these materials as conditioners or amendments to agricultural soil at doses of 10-15 t ha^{-1} may be viable and can contribute to reducing environmental externalities through the use of these anthropic waste materials.

Key words: substrate, tomato, pyrolysis, soil fertility.

RESUMEN

La generación de lodos como residuos antrópicos es un problema fundamental de contaminación. Sin embargo, su conversión a biocarbón puede ser una alternativa a la fertilización convencional para su manejo y uso en la agricultura. En este trabajo se evaluó el efecto de la aplicación de diferentes dosis de lodos secos (LS) y biocarbón de lodos pirolizados (LP) sobre la altura y materia seca de un cultivo de tomate (*Solanum lycopersicum* L.) y sobre el contenido de nutrientes en el sustrato. El biocarbón se elaboró por pirolisis rápida, y el sustrato y la materia seca de plantas se analizaron mediante diferentes métodos físicos y químicos. Se evaluaron 11 tratamientos en medidas alométricas de plantas, sustratos y materia seca foliar, en tres réplicas con dos materiales (LS y LP) adicionados en diferentes niveles al sustrato. La altura y materia seca de la planta se evaluaron bajo un diseño factorial incompleto en arreglo completamente al azar, realizando un análisis estadístico de varianza multivariante. Se observó un incremento en la altura y materia seca en las plantas cuando aumentaron las dosis de LS y LP; sin embargo, no existieron diferencias estadísticas entre los dos materiales evaluados. La cantidad de carbono, la materia orgánica y las concentraciones de Ca en el sustrato aumentaron con la adición de LS y LP. Así mismo, el uso de estos materiales como acondicionadores o enmiendas del suelo agrícola puede ser viable en dosis de 10-15 t ha^{-1} aportando en la disminución de externalidades ambientales mediante el uso de estos materiales de desecho antrópico.

Palabras clave: sustrato, tomate, pirólisis, fertilidad del suelo.

Introduction

The accelerated process in urbanization and industry has generated an increase in the production of waste from industrial, domestic, and agricultural activities. Simultaneously to this development, protection policies have been established for the different ecosystems. However, the associated problems persist, particularly in water ecosystems. The construction of alternatives that mitigate pollution, such as aqueducts, sewers, and industrial and municipal treatment plants (wastewater treatment plants (WWTP)) has been encouraged. Although these plants manage to control water pollution problems to a large extent, some by-products, such as sludge, are generated.

Received for publication: 22 August, 2019. Accepted for publication: 8 June, 2020

Doi: 10.15446/agron.colomb.v38n2.81842

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These by-products are produced from the accumulation of solids found in the effluent (primary sludge) or from the suspension of solids (activated sludge) that results from dissolved solids in wastewater (Morales, 2005).

For the first decade of this century, the average sludge production worldwide was estimated at approximately 30 kg per person/year (Hospido *et al*., 2010). In Colombia, approximately 247 t of these sludges are generated (94 t dry weight), of which 97% are produced in three treatment plants: Cañaveralejo, San Fernando, and Salitre (PTAR, 2009). Specifically, Salitre treats wastewater from the Salitre river and the Torca and Conejera wetlands, generating about 150 t/d of sludge that could be used in the reforestation of degraded soils (EAAB, 2009). These sludges are rich in macronutrients such as N and P, micronutrients such as Zn and Mo, and organic matter. However, they also contain some pathogens and heavy metals (Hartman *et al*., 2003); in consequence, the disposition of these materials must be done carefully, both for the volumes that are generated and for the environmental risks they represent.

An alternative for improving fertility indicators and the quality of degraded soils is the inclusion of exogenous organic materials. Through the application of organic amendments, the nutrient status in the soil is improved, and these amendments can serve as a source of macro and microelements to improve the functions and physical-chemical processes of the soil (Lal, 2016). So, the use of sludge in the soil or as an agricultural substrate can serve as an option for increasing yields of different crops. However, it should be noted that many of these materials must be stabilized before application because of potentially toxic elements and pathogens. Through the composting process, it is possible to obtain dry sludge (DS) for uniform and biologically stable products that can act as a source of nutrients for plants (Sullivan *et al*., 2002).

One of the strategies reported in the literature for improving soils and reducing or neutralizing these adverse elements is the incineration of these materials through pyrolysis, which consists of the burning of organic materials in the absence or low levels of oxygen. One of the products obtained under this process is biochar, also known as pyrolyses or biocarbon. These are solid products of fine and porous grain obtained from the thermal conversion of biomass in a limited oxygen environment. Biochar is similar to coal, which is produced by natural burning, and that reaches great stability in the soil compared to the nitric Nitrogen from which it comes (Lehmann and Joseph, 2009; IBI, 2012). According to Amonette (2009), biochar has a high content of organic carbon, with high resistance to decomposition and high residence time in soils. These characteristics prevent the transformation of biochar and its early release of CO_2 into the atmosphere. Biochar creates a recalcitrant carbon deposit (carbon-negative) that functions as a carbon sequestration network (FAO, 2004). Likewise, this material, acting as an amendment or soil conditioner, can improve the soil's physical condition towards better nutrients adsorption, increased cationic retention, and reduced N_2O emissions (Lal, 2004; Lehmann *et al*., 2005). In addition, biochar can promote the sorption of organic compounds such as pesticides, herbicides, and enzymes, retain pollutants such as cadmium and chlorinated compounds (Escalante-Rebolledo *et al*., 2016), toxic organic compounds such as dioxins, furans, esters, polycyclic aromatic hydrocarbons and other organic pollutants (Agrafioti *et al*., 2013).

Both the direct application of dry sludge (DS) in agricultural systems and the conversion of DS to pyrolyzed sludge (PS) for later incorporation can represent an economically and environmentally viable alternative for the disposal of these materials reducing their polluting potential. Kistler *et al*. (1987), Paterson *et al*. (2008), and Hossain *et al*. (2010) showed that the addition of biochar from sludge to tomato crops increased the agrological properties of the soil, which increased crop yield and production. Likewise, these authors claim that the heavy metals concentrated in the solid product become more chemically and biologically inert, decreasing transport or bioaccumulation in the plant and in soils when biochar is used as an amendment.

Nzanza *et al*. (2012) report that no benefits were found for fruit yield and nutrient absorption with the addition of PS and tree mycorrhizae to the soil of a tomato crop. Because of contrasting results like these found in the literature, more research is needed for plant species of great agricultural importance regarding the effect of biochar application to the soil/substrate, particularly when DS is used.

The objective of this research was to evaluate the variables (height (cm) and dry matter (g)) of tomato plants in pots, by analyzing the characterization of DS and PS and dry leaf weight, after adding DS and PS to the substrates at different doses. The results showed that the plant height and dry weight increased when these doses of sludge increased. However, no significant differences were found when the treatments between the two types of materials were compared.

Materials and methods

Analysis of soil samples

The soil used in the experiment was a degraded soil from the municipality of La Vega (Colombia). The soil samples were used as a substrate and were placed in each of the experimental units: pots of 15.5 cm for the upper diameter, 11.5 cm for the lower diameter, with heights of 11.0 cm and two-liter capacity. Previously, the samples were dried at room temperature for 10 d and then placed in a REDLINE RF 115 mechanical convection drying oven (General Lab & Cleanroom Supply, California, USA) at 70°C for 72 h. The samples were then ground and passed through a 2 mm sieve and sent to the Soil and water laboratory at Universidad Jorge Tadeo Lozano, Bogota, Colombia, for analysis.

The samples were evaluated for the following characteristics: texture, organic matter, pH, cation exchange capacity (CEC), macro and micronutrients, among which heavy metals (totals) were also analyzed. We determined the percentage of clays, silt, and sand using the Bouyucos method. It is important to indicate that the characterization of the chemical elements of the soil used in the research is represented by the T_0.

We quantified organic matter according to the methodology of Walkley and Black (Kumada, 1987) and SSL (Soil Survey Laboratory) (1995). N was determined using Kjedahl digestion. We measured the pH in water in a 1:1 ratio (You *et al.*, 1999) in 20 g of soil/20 g of H_2O. The CEC was determined based on the sum of the bases, extracted with NH_4O Ac 1 N at pH 7 (BT). We determined the exchangeable acidity (EA) with KCl 1 N (Motta, 1990) and phosphorus availability with lactate (Egner, 1941). The B was analyzed with azomectin H (Wolf, 1974), the S was determined with turbidimetry (Combatt *et al.*, 2014), and the Fe, Mn, Cu and Zn were analyzed using the diethylene triamine-pentacetic acid (DTPA) method.

Foliar analysis in the different treatments

Destructive sampling was carried out using six-month-old plants, which were dried at 70°C for 72 h and then incinerated. The incinerated material was analyzed to determine different macro and microelement values, using the following techniques: N by Kjeldahl method, P and B by colorimetry, K, Ca, Mg, Na, Fe, Mn, Cu and Zn by atomic absorption, and S by turbidimetry (Combatt *et al.*, 2014).

Preparation of dry sludge (DS) and biochar (PS)

The DS was obtained from the saltpeter PTAR located in Bogota D.C. (Colombia). DS was then dried outdoors for 30 d at room temperature (30°C) in the greenhouses of the Faculty of Agricultural Sciences of the Universidad Nacional de Colombia. Approximately 5 kg of DS were used for the production of the PS biochar. A proportion of this material was pyrolyzed in the rotary kiln of the Department of Mechatronics of the Faculty of Engineering of the Universidad Nacional de Colombia, Bogota campus. The PS was obtained under rapid pyrolysis with a temperature of 850°C for 40 min and a heating rate of 80-100°K/min. The PSs were prepared according to the methodology proposed by Jeffery *et al.* (2011).

The obtained PS (1.5 kg) was packed in bags and stored at room temperature at 15°C as average temperature and then was taken to the Soil biology laboratory at the Faculty of Agricultural Sciences of the Universidad Nacional de Colombia, for chemical and physical characterization. Before applying the different treatments, a ball hammer and two sieves of number 10 and 20 with openings of 2.0 and 0.85 mm, respectively, were used to reduce the particle size of the two materials. For the PS, an approximate grain size of 2 mm was used. These assessments were performed considering the International Biochar Initiative and the set of characteristics that define the quality of biochar for use in agriculture. Those parameters include particle size distribution of these materials, pH, specific area, porosity, C, and nutrient content, as well as pollutant content (heavy metals and polycyclic aromatic hydrocarbons) (IBI, 2012). The chemical analysis of both PS and DS was determined under the same parameters of the soil samples. The chemical characterization of the two materials is shown in Table 1.

We performed a laboratory characterization of the two sludges of the treatments with the following variables: bulk density, cation exchange capacity (CEC), organic carbon, organic matter, ash, carbon/nitrogen ratio, pH (acidity reaction), total nitrogen, ammoniacal nitrogen, nitric nitrogen, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), sodium (Na), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn) and boron (B) (Tab. 1).

Experimental design

We carried out the test in the greenhouses of the Faculty of Agricultural Sciences of the Universidad Nacional de Colombia between February and July 2015, under average daytime temperatures of 24°C and average nighttime temperatures of 18°C. The experiment was carried out in the pots. The soil mixed with the biocarbon and DS (substrate) was placed in the pots. We planted five seeds of the tomato variety Miland at a depth of 3 cm. We previously treated the seeds with hot water to counteract possible pathogens. Once

TABLE 1. Evaluated properties of dry and pyrolyzed sludge.

Variables		Dry sludge	Pyrolyzed sludge	Relative change (%)
	Units	Dry base	Dry base	
Bulk density	g cm^{-3}	0.88	0.79	-10.23$^{(+)}$
Cation exchange capacity (CEC)	cmol kg^{-1}	28.17	64.45	128.79
Organic carbon	%	20.4	19.31	-5.34
Organic matter	%	44.26	41.9	-5.33
Ashes	%	55.74	58.1	4.23
Carbon/Nitrogen ratio	w/w	8.5	8.05	-5.29
pH (acidity reaction)		5.8	5.9	1.72
Total Nitrogen	%	2.4	2.4	0.00
Ammoniacal Nitrogen	%	0.024	0.084	250.00
Nitric Nitrogen	%	0.075	0.123	64.00
Phosphorus (P)	%	0.93	1.1	18.28
Potassium (K)	%	0.21	0.35	66.67
Calcium (Ca)	%	1.900	2.8	-99.85
Magnesium (Mg)	%	0.24	0.27	12.50
Sulfur (S)	%	0.62	2.1	238.71
Sodium (Na)	%	0.056	0.062	10.71
Iron (Fe)	ppm	4183	17372	315.30
Manganese (Mn)	ppm	179	286	59.78
Copper (Cu)	ppm	29.6	37.2	25.68
Zinc (Zn)	ppm	360	777	115.83
Boron (B)	ppm	14	13.5	-3.57

(+) Values given by 100*(end _ value-start _ value)/start _ value). The sign (-) means a decrease.

the seeds germinated after 10 d, we transplanted those with the most vigor into the center of each pot, which were randomly arranged on the greenhouse tables. We irrigated the plants by sprinkling with a flow rate of 2 L/h, three times a week, based on the needs of the crop. We subsequently sampled the plants destructively six months after sowing when they had grown eight branches; the biomass on the soil surface was collected by cutting at the base of the stem. No chemical and organic synthesis products were applied during the test. In the absence of reference levels for the doses established for both DS and PS, we based the amounts that we applied in this research on studies by Chan *et al.* (2007) and Van Zwieten *et al.* (2009), who determined benefits of biochars produced from paper sludge and poultry feces with an average dose of 10-15 t ha^{-1}.

The experimental design was associated with an incomplete factorial in a completely randomized arrangement, since the doses were nested for each material, with DS and PS materials. The nested doses were 0.0, 2.5, 5.0, 7.5, 10.0, and 15.0 t ha^{-1} consisting of 12 randomized treatments on the experimental units (pot with a tomato plant), using three repetitions per treatment. The treatments were labeled as follows: (T_0) control (only soil for both materials); (DS_1) 2.5 t ha^{-1}; (DS_2) 5 t ha^{-1}; (DS_3) 7.5 t ha^{-1}; (DS_4) 10 t ha^{-1}; (DS_5) 15 t ha^{-1}; (PS_1) 2.5 t ha^{-1}; (PS_2) 5 t ha^{-1}; (PS_3) 7.5 t ha^{-1}; (PS_4) 10 t ha^{-1}; and (PS_5) 15 t ha^{-1}. The response variables evaluated simultaneously were dry matter (g), and height (cm) of the plants measured six months after planting. Finally, with the same treatment structure, we evaluated the macro and microelements (N, P, K, Ca, Mg, Cl, Fe, Mn, Cu, and Zn) in leaves 6 months after sowing.

Statistical analysis

The relative change was analyzed taking into account the final values of the variables of PS compared to the initial values of DS, represented by a radial diagram. An exploratory analysis of the data was carried out to describe the variables involved in the study statistically. The analysis included calculations of the mean, standard deviation, and coefficient of variation of the two response variables (height and plant weight), discriminated by treatment. A conditional graph was constructed to show the relationships of all the variables involved.

A bivariate analysis of variance was used for the evaluation of the effects of the added material and its nested doses on the height and weight of the plant, for the incomplete factorial experimental design in a completely randomized arrangement. We validated the assumptions of bivariate normality and equality of matrices of variances and covariances by treatments using the Roystone test and the Box M test, respectively. The statistical package R was used for all analyses. For the analysis of the macro and micro nutritional elements of the leaf, the relative percentage change of the treatment was measured with a higher average compared to the control.

Results and discussion

Under the conditions of this study, the apparent density showed a 10.23% reduction in the conversion of DS to biochar or PS, which could be caused by the micropores that are generated when the temperature in the pyrolysis process increases (Verheijen *et al*., 2009). The pH level remained stable in the conversion from DS to PS, despite rapid pyrolization (high temperature and short residence times), which is thought to increase alkalinity due to the loss of carboxylic acid groups by temperature (Harris and Tsang, 1997). This situation could be due to the fact that there was no significant change in the amounts of organic carbon in this conversion, i.e., there would not be a noticeable loss of these functional groups. In addition, higher levels in the contents of P and K were found in treatments with PS as well as a greater positive percentage difference for these treatments (Tab. 1).

There could be a significant contribution of P from protein materials and polyphosphates (which were not lost in the pyrolysis process) from detergents that might be constituents of the evaluated DS (Korboulewsky *et al*., 2002; Esteller *et al*., 2009). However, the levels of total N, Mg, and Na were similar for the two materials (with increases not greater than 13% in the percentage change in the conversion from DS to PS). The permanence of the levels of these elements after pyrolysis in the PSs could be due to the fact that the temperatures did not reach the point of volatilization. In contrast, Gaskin *et al*. (2008) found the volatilization of N in sludge when the temperature was increased from 300 to 700°C.

In general, the percentages of micronutrients were higher in the PS, while organic matter showed higher levels in the DS. In contrast, authors such as Okuno *et al*. (2005) consider that Ca begins to decrease in the biochar matrix in pyrolysis with temperatures above 600°C. The higher values of Ca in the PSs in this study may be associated with higher levels in the height and dry matter of the plant. With the addition of PS, there is an increase in water retention capacity and a greater uptake of nutrients due to an increase of the CEC (Fig. 1).

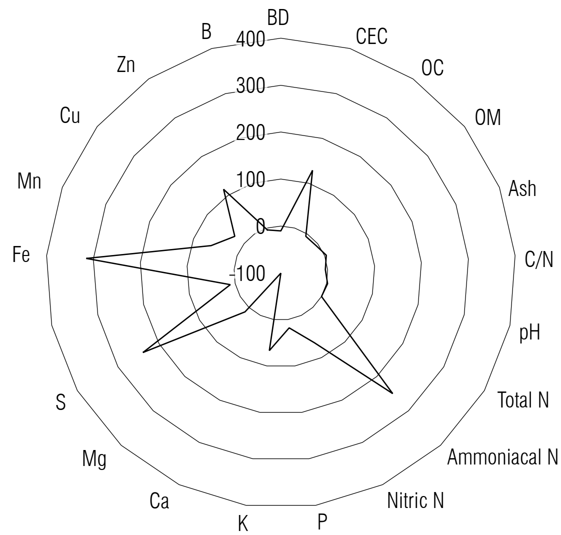

FIGURE 1. Relative changes in physical and chemical properties of biochar from sludge to dry sludge. BD - bulk density, CEC - cation exchange capacity, OC - organic carbon, OM - organic matter, Ash - ashes, C/N - carbon/nitrogen ratio, pH - potential reduction, Total N - total nitrogen, Ammoniacal N - ammoniacal nitrogen, Nitric N - nitric nitrogen, P - phosphorus, K - potassium, Ca - calcium, Mg - magnesium, S - sulfur, Fe - iron, Mn - manganese, Cu - copper, Zn - zinc, B - boron.

Fe, Cu, and Zn increased with the conversion from DS to PS in percentages of 315.35%, 25.6%, and 115.8%, respectively (Tab. 1). Some studies corroborate the results of our research, in which authors such as Lehmann *et al.* (2006) establish that, although nutrients such as N and P in the sludge may decrease due to volatilization during pyrolysis, heavy metals, such as Cu and Zn, can increase their concentration. In studies by Hossain *et al.* (2010), different heavy metals such as Zn, Pb, and Ni increased their contents in sludge pyrolysis at temperatures greater than 500°C. This implies that the increase of these elements with PS in the substrate can affect the chemical properties of the sludge, so that there is a competition of nutrients with a high amount of Fe.

Regarding the CEC, a relative change (increase) of 128.8% was found for the PS with reference to DS. This result is contrary to the expected decrease in the values of this variable, as reported by Lin *et al.* (2012) and Rajkovich *et al.* (2012), and could happen due to the removal of functional groups that increase ion retention with their load.

The higher level of CEC in the PSs in this research could be due to a high number of these groups and also to the conservation of heteroatoms within them (Cantrell and Martin, 2012).

With increasing doses of both PS and DS in each treatment, there was a tendency to increase the dry weight and height of the plants (Fig. 2). The bivariate analysis of variance showed no significant effect attributable to the PS and DS materials on the height or the dry matter (*P*=0.788) of the plants but rather between doses of each material (*P*<0.001) (Tabs. 2 and 3).

TABLE 2. In-treatment dose test statistics.

Statistics	Value	F-Value	Num DF	Den DF	Pr>F
Wilk'Lamda	0.979	0.24	2	23	0.788

TABLE 3. Inter-material dose test statistics.

Statistics	Value	F-Value	Num DF	Den DF	Pr>F
Wilk'Lamda	0.003	9.21	20	46	<.0001

In both DS and PS, the control was below average compared to the other treatments. Taking as reference the treatments with higher plant heights (DS_5 and PS_5), the control plants were found to be 27.63% and 30.92% shorter than PS_5 and DS_5 plants, respectively (Tab. 4). As in the present study, Hossain *et al.* (2001) reported significant effects on the height of cherry tomato plants with applications of biochar made with sludge from treatment plants in the Sydney area (Australia). In that study, applications of biochar were evaluated in the greenhouse, both alone and in mixtures with inorganic fertilizers, using doses of 10 t ha^{-1}. Likewise, Silva *et al.* (2017) found similar results in seedlings of *Eucalyptus grandis* W. evaluating DS and PS.

In accordance with the present research, Cabrera *et al.* (2007) also found a positive effect on the height of tomato plants with the addition of DS to the soil from a WWTP, compared to soils fertilized with urea and soils without fertilization in the greenhouse. Such results can be attributed to improvements in some chemical properties of soils

TABLE 4. Descriptive statistics for response variables height (cm) and dry weight (g) of plants.

		Dry sludge						Pyrolyzed sludge					
		Dose											
		0	2.5	5	7.5	10	15	0	2.5	5	7.5	10	15
Variables													
Height	Ẋ*	16.100	20.900	28.733	31.066	39.200	58.266	16.100	20.766	29.566	35.800	42.466	52.066
	S**	2.080	4.300	3.611	3.827	6.148	3.295	2.080	3.234	2.274	6.791	6.143	5.772
	CV***	12.924	20.574	12.569	12.321	15.686	5.656	12.924	15.576	7.692	18.969	14.466	11.087
Dry weight	Ẋ*	6.217	9.260	16.715	21.071	30.678	49.717	6.217	7.913	15.922	25.221	30.478	46.175
	S**	2.883	2.065	2.692	2.316	3.397	5.767	2.883	1.012	1.060	7.519	5.719	7.839
	CV***	46.37	22.30	16.109	10.991	11.074	11.600	46.378	12.792	6.662	29.812	18.766	16.977

*Ẋ: average, **S: standard deviation, ***CV: coefficient of variation.

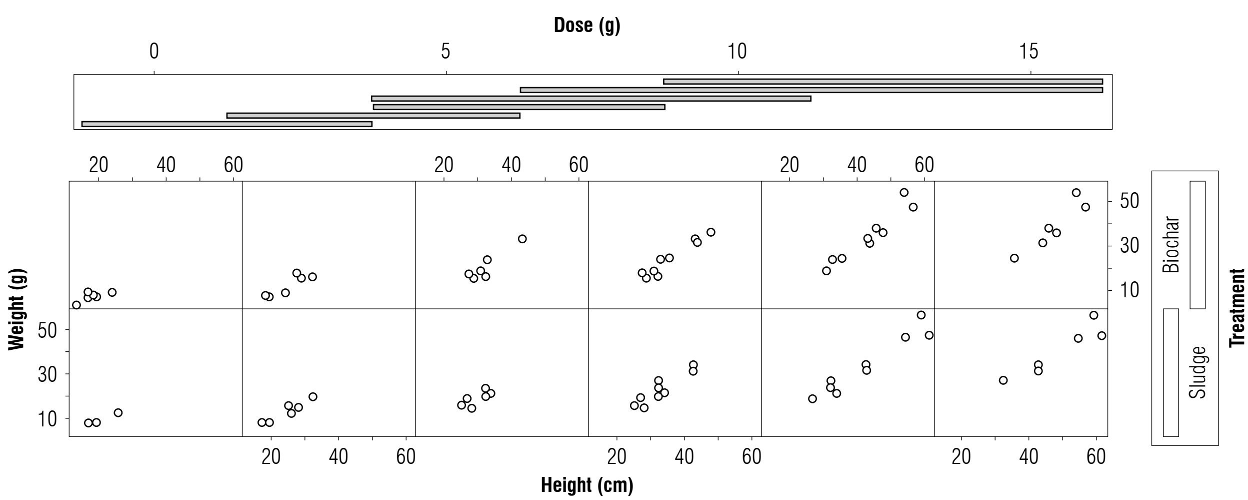

FIGURE 2: Dry weight distribution as a function of plant height per nested dose in each experimental treatment.

produced by an application of these materials, due to the contribution of immediate and gradual inorganic forms of organic molecules.

In this research, dry matter and plant height increased with the addition of higher doses of both LS and LP. The control plants (with an average of 6.2 g of dry matter) were found to have 12.5% and 13.2% less dry matter than the DS_5 and PS_5 plants, respectively (Tab. 4). This could be due to the fact that these types of sludge contain high amounts of nutrients and organic matter that could have a positive effect and contribute to a greater gain of dry matter given higher doses of these materials (Melo *et al.*, 2007). In this regard, Moral *et al.* (2005) also state that higher production of plants may be due to a greater amount of organic matter present in the biochar. These organic elements are composed of proteins, simple sugars, organic acids, amino acids, and peptides that are easily degraded by microorganisms, increasing those populations that contribute to a greater dynamic of transformation from non-soluble elements to elements available to plants. The addition of PS could cause greater production and growth in the plant by the reduction in the leaching of nutrients and the increase in the union of organic matter and nutrients through the cation exchange capacity (Amonette, 2009; Granatstein *et al.*, 2009; Atkinson *et al.*, 2010; Lehmann *et al.*, 2011).

In other studies, in tomato, Hossain *et al.* (2010) found no significant differences with the addition of PS at doses of 10 t ha^{-1} and inorganic fertilizers. However, the researchers reported higher plant growth with amendments added to sludge biochar mixtures and chemical fertilizers. In the present research, with the comparative analysis of the application of the two materials, the profiles and effects were similar to the response in dry weight (g) and height (cm) of the evaluated tomato plants (Fig. 2).

The increase in dry matter and height in the plants with the addition of PS in this study could be related to the contribution of these materials to generate better conditions and dynamics of the different properties of the substrates and, therefore, improve plant growth. In this sense, studies such as those by Glaser *et al.* (2002) describe improvements in the different properties of the soil with the addition of biochar or pyrolysis and the increase of dry matter in plants. The researchers argue that *terra preta* soils have approximately 18% higher water retention values, compared to adjacent soils. Thus, the addition of any organic amendment produces an increase in water retention, which will be represented as a positive increase in the different properties of the soil, and consequently, in improved nutrient uptake by plants. On the other hand, Hue and Ranjith (1994), McBride *et al.* (1997), and Shuman (1998) state that dry sludge can increase nutrient availability due to the low molecular weight of its aliphatic components and the increase of CEC in the soil.

Comparing the application of the DS and PS carried out according to the norms of this study, the use of biochar from PS could be a better option because of the stabilization of this material that occurs in its conversion to biochar through the pyrolization process. For example, the use of PS can reduce the availability of heavy metals included in the soil, which pass into the trophic chain through the root absorption of plants (Mtshali *et al.*, 2014). Although present at low values, the increase of metals such as Fe and Cu in the conversion of dry sludge to biochar in percentages of 3.1 and 0.2%, respectively, was evident in this research (Tab. 1).

Foliar analysis

According to the different percentages of nutrients from the foliar samples found in the various treatments compared to the control, generally, higher levels of micronutrients were found in the PS treatments. However, higher values were found in the macronutrient levels of the DS (except for K) (Tab. 5).

The absorption of N by tomato plants was present at higher levels within the PS treatments for treatments with higher doses of this material. For example, treatment LP_5, with the highest dose of PS in the substrate, showed the highest concentration of N in plant tissues in the pyrolyzed treatments. This could be due to the concentration of N in the ashes of the biochar adsorbed by the plant from the substrate. In this sense, authors such as Steiner *et al.* (2008), Zimmerman (2011), Lehmann *et al.* (2010) and Rajkovich *et al.* (2012) suggest that the uptake of nutrients such as N increases in biochar that comes from high temperatures because they contain a lower labile fraction. This means that there is less immobilization by microorganisms and, therefore, there is a greater amount of N available to be absorbed by the plant. Among the PS treatments, the PS_5 showed the highest level of Ca in the leaf tissue of the plants (Tab. 5), which could be correlated with a higher level of biochar for this treatment, due to the initial high concentration of Ca in the added PS material (Tab. 1).

However, the function of K is associated with root growth, tolerance to water stress, cellulose formation, enzymatic activity, and photosynthesis (Thomson, 2008). Although the treatments with higher doses of the two materials in this study had the highest yields (dry matter) and heights (DS_5 and PS_5), the same was not found regarding K uptake

TABLE 5. Foliar analysis of nutritional elements in different treatments with applications of dry sludge and sludge biochar in *Solanum lycopersicum* L.

Treatments	Macro elements (g*100 g^{-1})						Micro elements (g*100 g^{-1})					
	N	P	K	Ca	Mg	S	Na	Fe	Mn	Cu	Zn	B
T_0	0.16	6.51	0.72	4.86	1.20	-	-	42.8	1.93	0.31	0.36	0.51
DS_1	2.25	0.19	3.50	1.90	0.63	0.52	0.129	3793.0	193.0	9.7	67.9	17.7
DS_2	1.49	0.20	2.80	1.40	0.34	0.41	0.059	14036.0	150.0	5.2	44.7	15.3
DS_3	1.11	0.20	2.40	1.50	0.25	0.39	0.055	3693.0	121.0	8.1	39.4	16.1
DS_4	2.26	0.24	2.70	1.60	0.42	0.41	0.073	7608.0	184.0	8.9	71.6	19.1
DS_5	1.68	0.22	3.10	1.90	0.45	0.48	0.0071	4448.0	164.0	8.8.	58.4	20.2
PS_1	1.46	0.24	3.30	1.70	0.55	0.39	0.150	4786.0	178.0	7.4	62.1	16.0
PS_2	1.86	0.24	3.00	1.80	0.52	0.31	0.081	6135.0	213.0	7.6	62.3	17.4
PS_3	1.87	0.22	3.80	1.40	0.53	0.35	0.094	3769.0	170.0	12.8	86.8	28.6
PS_4	1.33	0.24	3.40	1.40	0.32	0.38	0.056	2164.0	93.3	8.1	65.5	21.2
PS_5	2.03	0.24	2.80	1.90	0.45	0.38	0.077	3675.0	170.0	12.4	93.5	33.1
Minimum optimal level	2.80	0.30	3.50	1.60	0.36	0.64	0.05	84.0	55.0	6.0	40.0	54.0
Maximum optimal level	4.20	0.45	5.00	3.20	0.49	1.94	0.2	112.0	65.0	15.0	60.0	76.0

TABLE 6. Relative changes for different elements in foliar tissue samples for treatments and evaluated doses.

	N	P	K	Ca	Mg	Cl	Fe	Mn	Cu	Zn
DS_1	1306.3	-97.1	386.1	-60.9	-47.5	8762.1	9900	3029.0	18761.1	3370.5
DS_2	831.3	-96.9	288.9	-71.2	-71.7	32694.4	7672.0	1577.4	12316.7	2900.0
DS_3	593.8	-96.9	233.3	-69.1	-79.2	8528.5	6169.4	2512.9	10844.4	3056.9
DS_4	1312.5	-96.3	275	-67.1	-65	17675.7	9433.7	2771.0	19788.9	3645.1
DS_5	950	-96.6	330.6	-60.9	-178.6	10292.5	8397.4	2738.7	16122.2	3860.8
PS_1	812.5	-96.3	358.3	-65.0	-54.2	11082.2	9122.8	2287.1	17150	3037.3
PS_2	1062.5	-96.3	316.7	-63.0	-56.7	14234.1	10936.3	2351.6	17205.6	3311.8
PS_3	1068.8	-96.6	427.8	-71.2	1.9	8706.1	8708.3	4029.0	24011.1	5507.8
PS_4	731.3	-96.3	372.2	-71.2	-73.3	4956.1	4734.2	2512.9	18094.4	4056.9
PS_5	1168.8	-96.3	288.9	-60.9	-62.5	8486.4	8708.3	3900	25872.2	6390.2

in plant tissues in these same treatments. In fact, the lowest amounts of K absorbed were found in treatments DS_5 and PS_5 (Tab. 6). This reaction can be possibly due to the long-term action of biochar, as described by Major *et al.* (2010) in studies conducted in corn crops between 2003 and 2006, where there were increases in elements such as K, Ca and Mg until the third year, with the addition of biochar made from wood residues. However, it is expected that the amounts of Ca and Mg contributed by biochar in the soil will increase in the long term, which may have an impact on leaf tissues through the uptake of the elements by the plant, as established by authors such as Major *et al.* (2010).

It is known that P is usually conserved during the volatilization of associated organic molecules and is present as ashes within the biochar, which when solubilized, becomes available to plants (Mašek and Brownsort, 2011; Escalante-Rebolledo *et al.*, 2016). However, McLaughlin *et al.* (2009) demonstrated that P in the sludge acts as a slow-release fertilizer in soils deficient in this element (Hossain *et al.*, 2010). In addition, the concentration of P in the sludge can be reduced by the conditions of pyrolysis through the evolution of volatile compounds of greater molecular weight, while the concentration of metals present in the biochar is expected to increase (Hossain *et al.*, 2010).

This could explain the results of this study regarding the lower content of P in both DS and PS compared to the control and the higher Fe content found in these two materials. In this research, although the amounts of P are significantly lower in the two sludge materials compared to the control (Tab. 5), it could be inferred that in T_0 the element is neutralized (due to high amounts of bases like K). For this reason, it is not available for the plant and could not provide a contribution to its production (interpreted in terms of height and dry matter).

Na ions in large quantities can affect the seeds of *S. lycopersicum* by decreasing the water potential in the substrate (El-Habbasha *et al*., 1996; Cuartero and Fernández-Muñoz, 1998). These concentrations also affect the growth of the roots of the plant by altering the absorption of water (an osmotic component) (Shannon and Grieve, 1999). The above could be reflected in this research given the results obtained regarding the high content of Na since higher levels of this element were found in the leaf samples of the treatments with lower height and dry matter (DS_1 and PS_1), and lower levels of Na in treatments with higher height (DS_5 and PS_5) (Tab. 4).

In the analysis of Mn, Zn, and B, there was no clear trend that could relate a higher dose of treatments to an increase in the content of these elements in plant tissues. Foliar analyses revealed significant amounts of Fe, particularly in DS in treatments DS_2 and DS_4. The PS treatments that were found with greater amounts of this element were the PS_1 and PS_2. In relation to this, Pérez-Sanz *et al*. (2002) investigated the efficiency in the growth of citrus crops with the application of sludge enriched with Fe without finding significant improvements in this growth parameter. These results are in line with what was obtained in our study, particularly with the application of treatments that include biochar, since it was found that treatments with high amounts of Fe such as PS_1 and PS_2 had the lowest plant height and dry matter values.

Conclusions

The results obtained indicated that the applications of DS and PS on sludges with tomato plants under greenhouse conditions generated an effect on the height and dry matter of the plants, which was proportional to the increase in the doses of these materials to the substrate. Although no significant differences were found in the application of the two materials, there were statistical differences found in the nested doses for each material, and greater response in the evaluated variables at higher doses of each material.

With the addition of PS to the substrate, an improvement in the availability of nutritional elements of the soil, such as K was observed. Additionally, an increase in the absorption of these elements by tomato plants (particularly in the PS_3) was observed, which positively influenced greater heights and values of dry matter obtained in the plants. Essential elements such as Ca increased in the substrate with the application of DS and PS. However, increased amounts of Fe were also found in the PS, which could have a negative impact on the chemical conditions of the soil and plants. When higher levels of nutrients (particularly nitrogen) are found in the plants under treatment with PS, a contribution of nutritional elements by this material was inferred. This is a very important aspect that must be investigated in depth due to its potential benefits in the nutrition and production of cash crops.

The application of DS and PS could be a viable proposal for agricultural systems as an alternative to the disposal of sewage sludge and as an amendment or soil conditioner. Although greater benefits were found in some variables measured in this study with the application of some DS, there could be a greater benefit in environmental terms with the use of PSs given that the heavy metal load is reduced when pyrolysis is applied to the soil. This benefit may mean a lower impact in terms of bioaccumulation of these metals in the plant.

However, for future studies, it is necessary to analyze the content of toxic organic compounds such as dioxins, furans, phthalic acid esters, polycyclic aromatic hydrocarbons, and other organic contaminants that may be present in DS and PSs. This information can be important to define criteria for the selection of one of these materials to be used as a soil improver.

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