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ORIGINAL RESEARCH

Cultivation of sorghum and sunflower in soils with amendment of sludge from industrial landfill

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Abstract

Purpose The purpose of this work was to evaluate the impacts of the amendment of industrial landfill sludge (ILS) in two different soils with cultivation of sunflower and sorghum plants.

Methods The plants grew in two types of soils (Typic Paleudult—TP, and Grossarenic Hapludult—GH) with different doses of ILS (0, 2, 5, 10, and 20 Mg ha^{-1}). The evaluation of the pH, electrical conductivity, available concentrations of P, K, Ca, Mg, and Na, and the hydrolysis of FDA in the soils were tested. The height and dry mass of both plants were measured, as well as the stem diameter of the sunflower. The total concentration of Cu, Cd, Cr, and Pb was evaluated in the plants and soils, in addition to the translocation factor of those in the plants.

Results The amendment of ILS in the soils was efficient to increase the pH and macronutrients, as to increase the biomass production. The largest production occurred with 10 Mg ha^{-1}, and the highest dose (20 Mg ha^{-1}) had negative effects in all treatments. Both plants had low accumulation of Cu, Cd, and Pb in their tissues. Cr increased in the roots of sunflower plants (especially in the TP soil) without translocation to the shoots.

Conclusions The amendment of ILS in soils is an alternative to disposal with benefits to plants and soil quality. TP soil presented better results, being more secure to receive the sludge due to its higher content of clay when compared to the GH soil.

Keywords Heavy metals · Chromium · Tannery · Waste disposal · Pollution

Introduction

Urban and industrial activities generate a wide range of wastes, which have high potential for environmental impact, high-cost treatments, and environmental problems when sent to landfills. The amendment of wastes in soils may solve many problems, and it has some advantages, such as being organic fertilizers in total or partial replacement for chemical fertilizers commonly used in agriculture (Santos et al. 2011; de Andrade et al. 2016; Lloret et al. 2016). If the wastes should contaminate the plants with heavy metals, this biomass should be used for biofuels and other applications in which these cannot be a health hazard, thus, avoiding the contamination of animals and humans.

Landfills are a main destination of by-products from industrial processes (Celary and Sobik-Szołtysek 2014). These landfills generate long-term effluents named leachate. Leachate derives from disposed wastes in waterproofed cells, varying its composition according to the characteristics of the waste disposed. A simple return of leachate sludge to cells can promote a concentration of chemical elements which extend environmental liabilities (de Andrade et al. 2016).

Leather and Footwear Industry has significant importance for the economy of Rio Grande do Sul (RS—Southernmost Brazilian state). These activities generate many hazardous materials due to the high concentration of chromium in the wastes from leather treatment; although some of those wastes may have conditioner, fertilizer, and corrective properties to the soil (Gianello et al. 2011; Oliveira et al. 2015). Some of the elements most found in the tanning industry

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sludge are N, P, K, S, Ca, Mg, Zn, Fe, Cu, Mn, Cr, and Na (Silva et al. 2010; Gianello et al. 2011). Part of these elements is macronutrients (N, P, K, S, Ca, and Mg) and micronutrients (Zn, Fe, Cu, and Mn) essential for plants, microorganisms, or metabolic enzymes components. Other elements, such as heavy metals (Al, As, Cd, Cr, and Pb), are not biologically essential for plants and may be toxic for living organisms above certain levels (Sposito 2008; Kabata-Pendias 2011).

The amendment of sludge in soils can be recommended according to the waste characteristics and to their interaction with the soil. Nonetheless, there may be positive or negative effects depending on the dose and concentration of heavy metals and nutrients in the sludge (Santos et al. 2011; de Andrade et al. 2016). Some studies have proved that the sludge can stimulate microbial communities in edaphic environments (Nakatani et al. 2012; Silva et al. 2014), and plants (Silva et al. 2010; Patel et al. 2015; Nessa et al. 2016) due to the pH regulation and the increment of nutrients and organic carbon. Moreover, the amendment of wastes with high concentration of heavy metals may cause toxicological damage to soil systems (Celary and Sobik-Szołtysek 2014; Oliveira et al. 2015). Regarding sludge from leachate treatment plant (LTP), its characteristics depend on the type of waste disposed in the landfill cells (de Andrade et al. 2016).

Disposal of organic waste on soil may be recommended due to the potential use for increasing the soil pH and nutrients. These provide a reduction in the application of mineral and commercial inputs, reducing costs of agricultural cultures and improving soil quality, once organic waste can act as soil conditioner (Gianello et al. 2011; Bose and Bhattacharyya 2012; Nessa et al. 2016; Joardar and Rahman 2018). Therefore, the amendment of soil with industrial landfill sludge (ILS) may be seen as an environmental alternative to the final disposal of those wastes. However, there is a lack of studies on the topic, and analyses should be conducted to assess the feasibility of waste use due to the possible contaminants and effects on edaphic systems. Thus, the aim of this study was evaluate the impacts of the amendment of ILS on two different soils which cultivate sunflower and sorghum plants.

Materials and methods

The experiments were carried out under greenhouse conditions, and the analyses were performed at the Bioremediation Laboratory from the Soil Department of the Federal University of the Rio Grande do Sul (UFRGS, Brazil).

Industrial landfill sludge

The sludge used in this study was collected (mixed composite sample) in the drying beds of an industrial landfill Leachate Treatment Plant (LTP). This landfill was located in Estancia Velha (a city in the state of Rio Grande do Sul, Brazil—29°40′36.7″S; 51°12′45.3″W), and it has a history of receiving wastes from Leather and Footwear companies.

A sample of ILS was oven dried at 65 °C, pounded and sieved (2 mm), and analyzed by nitric–perchloric digestion method, with ICP–OES (inductively coupled plasma with optical emission spectrophotometry) quantification, thus, presenting the following characteristics: Ca—20%; C_{org}—7.3%; Fe—4.7%; N—3.9%; Na—2.6%; S—1.2%; Mg—0.81%; K—0.31%; P—0.19%; Mn—658 mg kg^{-1}; Cr^{+3}—602 mg kg^{-1} ($Cr^{+6} < 1$); Ni—38 mg kg^{-1}; Zn—32 mg kg^{-1}; B—34 mg kg^{-1}; Ba—31 mg kg^{-1}; Cu—23 mg kg^{-1}; V—20 mg kg^{-1}; As—12 mg kg^{-1}; Pb—2 mg kg^{-1}; Mo—0.4 mg kg^{-1}; Cd—0.3 mg kg^{-1}; Hg—0.01 mg kg^{-1}; Se—< 4 mg kg^{-1}; pH (H_2O 1:1)—7.9; electrical conductivity (EC)—12.8 dS m^{-1}; neutralizing power (NP)—49%.

Experimental units

The experimental design was carried out as a factorial 2 × 2 × 5 with three randomized blocks, as follows: two soils (Typic Paleudult and Grossarenic Hapludult), two plants (sunflower—*Helianthus annuus* L. and sorghum—*Sorghum* sp.) and five sludge doses (0, 2, 5, 10, and 20 Mg ha^{-1}).

Both studied soils occur in the landfill region, being chosen due to their physical–chemical differences. Both plants have been commonly used in environmental studies because of their potential agricultural uses in the region as biomass and fuel sources. The sludge doses were defined based on the previous laboratory germination tests. The plants were cultivated in a greenhouse, in pots (25 × 30 cm) with 4 dm^3 of soil. Three seeds were planted, leaving one plant per pot after germination. There was no adjustment in the soil pH and nutrients, since they had their only source in the sludge.

Soils were classified as Typic Paleudult (TP), and Grossarenic Hapludult (GH), according to Soil Taxonomy (Soil Survey Staff 2014). They were classified as Argissolo Vermelho Distrófico (Pvd) and Argissolo Vermelho-Amarelo Distrófico espessarênico abrúptico (Pvad), respectively, according to the Brazilian Soil Classification System (SiBCS). The Typic Paleudult soil was sampled (0–20 cm) at the Agronomic Experimental Station (UFRGS) located in Eldorado do Sul (RS—30°05′S; 51°40′W) in native grass area. The Grossarenic Hapludult soil was sampled

(0–20 cm) in Viamão (RS—30°10′S; 50°59′W) also in native grass area. The following physicochemical (assimilable) characteristics were for Typic Paleudult (clay—26%; pH—5.4; pH-SPM—6.1; C_{org}—1.1%; cation exchange capacity—CEC—7.5 $cmol_c$ dm^{-3}; P—5.5 mg dm^{-3}; K—80 mg dm^{-3}; Cu—1.1 mg dm^{-3}); and Grossarenic Hapludult (clay—12%; pH—5.2; pH-SPM—6.5; C_{org}—0.8%; CEC—3.4 $cmol_c$ dm^{-3}; P—2.9 mg dm^{-3}; K—28 mg dm^{-3}; Cu—0.5 mg dm^{-3}).

Evaluations and analyses

In the end of the experiment (90 days after the application of ILS), both soils were sampled (0–20 cm) and evaluated for pH (H_2O 1:1); electrical conductivity—EC (1:5); and available concentrations (Mehlich-1) of P, K, Ca, Mg, and Na. The sorghum and sunflower plants were evaluated 50 and 75 days after germination, respectively, for height (sorghum), stem diameter (sunflower), and dry mass of the shoots and roots (both plants). The height of the shoots was measured with a graduated scale from the base of the seedlings to the top of the shoots; stem diameter was measured with a digital caliper with a precision of 0.01 mm. To determine the dry mass of the roots and shoots, both parts were separated in the cervical region of the plants. The roots were washed with water until all soil particles were removed, and after that washed again with distilled water. Subsequently, the biomass was dried in a forced-air oven at 60 °C. For both plants and soils, the measurements of the total concentrations (nitro-perchloric extract 3:1) of Cu, Cd, Cr, and Pb were carried out. Analyses of nutrients and metals were quantified in ICP–OES.

The translocation factor (TF) was estimated by the relation between the concentration of metals in the shoots (S) and roots (R) of the plants, according to Eq. (1):

$$TF = S/(S + R). \quad (1)$$

FDA hydrolysis was measured in samples of surface soil (0–5 cm) at 15, 30, 60, and 90 days after ILS amendment. The evaluation followed the methodology described by Adam and Duncan (2001).

Statistical analyses

Results were submitted to analysis of variance (ANOVA), and, when significant, means were compared by the Tukey test with 5% of error probability. The statistical software Assistat 7 was used, being the "sludge doses" (treatment) the quantitative factor. Graphical models and regressions were developed in the software SigmaPlot 11. Principal component analysis (PCA) was calculated with the Statistica 13 software.

Results and discussion

The biomass production of both sunflower and sorghum plants was affected by the doses of industrial landfill sludge (ILS), with positive effects until some doses and negative effects with the highest dose, 20 Mg ha^{-1} (Fig. 1). The stem diameter of the sunflower plants had the highest mean values with a 10 Mg ha^{-1} dose of ILS in the Typic Paleudult (TP) soil (4.5 mm) and with 2 Mg ha^{-1} (Fig. 1a) in the Grossarenic Hapludult (GH) soil (4.2 mm). Moreover, the sunflower plants had the highest mean values of the dry biomass production after amendment of 10 Mg ha^{-1} of ILS in the TP soil (Fig. 1b, c) for both shoots (5 g) and roots (0.4 g); and of 5 Mg ha^{-1} in the GH soil for both shoots (3.3 g) and roots (0.3 g). The sorghum plants showed the highest values for plants height (58 cm), dry biomass of shoots (4.2 g), and roots (2.7) after amendment of 10 Mg ha^{-1} of ILS in the TP soil (Fig. 1d–f). In the GH soil, the sorghum plants showed the highest values after the amendment of 2 Mg ha^{-1} of ILS for height (50 cm), and the dry mass of the shoots (1.9 g) and the roots (0.9 g).

Beneficial effects on the growth of both plants occurred until the 10 Mg ha^{-1} dose of ILS, presenting the largest biomass production, especially on the TP soil (with more clay, organic matter, and CEC). The highest dose of ILS (20 Mg ha^{-1}) had negative effects on all treatments, being a non-recommended dose to this waste (Fig. 1). Variations in the growth of the plant with the addition of ILS may be due to different soil characteristics: the TP soil has 26% of clay, while the GH soil has only 12% of clay. Clay is an important source of charges in the soil for, which bounds other elements, such as heavy metals and P, also reducing the availability of these elements in the soil solution and, consequently, the plant uptake (Sposito 2008). The GH soil had the worst results for all physical parameters in the plants. A visible detrimental effect on the growth of the plants occurred with the highest levels of ILS (20 Mg ha^{-1} dose) on the GH soil: reduction of the stem diameter and of the biomass of the roots of the sunflower plants (Fig. 1).

The reduction in the stem diameter of the sunflower with ILS doses ($r = -0.61$) may cause problems with plant support, breaking the stem and toppling with wind and other climate issues. A similar effect occurred on the height of the sorghum plant when there was a significant reduction of the doses on the GH soil (Fig. 1). Nutritional unbalance may cause different effects on physiological parameters of the plants. When there is a great concentration of some nutrients, they can reduce the uptake of other essential nutrients (Sposito 2008; Kabata-Pendias 2011). Some heavy metals can be toxic for plants, being able to reduce their nutrient uptake and growth (Sridhar et al. 2011; Barbosa et al. 2013).

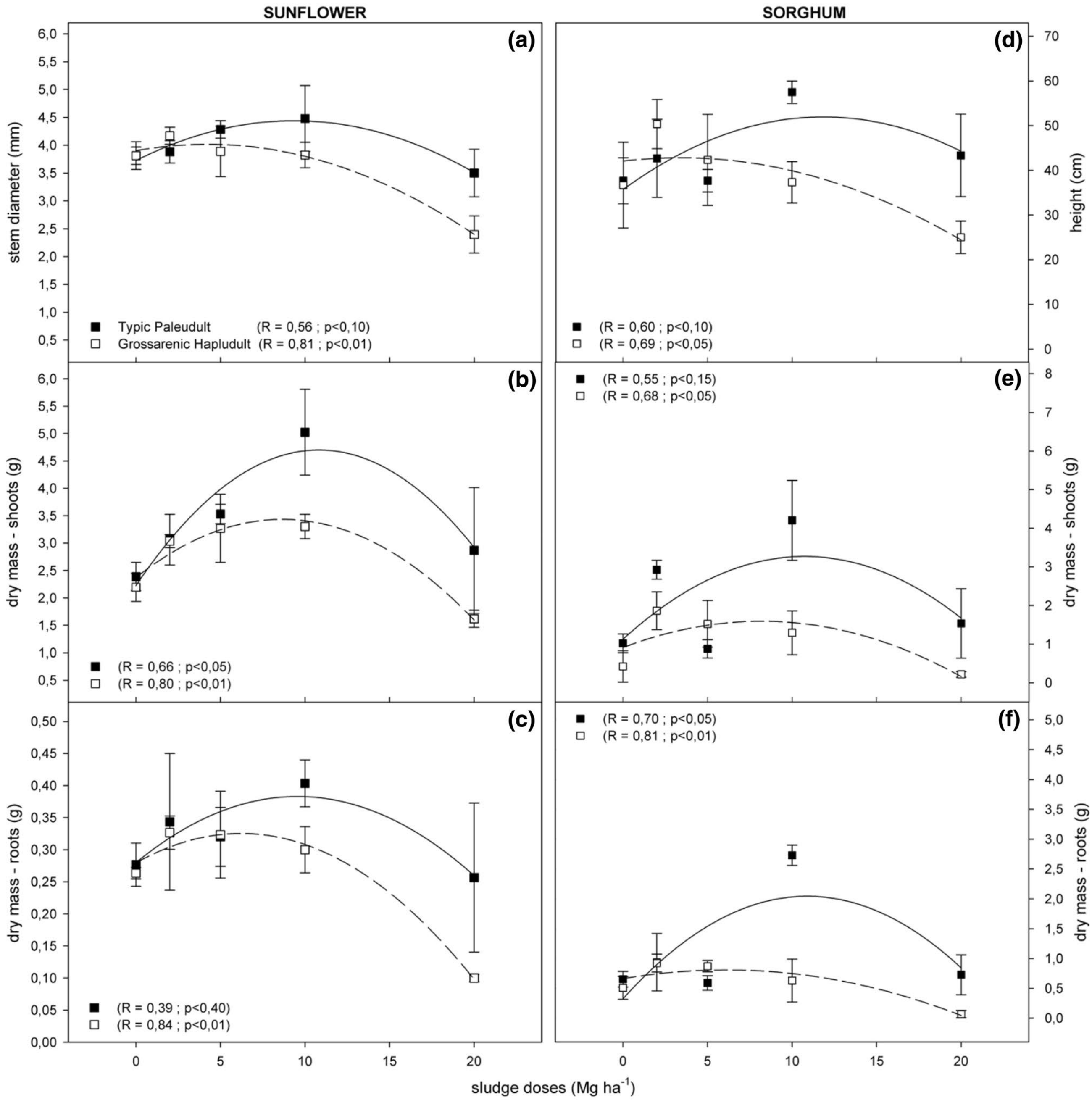

Fig. 1 Changes in sunflower stem diameter (**a**); shoots dry mass (**b**); root dry mass (**c**); and sorghum height (**d**); shoots dry mass (**e**); and root dry mass (**f**) cultivated under industrial landfill sludge (ILS) at 0, 2, 5, 10, and 20 Mg ha^{-1} doses on Typic Paleudult (filled square) and Grossarenic Hapludult (open square) soils

The soil pH value increased from 5 to 6 with the amendment of 5 Mg ha^{-1} of ILS (Fig. 2) in both soils (TP and GH) and plants (sunflower and sorghum). The different doses of ILS applied to the soils increased the pH values to 5.0, 5.6, 6.3, 6.6, and 7.4 (mean for all treatments) after the addition of 0, 2, 5, 10, and 20 Mg ha^{-1} of ILS, respectively. It demonstrates a high potential of the ILS for increasing the soil pH. Amendment of ILS in the TP and GH soils was efficient to increase the pH, decreasing the acidity, which is one of the key benefits provided by this waste. The 5 Mg ha^{-1} dose was sufficient to reach pH 6 on soils, and exceeding pH 6.5 with doses above 10 Mg ha^{-1} (Fig. 2). Increases in organic carbon can improve soil conditions (Gianello et al. 2011; Oliveira et al. 2015), even though there is a lack of studies on ILS due to heavy metal contents and environmental risks.

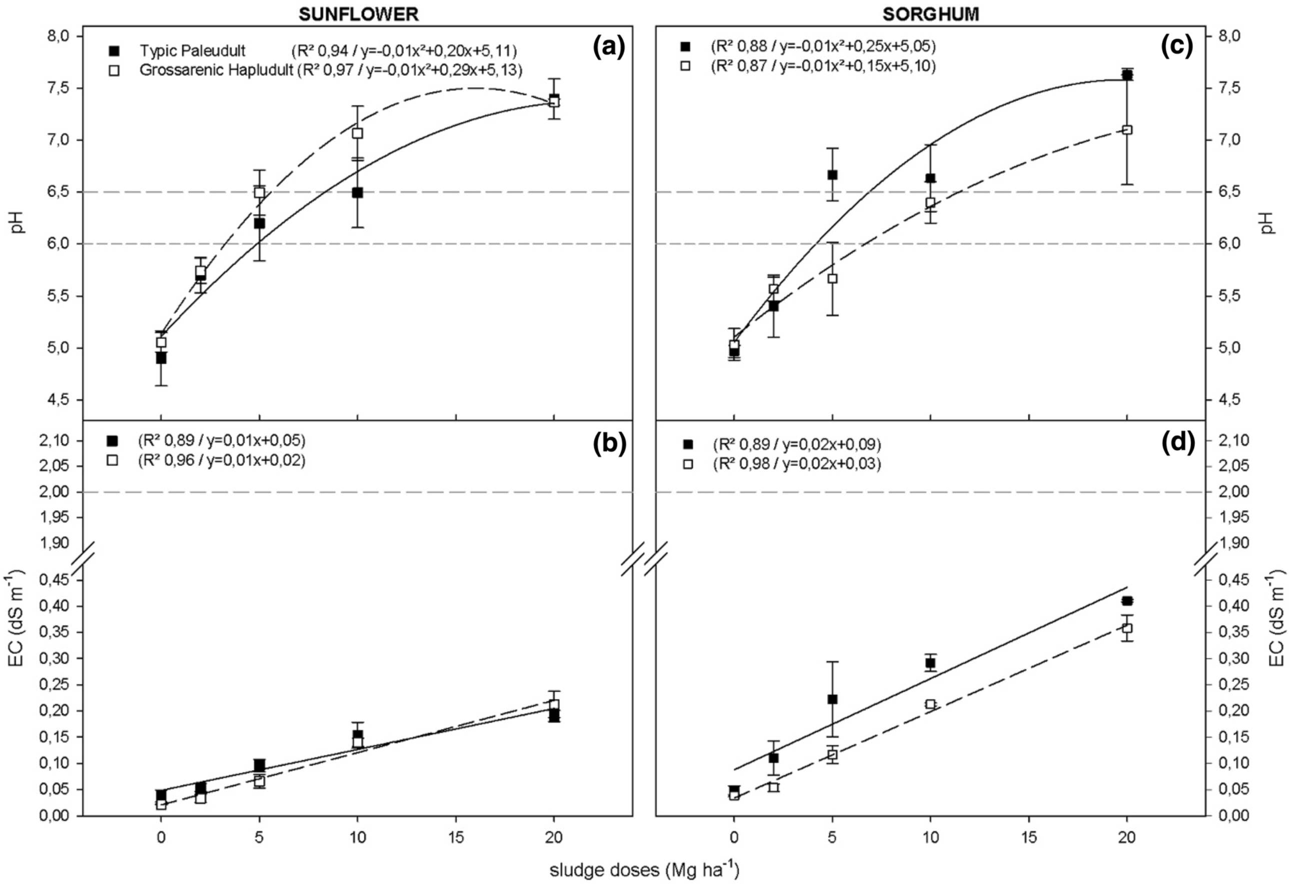

Fig. 2 pH and electrical conductivity (EC) values on Typic Paleudult (filled square) and Grossarenic Hapludult (open square) soils with sunflower and sorghum cultivation 90 days after the amendment of industrial landfill sludge (ILS) at different doses (0, 2, 5, 10, and 20 Mg ha^{-1})

High concentration of organic carbon (7.3%) and neutralizing power (49%) in ILS can contribute to complexation and unavailability of metals to the soil micro-biota and plants, due to the increase in pH dependent electrical charges and negative charges of organic matter (OM), hence, increasing the metal cations connections (Sposito 2008). Nevertheless, negative charges of OM are pH dependent; thus, the pH needs to be constantly monitored due to the risk of desorbing the metals. At the same time, excessive increases in the soil pH should also be monitored because of the unavailability of micronutrients to the plants (Sposito 2008).

pH increases occur mainly as a result of high levels of calcium carbonate present in the sludge (Ca—20%). Those increases are highly correlated (r) with the doses of sludge and Ca levels in the TP and GH soils. The calcium (Ca) content in the sludge comes partially from the operations of the Leachate Treatment Plant (LTP) of the industrial landfill, originated from the limestone used to neutralize the effluent. Iron and sulfur are other elements derived from the LTP, both from ferrous sulfate ($FeSO_4$), which is used as a coagulant in the treatment of the effluent. Similarly, elements such as Na and Cr derive from the processes of preparation of skin tanning, in the tanneries commonly found in the landfill region from where the samples were taken. In addition, the same processes originate contents of N, P, and C_{org} during the dissolution of leather protein (Benlboukht et al. 2016).

The electrical conductivity (EC) of the soil increased linearly with the amendment of the ILS doses, achieving a maximum value with the highest dose of ILS (20 Mg ha^{-1}) of 0.20 dS m^{-1} for the sunflower (Fig. 2b), and 0.38 dS m^{-1} for the sorghum (Fig. 2d). Although having the same initial EC (0.04 ± 0.01 dS m^{-1}) in the control treatment (without sludge), the doses led to different results, having more significant effects on the plants (both sunflower and sorghum) than on the soils (TP and GH). The highest EC values ($p < 0.05$) occurred in the TP soil with sorghum cultivation, having, thus, positive interaction between the factors (soil and plant). The EC increased linearly with the sludge doses ($r = 0.84$) due to the cations in the sludge, especially sodium ($r = 0.82$), which has a high correlation with the ILS doses ($r = 0.92$). Sodium (Na) is not a nutrient required in large concentrations for plants, and its accumulation can damage plants and soils. Even the EC did not achieve values determined as critical. An increase in monovalent cations can change the soil ionic balance and osmotic effects (Sposito 2008), which can reduce the plants nutrient uptake, and consequently their growth.

The concentration of macronutrients, such as P, K, Ca, and Mg increased in the soil after the amendment of ILS. However, the same occurred with Na (Table 1). All macronutrients had high values ($p < 0.05$) available in the TP soil, except for phosphorus. Phosphorus (P), a limited nutrient in Brazilian agriculture, had high correlation (r) with the doses of the ILS (0.79) and the soil pH (0.84). Increases in the pH reduce the phosphorus link with the clay in the soil (making this nutrient available). Similarly, the degradation of ILS increases P concentrations in the soil, being a two-way benefit.

Concerning the plants, the elements were present in higher values in the sorghum, except for Na, which had higher levels in sunflower treatments. Available amounts of Mg, Ca, and Na in the soil had linear increases ($R^2 = 0.97^{**}$; 0.96^{**}; 0.98^{**}), corresponding to increases of up to 2, 8, and 20 times in comparison of the control treatment (with no sludge amendment) and the treatment with the highest dose evaluated (20 Mg ha^{-1}).

Both plants exhibited low accumulation of Cu, Cd, and Pb in the tissue for both shoot and root biomasses after amendment with ILS in both Typic Paleudult (TP) and Grossarenic Hapludult (GH) soils (Table 2). However, a significant Cu increase occurred in the shoots and roots of the sunflowers grown in the TP soil. In addition, high Cd uptakes occurred in the shoots and roots of sorghum plants in the GH soil and in the shoots of sunflower plants grown in the TP soil. A risk associated with the solid waste amendment in soils involves the possibility of accumulation of heavy metals in plants, which consequently enter into the food chain. Doses of ILS caused low metal translocation on both sunflower and sorghum plants (Table 3). Significant translocation of metals (> 0.5) occurred only for Cu (in the highest dose), and Cd, which have mobility into the plants (Kabata-Pendias 2011).

Despite the low accumulation of copper (Cu) in the roots, it correlates positively with the sunflower stem diameter (0.72) and root (0.65) biomasses (Table 4). Nevertheless, the translocation factor (TF) of Cu was correlated negatively with the stem diameter (– 0.81) and the biomass of the roots

Table 1 Available concentrations of macro elements on Typic Paleudult and Grossarenic Hapludult soils with sunflower and sorghum cultivation under the amendment of industrial landfill sludge (ILS) doses (0, 2, 5, 10, and 20 Mg ha^{-1})

Doses (Mg ha^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Na (mg kg^{-1})
Typic Paleudult (sunflower)					
0	3.3Ba	55.3Aa	1.8Aa	0.9Aa	7.7Aa
2	4.0Ab	52.3Ab	3.6Aa	1.1Aa	24.0Aa
5	7.6Aa	45.5Ab	3.4Ab	0.7Ab	40.0Ab
10	7.7Bb	52.3Ab	8.3Aa	1.2Aa	111.7Aa
20	9.5Ab	89.0Ab	11.3Ab	1.5Ab	143.3Aa
Grossarenic Hapludult (sunflower)					
0	7.0Aa	18.0Ba	0.4Ba	0.2Ba	8.0Aa
2	4.3Aa	10.0Ba	1.3Ba	0.3Ba	19.0Aa
5	6.0Bb	13.3Ba	2.2Ba	0.3Ba	38.3Aa
10	12.6Aa	18.5Ba	6.2Ba	0.5Ba	59.5Ba
20	9.9Aa	27.0Bb	5.4Bb	0.7Ba	117.0Ba
Typic Paleudult (sorghum)					
0	4.3Aa	63.5Aa	1.8Aa	0.9Aa	5.3Aa
2	6.6Aa	67.3Aa	3.7Aa	1.0Aa	25.3Aa
5	8.5Aa	80.7Aa	7.2Aa	1.3Aa	56.3Aa
10	11.4Aa	70.0Aa	8.7Aa	1.3Aa	103.5Aa
20	12.7Aa	121.3Aa	13.8Aa	1.7Aa	149.7Aa
Grossarenic Hapludult (sorghum)					
0	4.5Ab	17.0Ba	0.4Ba	0.2Ba	3.3Aa
2	5.2Aa	16.0Ba	1.4Ba	0.2Ba	11.3Ba
5	8.1Aa	21.3Ba	2.8Ba	0.3Ba	20.7Bb
10	8.6Bb	25.7Ba	4.9Bb	0.5Ba	58.7Ba
20	10.4Ba	41.0Ba	6.7Ba	0.6Ba	88.3Bb

Means followed by the same letter are not statistically different from each other. Capital letters compare different soils, while lower case letters compare different plants. Tukey's test was applied at 5% probability taking under consideration the "doses" as a quantitative factor

Table 2 Values of Cu, Cd, and Pb in sunflower and sorghum shoots and roots cultivated in Typic Paleudult and Grossarenic Hapludult soils under the amendment of industrial landfill sludge (ILS) at 0, 2, 5, 10, and 20 Mg ha^{-1} doses

Doses (Mg ha^{-1})	Cu (mg kg^{-1})		Cd (mg kg^{-1})		Pb (mg kg^{-1})	
	Shoots	Roots	Shoots	Roots	Shoots	Roots
Sunflower—Typic Paleudult						
0	19.44Ba	28.39Ba	0.22Ab	0.37Aa	1.15Aa	12.15Aa
2	19.31Aa	41.51Aa	0.22Aa	0.21Aa	0.52Aa	12.10Aa
5	22.74Aa	48.67Aa	0.29Aa	0.31Aa	0.64Aa	8.69Aa
10	26.32Aa	37.96Aa	0.28Ba	0.23Ba	1.46Aa	7.06Aa
20	32.04Aa	33.01Aa	0.33Ba	0.30Aa	1.79Aa	8.38Aa
Sunflower—Grossarenic Hapludult						
0	26.39Aa	41.90Aa	0.22Aa	0.15Ba	0.57Aa	10.42Aa
2	21.08 Aa	24.84Ba	0.22Aa	0.15Aa	1.15Aa	4.95Ba
5	26.78 Aa	26.25Ba	0.32Aa	0.19Ba	1.06Aa	7.12Aa
10	26.62 Aa	27.71Aa	0.41Aa	0.35Aa	0.73Aa	7.42Aa
20	23.45 Ba	9.58Ba	0.48Aa	0.33Aa	0.78Bb	8.25Ab
Sorghum—Typic Paleudult						
0	9.03Ab	37.23Aa	0.32Aa	0.29Ab	0.70Aa	7.77Aa
2	9.22Ab	28.94Ab	0.20Aa	0.23Aa	0.35Aa	7.59Aa
5	8.72Ab	25.93Ab	0.21Ab	0.23Ab	0.24Aa	10.38Aa
10	8.29Ab	25.32Ab	0.19Ab	0.20Aa	0.24Ab	8.17Aa
20	10.2Ab	37.44Aa	0.18Bb	0.25Aa	0.20Bb	9.05Ba
Sorghum—Grossarenic Hapludult						
0	8.22Ab	16.09Bb	0.24Ba	0.12Ba	1.13Aa	8.50Aa
2	7.92Ab	14.09Ba	0.12Bb	0.10Ba	0.85Aa	5.15Aa
5	7.84Ab	27.95Aa	0.12Bb	0.08Bb	0.97Aa	5.95Aa
10	9.72Ab	24.83Aa	0.18Ab	0.15Ab	0.66Aa	4.80Aa
20	7.56Ab	8.00Ba	0.28Ab	0.10Bb	4.35Aa	42.22Aa

Means followed by the same letter are not statistically different from each other. Capital letters compare different soils, while lower case letters compare different plants. Tukey's test was applied at 5% probability taking under consideration the "doses" as a quantitative factor

(−0.75). Cu is an essential micronutrient, even though it can be toxic above certain levels (Barbosa et al. 2013; Andreazza et al. 2015; Silva et al. 2015). Cadmium (Cd) in the shoots of sunflower had negative correlations with stem diameter (−0.69) and the biomass production of the roots (−0.63).

Chromium (Cr) was the metal found the most in the ILS, and it promoted an increase in the concentration of Cr in the roots of the sunflower plants, especially when grown in the TP soil. However, the plants did not show translocation to the shoots of the plants, accumulating Cr only in the roots (Fig. 3b). Values of Cr showed significant differences ($p < 0.05$) among treatments: the highest levels of Cr in the shoots of sorghum were found in the highest ILS dose (20 Mg ha^{-1}) on the GH soil (Fig. 3c); and in the roots of sorghum on the TP soil (Fig. 3d). The concentration of Cr in the roots of both sunflower and sorghum plants increased with the increment of ILS doses; yet, these concentrations did not reach critical values (Kabata-Pendias 2011). Despite its high concentration in the ILS, Cr did not present significant translocations to the shoots of the plants (Tables 3, 4 and Fig. 3). The accumulation of Cr in the roots is commonly reported in studies with application of sludge in soils, and this occurs due to a strategy mechanism of plant protection (Patel et al. 2015; de Sousa et al. 2018). Cr does not play any role in the plant metabolism; thus, its concentrations are always higher in the roots than in the shoots (Kabata-Pendias 2011; Sridhar et al. 2011). Studies have reported different growth effects in the cultivation of plants in soils with increased Cr, such as reductions (Fozia et al. 2008), no differences (Gianello et al. 2011), and increases (Patel et al. 2015; de Sousa et al. 2018) in plants biomass.

Principal component analysis (PCA) corroborated the increases of ILS doses with the soil pH, EC, and the concentrations of Na, Ca, P, and Cr (Fig. 4). Cr in the shoots showed negative correlations with the biomass of the roots of the sunflower plants (–0.63) and sorghum height (−0.69). Lead (Pb) and Cadmium (Cd), non-essential and toxic metals, also presented negative correlations with the plants development (Table 4). Pb levels were correlated (r) with the height of the plants (−0.69) and the biomass of the roots (−0.66) of the sorghum. Cd concentrations in the shoots were negatively correlated with the stem diameter (−0.69)

Table 3 Translocation factor of Cu, Cd, Cr, and Pb in sunflower and sorghum plants cultivated in Typic Paleudult and Grossarenic Hapludult soils under the amendment of industrial landfill sludge (ILS) at 0, 2, 5, 10, and 20 Mg ha^{-1} doses

Doses (Mg ha^{-1})	Cu	Cd	Cr	Pb
Typic Paleudult (sunflower)				
0	0.41	0.37	0.27	0.09
2	0.32	0.51	0.10	0.04
5	0.32	0.48	0.10	0.07
10	0.41	0.54	0.09	0.17
20	0.49	0.53	0.05	0.18
Grossarenic Hapludult (sunflower)				
0	0.39	0.59	0.24	0.05
2	0.46	0.59	0.16	0.19
5	0.51	0.62	0.08	0.13
10	0.49	0.54	0.07	0.09
20	0.71	0.59	0.13	0.09
Typic Paleudult (sorghum)				
0	0.20	0.53	0.18	0.08
2	0.24	0.47	0.08	0.04
5	0.25	0.47	0.11	0.02
10	0.25	0.49	0.06	0.03
20	0.21	0.42	0.11	0.02
Grossarenic Hapludult (sorghum)				
0	0.34	0.68	0.26	0.12
2	0.36	0.53	0.23	0.14
5	0.22	0.60	0.24	0.14
10	0.28	0.55	0.15	0.12
20	0.49	0.73	0.23	0.09

and the roots biomass production (–0.63) of the sunflower plants. Concentrations of copper (Cu) in the roots was correlated (r) positively with the sunflower diameter (0.72) and roots biomass (0.65) (Table 4). The translocation factor of Cu in sunflower plants had positive correlations (r) with the ILS doses (0.71) and negative correlations with the stem diameter (–0.81) and dry biomass of the roots (–0.75), similar to the TF of the Cd with the height of the sorghum plants (–0.61).

Fluorescein diacetate (FDA) hydrolysis results presented a wide range of values from 0.53 to 5.22 µg FDA g^{-1} h^{-1}, after the amendment of ILS on soils with cultivation of both sunflower and sorghum plants, increasing the values with the time (15, 30, 60, and 90 days) after the sludge amendment (Fig. 5). The FDA hydrolysis presented significant differences ($p < 0.05$), being the values from the TP soil (2.40 µg FDA g^{-1} h^{-1}) above the ones from the GH soil (2.08 µg FDA g^{-1} h^{-1}), and the results from the sorghum plants (2.37 µg FDA g^{-1} h^{-1}) higher than the ones from the sunflower plants (2.10 µg FDA g^{-1} h^{-1}), without significant interaction between these factors. Temporal variation in FDA hydrolyzed may have multivariate effects and factors (direct and indirect), such as waste (ILS) decomposition, plant development, and ion leaching (Bueno et al. 2011). FDA is a compound hydrolyzed by enzymes, which is an environmental bioindicator method. Distinct effects on FDA hydrolysis may be found in waste amendment on soils, such as increases, reductions, and variations according to the doses applied (Santos et al. 2011; Silva et al. 2014). These

Table 4 Pearson correlation coefficients (r) for shoots (S), roots (R), and translocation factor (TF) of sunflower and sorghum on soils under industrial landfill sludge (ILS) doses

	Sunflower			Sorghum		
	Doses	Stem diameter	dm *R*	Doses	Height	dm *R*
S						
dm	–	0.78	–	–	0.86	–
Cu	0.60	–	–	–	–	–
Cd	0.81	−0.69	−0.63	–	–	–
Cr	–	–	−0.63	–	−0.69	–
Pb	–	–	–	–	−0.69	–
R						
dm	–	0.95	–	–	0.87	–
Cu	–	0.72	0.65	–	–	–
Cd	–	–	–	–	–	–
Cr	0.82	–	–	0.62	–	–
Pb	–	–	–	0.60	−0.66	–
TF						
Cu	0.71	−0.81	−0.75	–	–	–
Cd	–	–	–	–	−0.61	–
Cr	–	–	–	–	–	–
Pb	–	–	–	–	–	–

Presented only values higher than ±0.60

dm dry mass

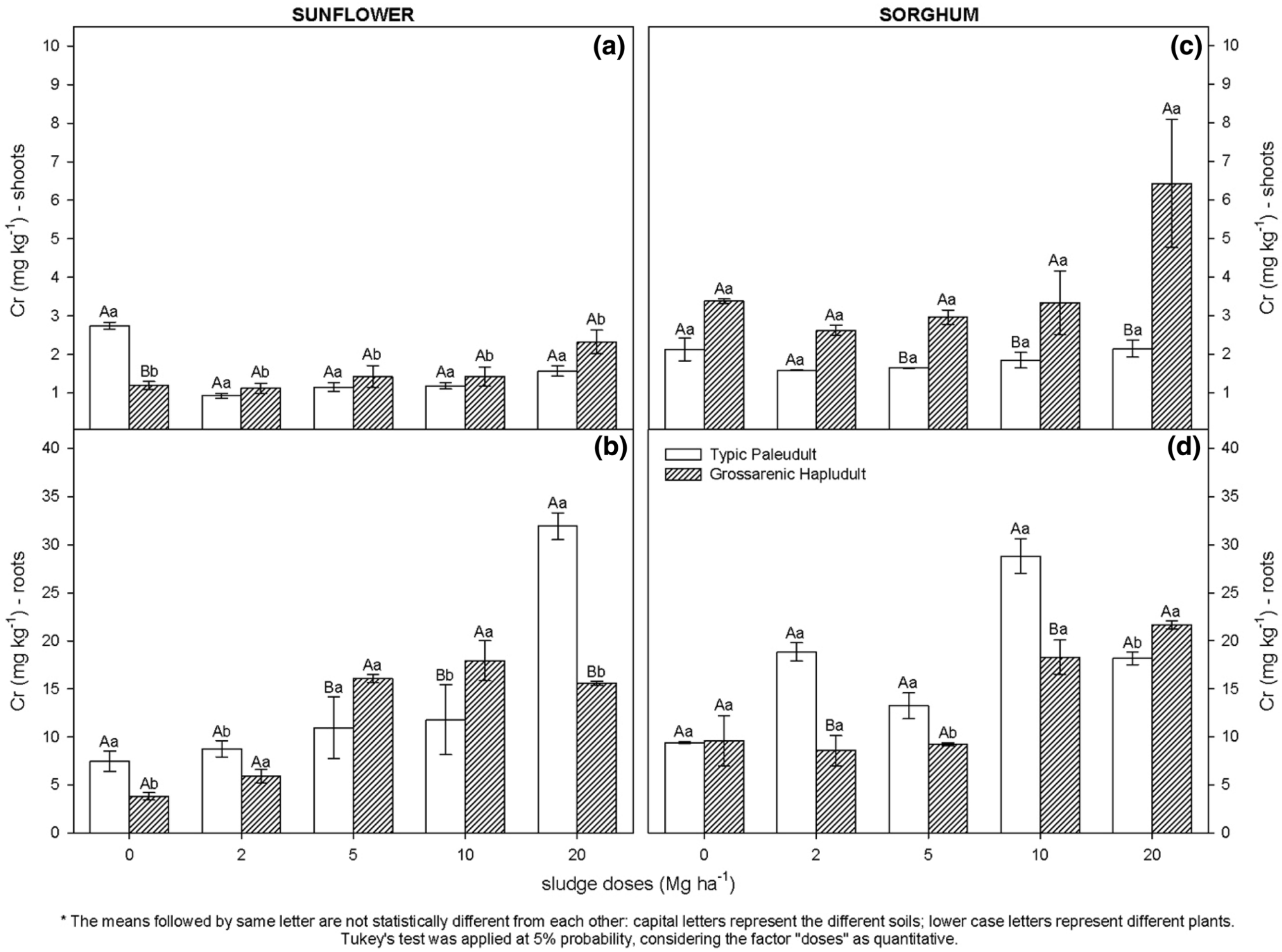

Fig. 3 Levels of Cr in sunflower shoots (**a**), and roots (**b**); and sorghum shoots (**c**), and roots (**d**) cultivated on Typic Paleudult and Grossarenic Hapludult soils under industrial landfill sludge (ILS) at 0, 2, 5, 10, and 20 Mg ha^{-1} doses

effects are dependent of the organic carbon and heavy metals content in the soil (Santos et al. 2011; Lloret et al. 2016).

Conclusions

The amendment of industrial landfill sludge (ILS) in soils is an economically and environmentally healthy alternative to waste disposal due to the high cost of landfills, because these wastes could be a source of carbon, nutrients, and pH increasing. These characteristics improved the growth of the plants (Sunflower and Sorghum) and the soil quality, especially in smaller doses of ILS (as 5 and 10 Mg ha^{-1}). Doses of up to 10 Mg ha^{-1} had the best results, with less damage to soil and plants, while negative effects in both soils and plants occurred with the highest dose (20 Mg ha^{-1}). The amendment of ILS in the Typic Paleudult soil had better results than the Grossarenic Hapludult soil, which makes the former a more secure soil to dispose of wastes due to its higher clay content. ILS amendment on soil should be monitored for soil quality and metal contents. The disposal of ILS in soils in correct doses can be a low-cost alternative when compared to commercial inputs, for increasing the nutrients and the soil quality.

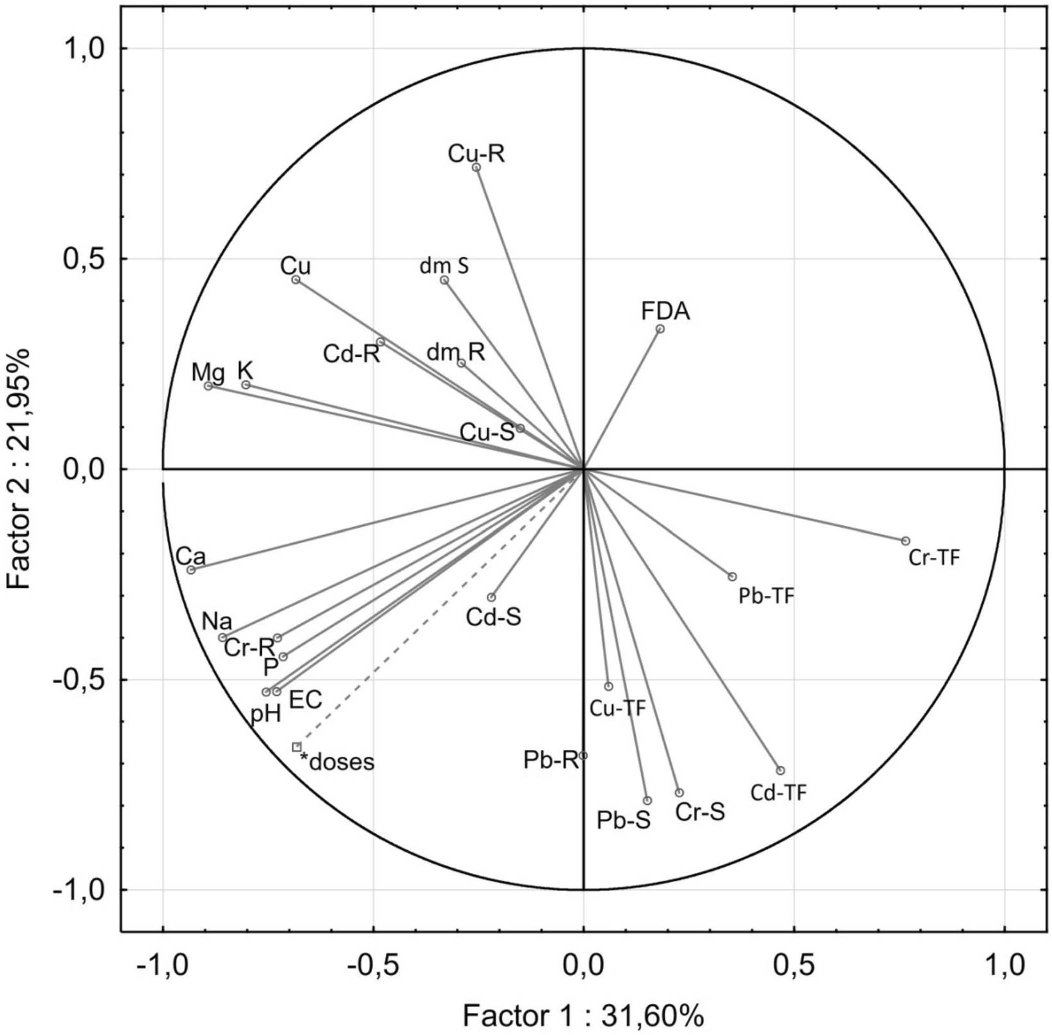

Fig. 4 Principal Component Analysis (PCA) in the amendment of industrial landfill sludge (ILS) doses (0, 2, 5, 10, and 20 Mg ha^{-1}) on Typic Paleudult and Grossarenic Hapludult soils. *dm* dry mass, *S* shoot, *R* roots, *TF* translocation factor

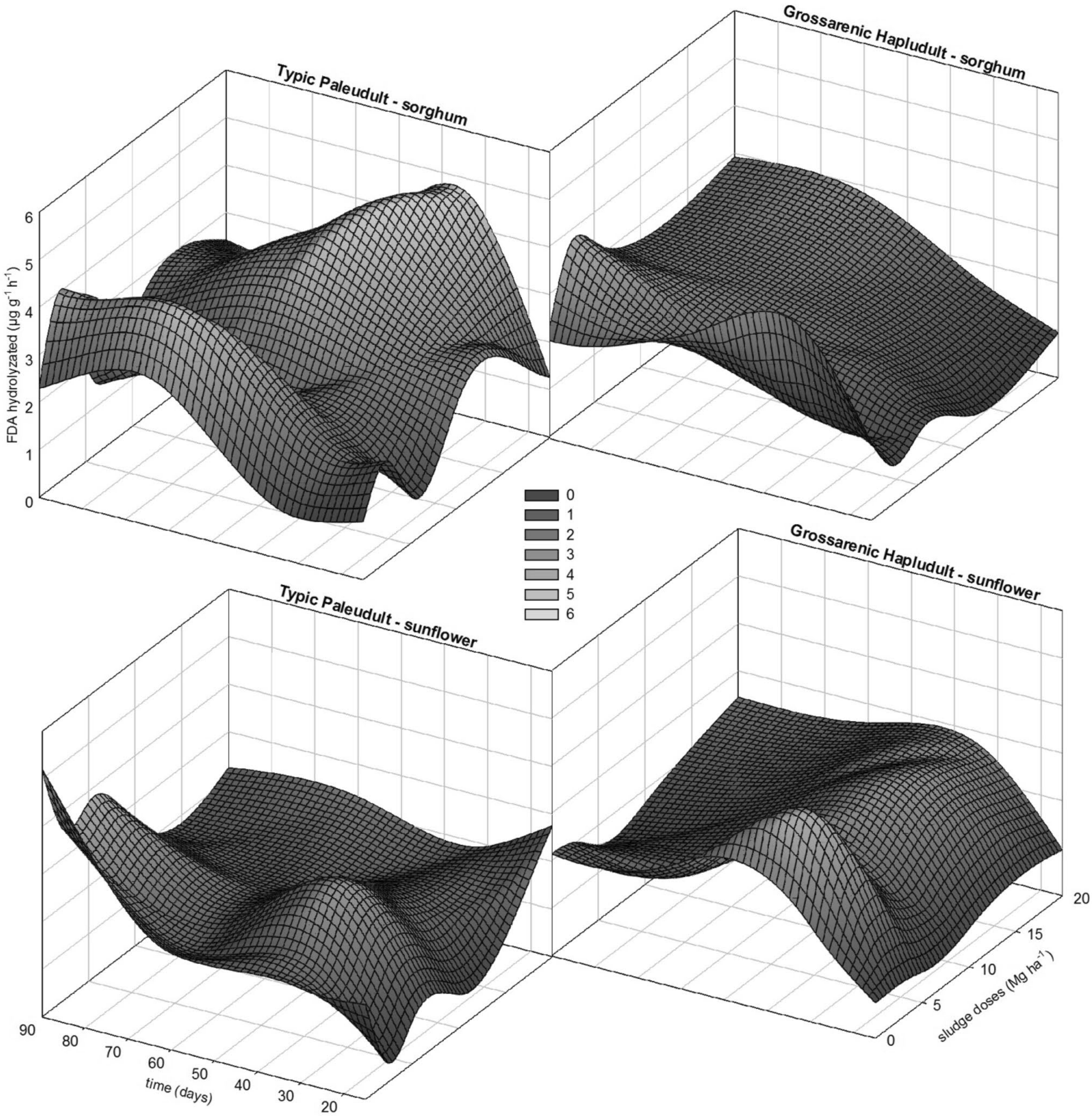

Fig. 5 FDA hydrolyzed (µg FDA g^{-1} h^{-1}) on Typic Paleudult and Grossarenic Hapludult soils with sunflower and sorghum cultivation at 15, 30, 60, and 90 days after the amendment of industrial landfill sludge (ILS) doses (0, 2, 5, 10, and 20 Mg ha^{-1})

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