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Soil properties and cowpea yield after six years of consecutive amendment of composted tannery sludge

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ABSTRACT. This study evaluated soil properties and cowpea yield after six years of consecutive amendment of composted tannery sludge. The compost was applied annually at 0, 2.5, 5, 10, and 20 Mg ha^{-1} and at the end of the sixth year, the chemical and physical properties of the soil were evaluated using a randomized block design. The Cr, P, K, Ca, Na and organic C contents and the pH and cation exchange capacity increased linearly after six years of compost amendment. The soil bulk density decreased linearly while the aggregate stability index increased after compost amendment. As a consequence of the changes in the chemical and physical properties of the soil, cowpea yield showed a quadratic response to the tannery rates, with an estimated maximum cowpea yield at 8.3 Mg ha^{-1}. In conclusion, the soil chemical and physical properties improved after six years of composted tannery sludge amendment. However, the soil pH and the Cr and Na contents increased with composted tannery sludge amendment, which influenced the cowpea yield and resulted in a quadratic response to the compost.

Keywords: waste management, soil fertility, soil quality.

Propriedades do solo e produtividade do feijão-caupi após seis anos de aplicações consecutivas de lodo de curtume compostado

RESUMO. Este estudo avaliou as propriedades do solo e a produtividade do feijão-caupi após seis anos de aplicações consecutivas de lodo de curtume compostado. Anualmente, o composto foi aplicado a 0, 2,5, 5, 10 e 20 Mg ha^{-1} e no sexto ano as propriedades químicas e físicas do solo e a produtividade do feijão-caupi foram avaliadas em experimento de blocos casualizados. Cr, P, K, C orgânico, pH, Ca, Na, e a capacidade de troca de cátions aumentaram linearmente após seis anos de aplicação do composto. A densidade do solo diminuiu linearmente enquanto a estabilidade de agregados aumentou após a aplicação do composto. Em consequência das mudanças nas propriedades químicas e físicas do solo, a produtividade do feijão-caupi apresentou resposta quadrática às doses de lodo de curtume compostado com máxima produtividade estimada encontrada na dose de 8,3 Mg ha^{-1}. Em conclusão, as propriedades químicas e físicas do solo melhoraram após seis anos de aplicação do lodo de curtume compostado. Entretanto, o pH do solo, bem como os teores de Cr e Na aumentaram com aplicação do lodo de curtume compostado e estes parâmetros influenciaram a produtividade do feijão-caupi que apresentou resposta quadrática.

Palavras-chave: manejo de resíduos, fertilidade do solo, qualidade do solo.

Introduction

The tannery industry generates and releases a high volume of solid wastes known as tannery sludge (Santos, Nunes, Melo, & Araújo, 2011). Due to the tanning process, tannery sludge can accumulate chromium (Cr), and the waste can contain high levels of organic matter and a significant amount of hydroxides, carbonates, and salts. Consequently, tannery sludge may cause environmental pollution if applied in its untreated form to the soil. However, if it is treated before application, it may instead be used to improve agricultural soils (Araújo, Monteiro, & Carvalho, 2007).

Composting has been used as an alternative and efficient process for recycling waste, including tannery sludge (Gonçalves, Araújo, Nunes, & Melo, 2014; Silva, Araújo, Nunes, Melo, & Singh, 2014; Araújo et al., 2015). Following the amendment of composted tannery sludge (CTS), its application to the soil can increase plant yield by supplying additional nutrients, increasing soil pH, and consequently reducing the exchangeable aluminum content (Santos et al., 2011). Because CTS contains high levels of organic matter, it may also improve the chemical and physical properties of the soil.

The improvement of chemical and physical properties is important for the plant-growing potential of the soil, particularly for sandy soils that generally lack the necessary fertility properties (Gonçalves et al., 2014). Previous studies showed that soil properties, soil organic matter, and crop yield could all be improved by the addition of different types of compost (Darby, Stone, & Dick, 2006; Mbarki et al., 2008; Arthur, Cornelis, & Razaghi, 2012). In particular, improving the organic matter in soil is known to promote many benefits, including increased soil fertility, improved soil structuration, and reduced soil bulk density (Lal, 2014).

Despite the known benefits to soil, studies focusing on the repeated application of composted wastes such as CTS under field conditions are scarce. Indeed, the limited information available from previous studies does not indicate a clear trend in the effects of this process on the chemical and physical properties of soil over time. Accordingly, we began a long-term study of CTS application in 2009 to evaluate its effects on soil properties after consecutive CTS amendment. In particular, we hypothesized that soil properties are affected by the consecutive and cumulative addition of CTS with respect to the high organic matter and inorganic compounds found in this waste. Therefore, in this study, we evaluated the effects of six years of repeated CTS amendment on the chemical and physical properties of soil and investigated cowpea yield in a treated sandy soil.

Material and methods

The experimental site is located at the Long-Term Experimental Field of the Agricultural Science Centre of the Federal University of Piauí, Brazil. The regional climate is dry tropical (Köppen) and is characterized by two distinct seasons: rainy summer and dry winter, with annual average temperatures of 30°C and rainfall of 1200 mm. The rainy season extends from January to April, when 90% of the total annual rainfall occurs. The soil is classified as a Neossolo Fluvico (Brazilian Soil Taxonomy) with the following composition at 0–20-cm depth: 10% clay, 28% silt, and 62% sand.

In each year of the study, the CTS was produced by mixing tannery sludge with sugarcane straw and cattle manure (ratio 1:3:1; v:v:v). The composting process was performed using the aerated-pile method for 85 days. The pile was 2 m long, 1 m wide, and 1.5 m high. The pile was turned twice a week during the first 30 days and twice a month during the remaining 55 days. At the end of the composting process, 20 subsamples were randomly collected from the CTS to produce a composite sample. The properties of the CTS, averaged across the six years, are shown in Table 1. The water content was determined after oven drying the samples at 105°C for 24h, the pH and electrical conductivity (EC) were measured directly, and total solids were measured by drying the samples at 65°C. The total organic C content was evaluated by dichromate oxidation of the samples under external heating (Nelson & Sommers 1996). The total N content was determined using the Kjeldahl method after sulfuric acid digestion of the samples. The total Ca, Mg, K, P, S, Na, Zn, Cu, Cd, Pb, Ni, and Cr concentrations were determined by atomic absorption spectrophotometry after nitric acid digestion of the samples in a microwave oven (United States Environmental Protection Agency [USEPA], 1996).

Table 1. Average of properties of CTS during the six years.

	CTS	Maximum limit permitted[a]
Water content (g kg^{-1})	680	
pH	7.5	
EC (dS m^{-1})	19.2	
Organic C (g kg^{-1})	201.2	
Total N (g kg^{-1})	15.1	
C/N ratio	13.3	
Total P (g kg^{-1})	4.91	
Total K (g kg^{-1})	2.90	
Total Ca (g kg^{-1})	121.18	
Total Mg (g kg^{-1})	7.21	
Total S (g kg^{-1})	10.20	
Total Na (g kg^{-1})	49.1	
Total Cu (mg kg^{-1})	16.38	1,500
Total Ni (mg kg^{-1})	23.26	420
Total Cd (mg kg^{-1})	1.93	39
Total Cr (mg kg^{-1})	1,943	1,000
Total Pb (mg kg^{-1})	40.31	300

[a] According with Conselho nacional do Meio ambiente (CONAMA, 2009).

CTS was applied annually from 2009 to 2013 at five rates: 0 (no CTS application), 2.5, 5, 10, and 20 t ha^{-1} of CTS (dry basis). The experimental site was arranged in a completely randomized design with four replicates. Each plot measured 20 m^2, with 12 m^2 of usable area for soil and plant sampling, and the rows were spaced 1.0 m apart. Each year, the CTS was applied 10 days before cowpea (*Vigna unguiculata*) sowing. The CTS was spread on the soil surface and incorporated into the 20-cm layer using a harrow. Cowpeas were grown at a density of 5 plants m^{-1} (approximately 62 000 plants ha^{-1}). Plant yield was evaluated at 60 days by sampling ten plants inside the plots and the grains were dried until a moisture content of 13%.

In this study (sixth year of CTS amendment), soil samples were collected 60 days after CTS amendment. In each plot, four samples were collected (0–20 cm), sieved, and stored prior to analysis. Soil pH was estimated in water (1:2.5 v:v) and measured using a pH meter (Tedesco, Gianello, & Bissani, 1995). The soil cation exchange capacity (CEC) and the P, K, Ca, Mg, and Na concentrations were evaluated according to Tedesco et al. (1995). Soil organic C was determined by wet combustion using a mixture of 5 mL of 0.167 mol L^{-1} potassium dichromate and 7.5 mL of concentrated sulfuric acid under heating (170ºC for 30 min.). The total Cr concentration was analysed according to USEPA (1996) after the soil was digested with HNO_3, HCl, and H_2O_2. The concentration of Cr from the soil samples was analysed using atomic absorption spectrophotometry.

The soil bulk density (SBD) of the 0–20 cm surface layer was determined using the core method (Black, 1965). The soil total porosity (TP) was calculated using an equation based on the relationship between the bulk density and particle density (Black, 1965). The aggregate stability index (ASI) was measured according to the method of Black (1965) using an oscillation device. The aggregation stability index was calculated as the ratio of the mass of the total sample and the mass of the sample retained in the 0.212-mm sieve mesh, expressed in percent.

The data were submitted to analysis of variance (ANOVA) and the means were compared using Student's test (5% level) and regression analyses. All statistical analyses were performed using the SPSS (version 15.0) software package. The data variables were analysed using multivariate ordination non-metric multidimensional scaling (NMS) with Sorensen distances. Ordination was performed using the PC-ORD v. 6.0 program.

Results and discussion

After six years of CTS amendment, the chemical properties of the soil increased linearly (Figure 1). Considering the highest CTS application rate (20 Mg ha^{-1}), the Cr content increased 50-fold and the P content increased 6-fold compared with the respective contents in unamended soil. In addition, compared with the measurements in unamended soil, both the TOC and Na content increased approximately 2-fold, whereas the K content, soil pH, and CEC increased approximately 0.4-fold. The regression equations showed constant increases of 11.2, 0.77, 0.72, 0.2, 0.08, 0.04, 0.03, and 0.07 units per ton of CTS applied for Cr, P, K, TOC, pH, Ca, Na, and CEC, respectively.

The amendment of organic wastes usually contributes to an increase in the soil organic matter and consequently soil fertility over time (Arthur, Cornelis, & Razaghi, 2012). After six years of amendment, CTS increased the organic C content in the soil because the waste has a high content of organic matter (Table 1). Our results are in agreement with those of others studies, which reported increased organic C contents after compost amendment (Garba, Cornelis, & Steppe, 2011; Arthur, Cornelis, & Razaghi, 2012). The soil pH increased after six years of CTS amendment, which is contrary to the general belief that organic residues decrease soil pH via the production of acids formed during the decomposition of organic matter. The increased soil pH observed in our study may be explained by the high pH and Ca content found in the CTS (Table 1). The CTS has a high pH and Ca and Na contents because the industry uses large amounts of hydroxides, carbonates, and salts during the tanning process (Santos et al., 2011). However, the soil pH observed after six years of CTS amendment in our study was lower than that reported by Martines et al. (2010), who used natural tannery sludge with a high pH and Ca content. This suggests that composting stabilizes some of the chemical properties of tannery sludge.

The increased P and K contents observed in the soil are also related to the CTS composition (Table 1). Thus, the CTS can apparently supply P and K to the soil as the application rates increase; this was also reported by Reynolds, Drury,Tan, and Yang (2015), who evaluated municipal waste compost and observed an increase in the P and K concentration. Our results are in agreement with those of Ozores-Hampton, Stansly, and Salame (2011), who reported an increase in the soil P and K after repeated amendment of composted waste over 10 years. Similarly, Ribeirinho, Melo, Silva, Figueiredo, and Melo (2012) found an increase in the CEC after six years of sewage sludge amendment that was directly related to the increase in the waste rates and which occurred because of the increased negative charge produced by the organic matter in the waste. However, the increased soil Na content in our study due to the amendment of CTS is a major concern in relation to compost use (Arthur, Cornelis, & Razaghi, 2012) because increased Na may limit the growth of plants at the highest CTS application rates.

After six years of CTS amendment, the soil Cr content increased (Table 1), and the amendment of the largest amount of CTS produced Cr levels in the soil at the upper limit proposed by Brazilian regulations (CONAMA, 2009), i.e., 150 mg kg^{-1}. However, it should be noted that as the soil pH increases above 7.0, the Cr in the soil is likely to remain inert with low mobility (Gonçalves et al., 2014).

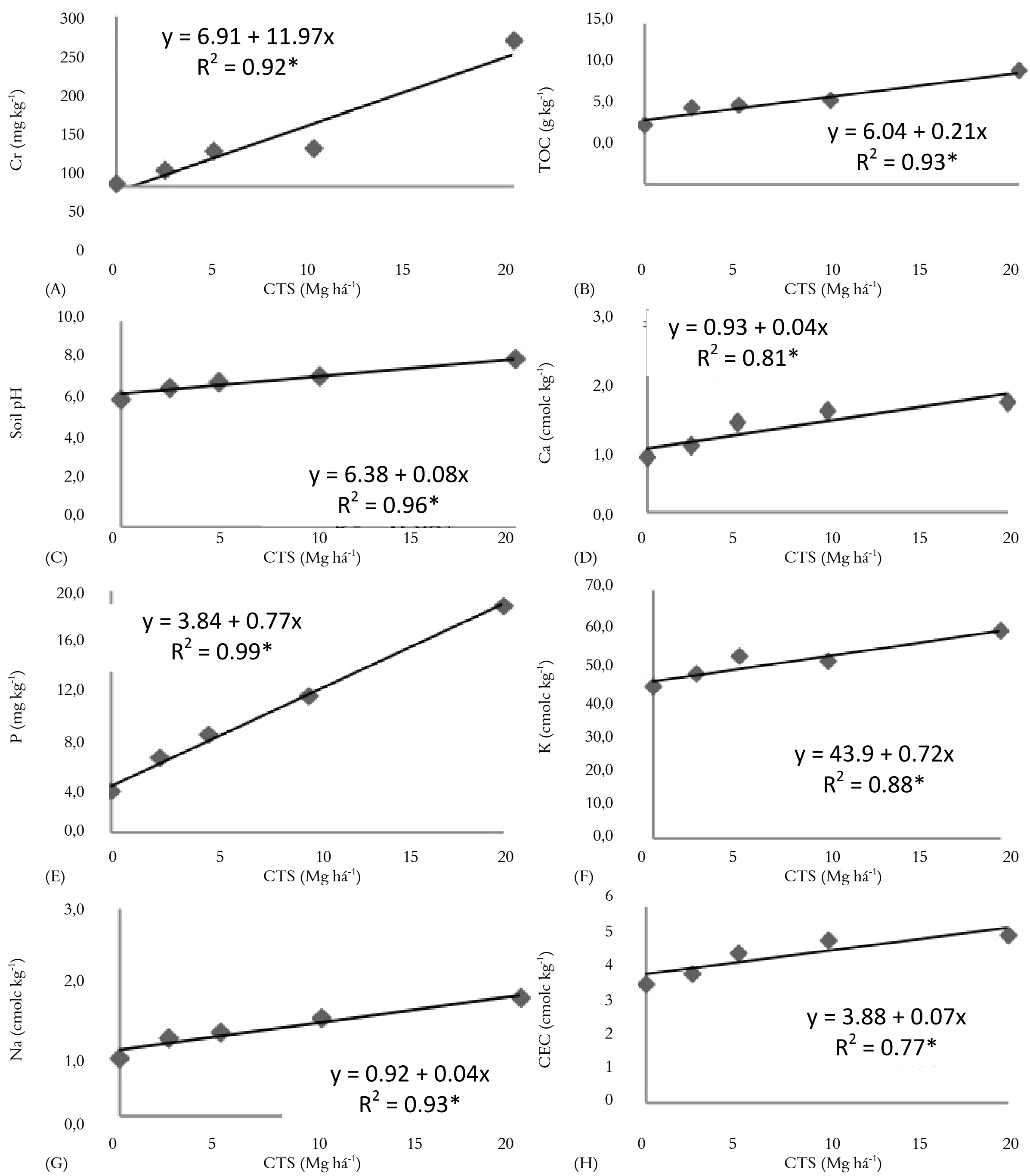

Figure 1. Soil chemical properties after 6 years of CTS amendment.

After six years of CTS amendment, the soil bulk density decreased linearly, whereas the aggregate stability index increased (Figure 2); however, there was no significant difference in the soil total porosity. Considering the highest CTS application rate, six years of CTS amendment resulted in a 15% decrease in soil bulk density and a 62% increase in aggregate stability index. The regression equations showed a constant decrease of 0.01 and an increase of 0.27 units per ton of CTS applied for the soil bulk density and aggregate stability index, respectively.

The decrease in the SBD after six years of CTS amendment may have occurred because of the increase in the organic C content of the soil. An increase in the soil organic matter after compost amendment is known to positively affect soil bulk density and may help to avoid soil compaction (Rivenshield & Bassuk 2007). Courtney and Mullen (2008) observed similar trends after the amendment of organic compost in sandy soils. In addition, the decreased SBD may also be related to the dilution of the denser mineral fraction by the CTS compost. According to Civeira and Lavado (2006), compost particles can penetrate into the soil matrix and decrease the soil density. Soil structuration improves with CTS amendment, and this change may be related to the permanent addition of organic compost. A previous study on composted municipal wastes showed a positive effect on aggregate stability (Reynolds, Drury, Tan, & Yang, 2015).

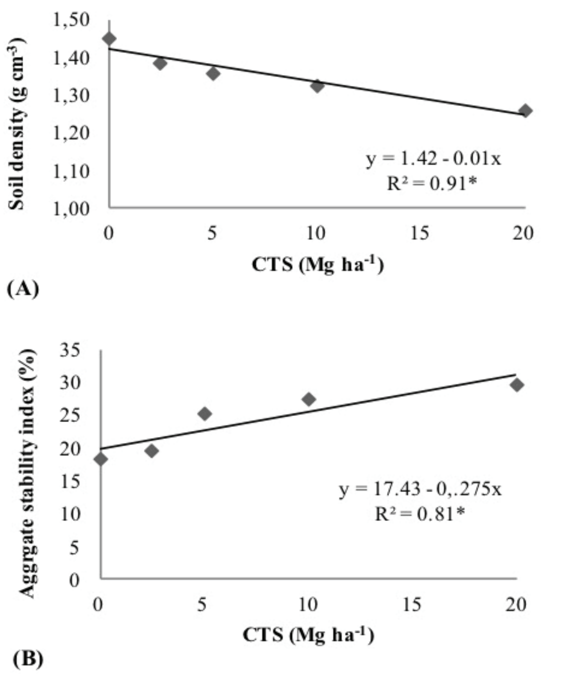

Figure 2. Soil physical properties after 6 years of CTS amendment.

Cowpea yield showed a quadratic response after six years of CTS amendment (Figure 3). According to the regression equation, the estimated maximum cowpea yield was 1.91 Mg ha^{-1} at an estimated CTS application rate of 8.3 Mg ha^{-1}.

Although the soil chemical and physical properties exhibited linear responses to the increase in the CTS rates, the cowpea yield showed a quadratic response and decreased when the CTS rate exceeded approximately 8.3 Mg ha^{-1}. This may have occurred due to the increase in the soil pH and Cr and Na contents, which might have limited the growth of the cowpea crop. High concentrations of Cr can affect the growth of plants and consequently reduce plant yield (Sundaramoorthy, Chidambaram, Unnikannan, & Baskaran, 2010). Previous studies have demonstrated the negative effects of Cr on cowpea (Gonçalves et al., 2014) and rice (Sundaramoorthy, Chidambaram, Unnikannan, & Baskaran, 2010). Similarly, Na can negatively affect plant yields via the reduction of plant growth because this element decreases water uptake, increases sodium toxicity in the shoot cells, and reduces photosynthesis (Tavakkoli, Rengasamy, & McDonald, 2010). With respect to the soil pH, cowpea grown at pH greater than 7.0 exhibits poor development caused mainly by deficiencies of Fe, Zn, and often Mn (Marschner, 2003). Goenaga, Gillaspie, and Quiles (2010) evaluated genotypes of cowpea in alkaline soils and observed that the plant height and pod length decreased by 50 and 37%, respectively, and they reported that high soil pH was a limiting factor for the adequate growth and development of cowpea.

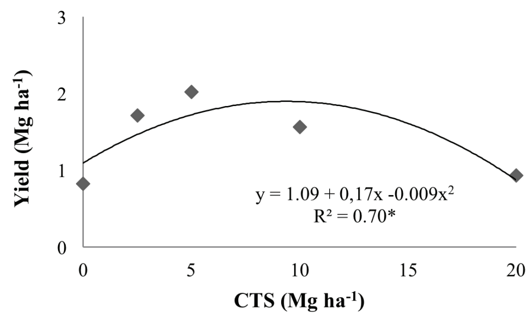

Figure 3. Cowpea yield after 6 years of CTS amendment.

NMS analysis explained approximately 91% of the variation and clustered three distinct groups according to the soil properties and cowpea yield (Figure 4). The first group comprised the unamended soil and was linked with soil density. The second group comprised the 2.5 and 5 Mg ha^{-1} CTS, which were grouped with cowpea yield. The third group comprised the 10 and 20 Mg ha^{-1} CTS, which were grouped with the soil chemical properties and ASI.

The NMS analysis showed different responses related to CTS amendment over the six years and suggested that there was an improvement in the chemical properties of the soil at the highest rate of CTS application. Previous studies with organic compost also found a strong improvement in soil fertility (Scherer, Metker, & Welp, 2011; Patel & Patra, 2014). In addition, the soil structure was better with the amendment of CTS at a high application rate, which indicates that high levels of CTS may improve the physical properties of soil in the long-term. However, CTS amendment at the lowest rate was clustered with plant yield, which indicates that the increase in the CTS rates did not promote high crop production, probably due to the accumulation of chromium and sodium, and the increase in soil pH.

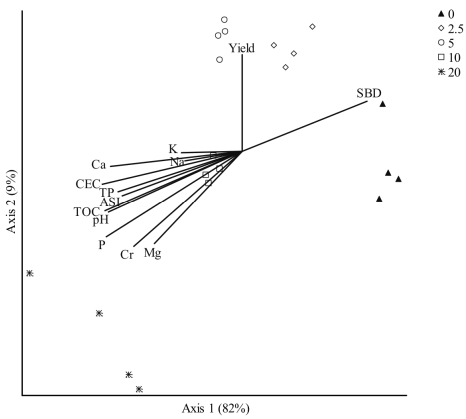

Figure 4. Non-metric multidimensional scaling of chemical and physical properties of soil after 6 years of CTS amendment.

Conclusion

In this study, the soil chemical and physical properties improved after six years of CTS amendment, and soil fertility was positively affected by CTS application. However, the soil pH and the Cr and Na contents increased with CTS amendment, which influenced the cowpea yield and resulted in a quadratic response to the CTS application. After six years of CTS amendment, the estimated maximum cowpea yield was 1.91 Mg ha^{-1} at an estimated CTS application rate of 8.3 Mg ha^{-1}.

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