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Soil Fertility and Electrical Conductivity Affected by Organic Waste Rates and Nutrient Inputs

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ABSTRACT: The composition of organic waste (OW) and its effect on soil processes may change soil fertility and electrical conductivity (EC). The side effects of waste use in crop fertilization are poorly understood for Brazilian soils. This study examined the effect of the addition of 15 different organic wastes to Oxisols and a Neosol on pH, base saturation, EC, cation exchange capacity (CEC at pH 7), and the availability of Al, macro (P, K, Ca^{2+}, Mg^{2+} and S) and micronutrients (B, Fe^{2+}, Mn^{2+}, Cu^{2+} and Zn^{2+}). Soil samples (150 g) were treated with chicken, pig, horse, cattle, and quail manures, sewage sludge 1 and 2, eucalyptus sawdust, plant substrate, coconut fiber, pine bark, coffee husk, peat, limed compost, and biochar. Wastes were added considering a fixed amount of C (2 g kg^{-1}), which resulted in waste rates ranging from 2.5 to 25.6 Mg ha^{-1}. The soil-waste mixtures were incubated for 330 days in laboratory conditions. The waste liming or acidification values were soil-dependent. The use of some manures and compost increased the pH to levels above of those considered adequate for plant growth. The soil EC was slightly increased in the Neosol and in the medium textured Oxisol, but it was sharply changed (from 195 to 394 µS cm^{-1}) by the addition of organic wastes in the clayey Oxisol, although the EC values were below the range considered safe for plant growth. Changes in the soil availability of P, K^+, Ca^{2+} and Zn^{2+} were highly related to the inputs of these nutrients by the wastes, and other factors in soil changed due to waste use. Organic waste use simultaneously affects different soil fertility attributes; thus, in addition to the target nutrient added to the soil, the soil acidity buffering capacity and the waste liming and agronomic value must be taken into account in the waste rate definition.

Keywords: organic fertilization, manures, liming value, micronutrients, nutrient cycling, sewage sludge.

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INTRODUCTION

The use of organic wastes in agricultural fields may increase crop yield and soil quality while reducing pollution and increasing farmer profits. The effects of waste application on soil fertility depend on waste chemical composition, which is highly variable and linked to its origin. The waste production system, storage and management of crop residues and postharvest by-products are other key factors controlling the organic waste chemical composition and its value as an agricultural input. In animal production systems, the composition and amount of feed furnished to animals are other factors that control the waste agronomic value; post-production treatments of composts and sewage sludge and by-products generated in the industry and agro-industries also exert an influence on the waste chemical composition (Melo and Silva, 2008; Silva, 2008).

Manures originating from intensive production systems are richer in nutrients than wastes produced by animals raised in extensive pastures or fed with poor nutritional grasses. In comparison to crop residues, pig, quail and chicken manures commonly have higher contents of N, P, K and Ca (Higashikawa et al., 2010). Animal manures enriched in carbonates or Ca oxides may also benefit crops, through soil acidity correction; however, the intensity of soil acidity neutralization also relies on the initial soil pH and amount of waste added to the soil (Hargreaves et al., 2008; Diacono and Montemurro, 2010). Besides the amount and chemical composition, the effects of wastes on soil properties are related to the nutrient mineralization rate, which is closely linked to chemical, physical and biological waste properties, humification degree and the biotic and abiotic factors in soil regulating the rate of waste decomposition (Abreu Júnior et al., 2005; Pavinato and Rosolem, 2008).

The effects of wastes on soil properties are mainly related to the rate of application and the waste chemical composition, but soil organic matter and clay contents are other key factors regulating changes in soil fertility (Müller and Hopper, 2004; Silva, 2008). Adverse effects of wastes on soil fertility attributes are associated with a sharp increase in pH (Mokolobate and Haynes, 2002; Dikinya and Mufwanzala, 2010), which may reach the alkaline range and decrease the availability of some micronutrients. High charges of micronutrients added in soils, especially Zn and Cu, and the addition of K and other chemical elements or pollutants at levels above those considered agronomically safe for agricultural soils are effects that have been reported for some soils successively fertilized with manures (Torri and Corrêa, 2012; Penha et al., 2015). Excessive levels of P in soil and its runoff from sites with intensive poultry activities are other adverse effects observed in fields intensively and continuously fertilized with poultry litter (Harmel et al., 2009).

The waste rate definition is a critical issue in organic fertilization and is typically based on the nutrient in the highest concentration, in most cases N, but the water content and N mineralization rate are factors that must be also taken into account (Smith, 2009). When fixing the amount of N added to soils, the input of other nutrients is highly variable and depends on the waste chemical composition and its nutrient charges. Thus, by choosing N as the target nutrient, the application of P and K at higher rates than those required by crops is common, mainly in crop fields where animal manures are successively used for crop fertilization (Bar-Tal et al., 2004). Continuous application of wastes could also increase the soil Ca content (Shanmugam, 2005), causing nutritional imbalances in K, Mg, and N-ammonium supplied to plants. Changes in the availability of nutrients and in other soil properties are the reasons why the waste rate in this study was calculated based on the C content. The fixation of the amount of C added to soils may allow the study of the side effects of varied waste rates on soil pH, electrical conductivity (EC), and nutrient availability. It may also allow for checking if these possible changes affect soil fertility negatively or in a synergistic way in order to assure optimal conditions for plant growth.

When rich-nutrient or animal wastes decompose, salts and ions in the soil and in its liquid phase are increased. Such changes exert an influence on soil EC, which is regulated by several soil fertility attributes, such as pH, P, K, Ca, Mg, OM, cation exchange capacity (CEC) and by the contents of other soluble salts and organic ligands (Bronson et al., 2005; Sudduth et al., 2005; Aimrun et al., 2009; Peralta and Costa, 2013). These EC-soil property interactions are not easily identified, since the magnitude of the reactions regulating soil EC levels are complex and dynamic. Thus, it is important to investigate the changes on EC in soils treated with different wastes, bearing in mind that EC reflects the sum of salts and ions in the soil solution, the levels of which are regulated by the type, composition and amount of waste added to the soil. Soil EC is an index used to delineate site-specific management zones, since it is highly correlated to crop yield (Li et al., 2008). Thus, EC could be an additional soil fertility index.

Organic waste rates added in crop fields, overall, are based on the amount of N required by crops. A fixed amount of C added by the waste is not a guarantee of equal chemical composition or rate of the waste added in soils. Thus, when organic waste rate is based on a previously determined amount of C, it is possible to assess if the waste humification degree and its chemical composition are determinants of the waste and soil organic matter (SOM) decomposition rate and, as a consequence, of the waste effect on soil nutrient availability.

We hypothesized that the use of derived-animal wastes is followed by an enrichment of nutrients in soils and by an effective correction of soil acidity. Coffee husk use may be an efficient way to increase the K content in soils. The effects of wastes on nutrients rely on soil pH change and on the inputs of nutrients by each OW. This experiment was carried out to evaluate the effect of manures, crop residues, composts, plant substrates, postharvest residues, peat and biochar on the soil acidity level, nutrient availability and EC of three organic matter and clay-contrasting soils from Minas Gerais, Brazil.

MATERIALS AND METHODS

This study was carried out under laboratory conditions. Samples of a *Latossolo Vermelho-Amarelo Distrófico* (Typic Haplustox-TH), *Latossolo Vermelho Distrófico* (Rhodic Hapludox-RH) and *Neossolo Quartzarênico* (Quartzipsamment-TQ) were dried, ground, sieved (mesh size of 2 mm) and stored. The soils were classified following both the Brazilian System of Soil Classification (Santos et al., 2013) and the USDA Soil Taxonomy (Soil Survey Staff, 2010). Soil fertility attributes and textural fraction contents (Table 1) of the samples collected at the 0.00-0.20 m depth were determined, according to the protocols described in Silva et al. (2009). Based on the soil analysis, a mixture of $CaCO_3$+$MgCO_3$ in a proportion of 4:1 was added to the soil, aiming to raise the base saturation to 60 %. The limed soil was incubated for 30 days under laboratory conditions in opened plastic bags, until the target base saturation level was reached. During the incubation of the soil-carbonate mixture, soil moisture content was kept close to 70 % of the soil field capacity, with replacement of deionized water every week. The soil C content was determined using an Elementar Vario TOC Cube model analyzer by incinerating the soil samples (0.25 mm sieved) at 950 °C and quantifying the C evolved using an NDIR detector, following the methodology described by Zinn et al. (2014).

Table 1. Chemical properties and texture of the three studied soils, under natural conditions

Soil	Clay	Texture class	pH(H_2O)	P (Mehlich-1)	K^+	Ca^{2+}	Mg^{2+}	CEC	V	C
	g kg^{-1}			mg dm^{-3}		cmol$_c$ dm^{-3}			dag dm^{-3}	
TH	180	Medium-clay	5.3	1	11	0.1	0.1	2.8	8	0.9
RH	660	Clayey	4.2	2	59	0.2	0.2	15.8	3	4.4
TQ	80	Sandy	5.4	9	22	0.7	0.1	5.4	16	1.2

Latossolo Vermelho-Amarelo Distrófico (Typic Haplustox-TH), *Latossolo Vermelho Distrófico* (Rhodic Hapludox-RH) and *Neossolo Quartzarênico* (Quartzipsamment-TQ). CEC: cation exchange capacity at pH 7 as a sum of basic cations plus titratable acidity measured by the SMP_{pH} method; V: base saturation; C: organic carbon determined by dry combustion in an automated analyzer.

The following OW samples were investigated: sewage sludge 1 from a wastewater treatment plant (WTP) where residential sewage is treated and sewage sludge 2 from a WTP where residential and industrial wastes are treated, chicken and quail manures (Nepomuceno, MG), cattle manure, eucalyptus sawdust, charcoal (obtained from the pyrolysis of eucalyptus at 450 °C), plant substrate (composed of a humified and stabilized mixture of peat, pine bark, vermiculite and coconut fiber), compost (from the garbage processing plant in Cristais, MG), coffee husk, coconut fiber and pine bark. The fresh cattle and chicken manures were obtained from dairy and egg production farms. The sewage sludge was physically and chemically stabilized. The sawdust was collected from the sawmill of the Federal University of Lavras (UFLA), immediately after the cutting of eucalyptus logs, and coffee husk was provided by the Coffee Research and Extension Center (CEPE-Café). Coconut fiber and pine bark were purchased on the market. Peat was obtained from the municipality of Boa Esperança, MG. Pig manure was obtained from a grow-finishing pig confinement system where the animals were nourished with a balanced diet. Fresh horse manure was obtained from the Zootechny facilities at the UFLA, MG. The organic wastes and their chemical characteristics are shown in table 2. For the chemical characterization, several analyses (Higashikawa et al., 2010; Abbruzzini et al., 2014) were performed with the following modifications: pH was determined using an organic waste:water ratio of 1:5, and total C content in the waste was determined in the same way as described for soil samples, in a TOC analyzer using 3-5 mg of dried waste sample.

Organic waste rates were calculated to add 2 g kg^{-1} of C to soils, which represented, according to the wastes tested, rates ranging from 2.5 (biochar) to 25.6 (peat) Mg ha^{-1} (Table 3), considering the addition of the waste at the 0.00-0.10 m soil depth. Such organic waste rates caused a high variation in the amounts of N (11 to 402 kg ha^{-1}) supplied to crops. Organic waste rates and their respective nutrient inputs are shown in table 3. Some soil samples were incubated without the addition of organic wastes (control). After acidity correction, soils samples were immediately mixed with the organic wastes, and, in sequence, water was added to the mixture in order to start the incubation. Incubation of the treatments (soil+organic waste mixtures) began in January and ended in December 2010. Organic wastes were mixed with whole soil mass (150 g), and incubated for 330 days in a 250 mL mini-lysimeter with two chambers. Soil samples incubated with the organic wastes were kept in the upper chamber, and the lower chamber was used to collect the

Table 2. Macro and micronutrient contents (dry basis), pH in water, carbon (C), and electrical conductivity (EC) of the studied organic wastes

Organic waste	pH(H_2O)	C	EC	P	K	Ca	Mg	N	S	Mn	Zn	Cu	B	Fe
		%	dS m^{-1}	g kg^{-1}						mg kg^{-1}				
Chicken manure	7.7	22.7	40.6	18.4	31	121	8.1	47.4	5.1	631	519	83.8	31	3.29
Pig manure	7.6	26.3	3.86	2.41	0.1	64.7	8.4	20.0	1.9	656	733	NI	NI	1.26
Horse manure	NI	39.4	NI	0.61	3.5	2.20	0.9	6.40	0.4	134	458	27.3	NI	7.95
Sewage sludge 1	4.4	19.8	10.6	4.1	3.9	23.4	1.9	22.3	6.2	265	1284	175	4.33	11.1
Sewage sludge 2	5.4	21.4	8.81	7.3	0.4	2.60	0.8	27.0	1.6	248	938	589	NI	4.75
Sawdust	4.2	44.6	0.51	0.01	0.3	2.10	0.3	3.40	0.03	23.9	10.4	8.10	5.9	1.78
Plant substrate	7.4	38.0	0.08	1.4	11.5	14.8	17.5	2.10	0.02	275	55.9	55.6	5.2	56.3
Coconut fiber	5.4	45.4	1.81	0.3	6.4	1.90	0.8	3.80	0.5	68.8	66.2	12.0	11.8	2.64
Pine bark	4.3	45.8	0.39	0.1	0.8	9.50	0.7	4.50	0.2	141	31.6	33.1	6.80	11.5
Cattle manure	9.3	23.9	19.0	5.5	35.7	8.00	5.3	18.4	1.8	460	102	38.4	12.9	21.5
Peat	4.7	7.80	0.15	1.0	0.82	0.60	0.02	12.2	1.3	1205	31.0	54.1	9.70	14.9
Quail manure	7.0	25.5	0.49	13.8	11.0	13.9	3.2	23.5	2.8	275	341	58.9	NI	1.22
Coffee husk	4.8	42.0	19	1.8	45.7	7.01	1.6	29.2	1.9	121	96.5	35.4	18.4	5.42
Compost	NI	18.4	NI	7.7	6.5	19.3	5.0	25.7	3.8	401	418	198	NI	26.3
Biochar	8.5	80.7	0.54	0.5	6.7	9.90	0.2	7.40	0.3	10.5	6.1	14.1	6.04	61.6

NI: not identified.

excess water that drained from the incubated plot, which was immediately returned to the upper chamber. During the incubation, the soil moisture was kept close to 70 % of the maximum water retention capacity of each soil-waste mixture, with replacement of deionized water every three days. The soil-waste mixtures were incubated in opened chambers. The temperature in the laboratory (soil organic matter laboratory) where the samples where incubated was not controlled, and ranged during the experimental period from 19 to 28 °C.

After incubation, soils were analyzed regarding the pH in water, Al^{3+}, Ca^{2+}, Mg^{2+}, base saturation (V), total carbon (TC), cation exchange capacity (CEC) at pH 7, S-sulfate, K^+, P (Mehlich-1), Zn^{2+}, Fe^{2+}, Mn^{2+}, Cu^{2+} and B, according to the analytical protocols described by Silva et al. (2009). Soil EC was determined with a TECNAL-TEC 4MP model conductivity sensor, at a soil:water ratio of 1:2 (10 cm^3 of dry soil:20 mL of deionized water); the soil:water mixture was stirred for 30 min, left to stand for another 30 min, stirred again for 30 s, and then the EC was measured.

A completely randomized design was used in a 3 × 15 factorial scheme, where three soils were incubated with 15 organic waste samples, with an additional treatment, i.e. soil incubated without waste (control), in three replicates for each soil type, totaling 144 experimental plots. The data set was submitted to analysis of variance and the treatment means were compared by the Scott-Knott test ($p<0.05$), using SISVAR software (Ferreira, 2014).

RESULTS AND DISCUSSION

Soil pH was modified by most of the wastes tested, and the amplitude of soil acidity changes was both waste- and soil-dependent. The increase in the pH of the TH samples was markedly influenced by the use of chicken and quail manures and compost, since in these waste-treated plots the pH reached values close to 8. In fact, the largest increases in pH were found for the TH samples, the soil with the lowest C content (Figure 1). In the RH and TQ samples, the addition of sewage sludges 1 and 2, peat and biochar significantly decreased the pH, in comparison to the control. The soil pH decrease can be explained by the concentrations of H^+ added to the soil by each waste; during decomposition in soil,

Table 3. Rates and nutrient inputs added for each of the organic wastes

Organic waste	Waste rate[1]		Waste nutrient input										
			P	K	Ca	Mg	N	S	Mn	Zn	Cu	B	Fe
	mg kg^{-1}	Mg ha^{-1}[2]	mg kg^{-1}										
Chicken manure	8,810	8.8	162	273	1066	71.4	418	44.9	5.56	4.57	0.74	0.27	29
Pig manure	7,604	7.6	18.2	0.76	492	63.9	152	14.4	4.99	5.57	NI	NI	9.56
Horse manure	5,076	5.1	3.05	17.8	11.2	4.57	32.5	2.03	0.68	2.32	0.14	NI	40.4
Sewage sludge 1	10,101	10.1	41.4	39.4	236	19.2	225	62.6	2.68	130	1.77	0.04	112
Sewage sludge 2	9,345	9.3	68.2	3.74	24.3	7.48	252	14.9	2.32	8.8	5.5	NI	44.4
Sawdust	4,484	4.5	0.00	1.35	9.42	1.35	15.2	0.00	0.11	0.05	0.04	0.03	8.03
Plant substrate	5,263	5.2	7.37	60.5	77.9	92.1	11.0	0.00	1.45	0.29	0.29	0.03	296
Coconut fiber	4,405	4.4	1.32	28.2	8.37	3.52	16.7	2.20	0.30	0.29	0.05	0.05	11.6
Pine bark	4,366	4.3	0.44	3.49	41.5	3.06	19.6	0.87	0.62	0.14	0.14	0.03	50.2
Cattle manure	8,368	8.3	46.0	299	66.9	44.3	154	15.1	3.85	0.85	0.32	0.11	180
Peat	25,641	25.6	25.6	20.5	15.4	0.00	312	33.3	30.8	0.79	1.39	0.25	381
Quail manure	7,843	7.8	108	86.3	109	25.1	184	21.9	2.16	2.67	0.46	NI	9.6
Coffee husk	4,761	4.7	8.57	218	33.3	7.62	139	9.05	0.58	0.46	0.17	0.09	25.8
Compost	10,869	10.8	83.7	70.6	210	54.3	279	41.3	4.36	4.54	2.15	NI	286
Biochar	2,478	2.5	1.24	16.6	24.5	0.50	18.3	0.74	0.03	0.02	0.03	0.01	0.22

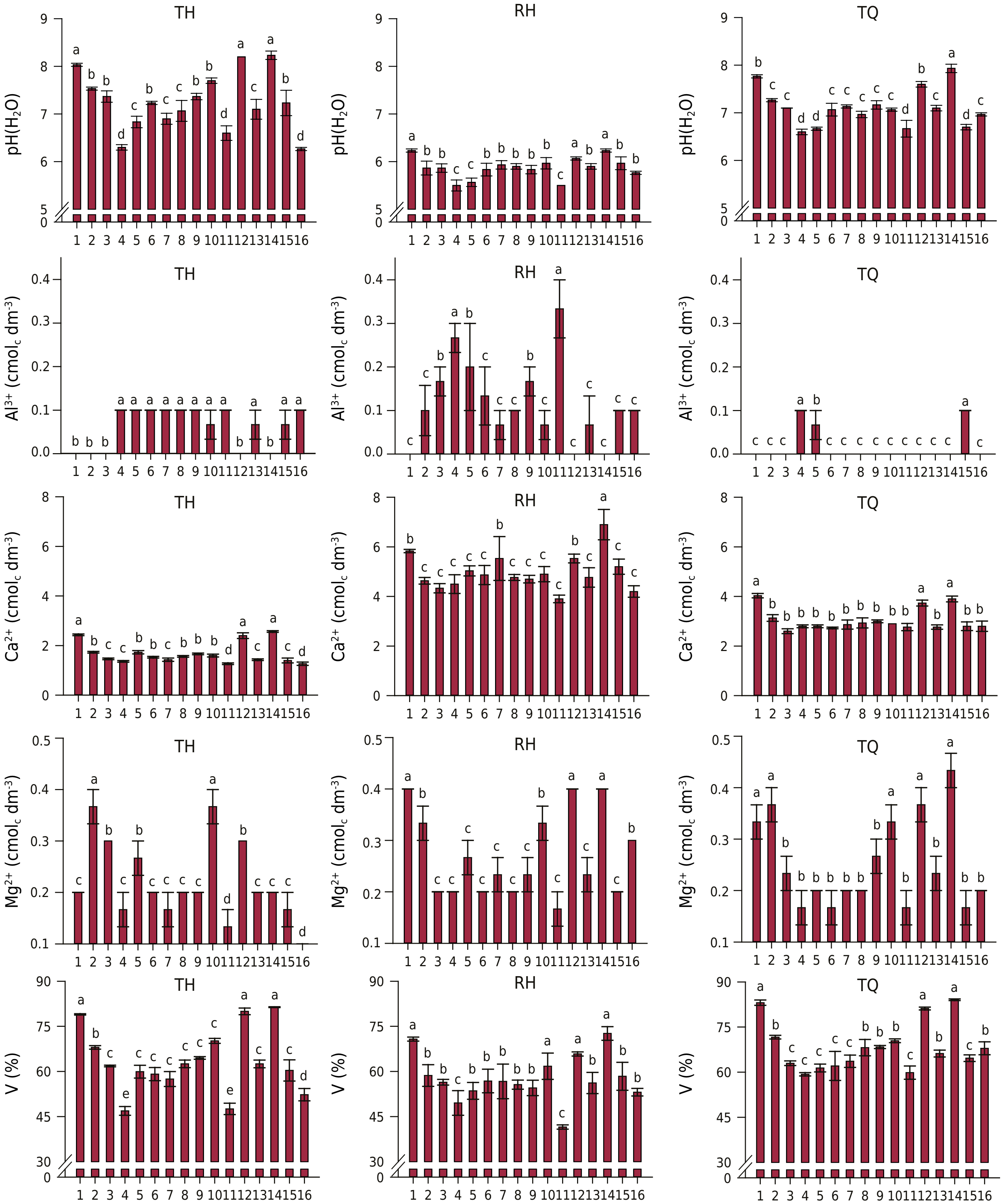
NI: not identified. [1] Organic waste rate used to add in soil 2 g kg^{-1} of C. [2] Rate calculated considering the waste addition at the 0.00-0.10 m soil depth.

waste can generate organic and inorganic acidic species, such as H_2SO_4 and HNO_3 (Galdos et al., 2004). Soil acidification due to the use of wastes in crop fields was also observed by Nascimento et al. (2004) and Simonete et al. (2003). Furthermore, the changes in soil pH are related to the nitrification rate, the oxidation of different chemical species and the production of organic acids during the waste decomposition (Mokolobate and Haynes, 2002).

The addition of wastes significantly increased soil pH in the TH plots, when compared to the controls, with the exception of the sewage sludge 1 and peat. Such high pH (above 7) values measured in some of the TH plots are above of the pH range (5.5-6.3) technically recommended for crops. In the RH and TQ samples, only quail and chicken manures and compost propitiated soil pH values significantly higher than those values measured for the control. It should, however, be mentioned that the initial pH (control) of TQ samples was close to 7. Evaluating the neutralization of soil acidity following swine, rabbit, goat, chicken and cattle manure use, Ano and Ubochi (2007) also verified this increase in soil pH when the waste rates were elevated from 10 to 40 Mg ha^{-1}. In this study, the waste rate ranged from 2.5 to 25.6 Mg ha^{-1}. Such a high waste rate amplitude is related to the substantial variations in the waste C content (Table 2). Among the wastes investigated, those originating from intensive animal production systems (chicken and quail manures) are rich in nutrients, have high pH values and ash contents, and low C contents. The lower the waste C content, the higher the waste rate used in the present study. Such characteristics possibly explain the marked effect of chicken and quail manures in increasing the pH of all soils investigated. The effect of the compost on soil pH is probably related to the fact that this residue was limed during composting. The increase in the pH of the TH plots treated with eucalyptus sawdust – the waste with the lowest pH value – was unusual, and deserves further investigation. Soil acidity neutralization caused by OW is explained by the rate applied, and waste initial pH, mainly for those residues whose pH values are within the alkaline range. Decarboxylation of organic anions due to decomposition, complexation of free H^+ and Al^{3+} ions with organic ligands and increased saturation of soil CEC by Ca^{2+}, Mg^{2+} and K^+ added by the wastes are other possible explanations for soil pH changes (Pavinato and Rosolem, 2008). N mineralization, with subsequent production of OH^- by organic ligands, is another process that could explain the soil pH increase (Mkhabela and Warnan, 2005).

High pH values were observed for some wastes added in the TH and TQ soils. Such high pH levels require care and demand adjustments to the waste rate added in soils, mainly for those wastes with high contents of nutrients and ash and a high initial pH. Thus, besides the nutrient input added by the waste used in agricultural fields, the increase in soil pH should also be considered when the waste rate is calculated, since, in most plots, the pH increased to values beyond the range suitable for cultivation of most crops (Souza et al., 2007). The results of this study show that, according to the waste used, the soil pH can be increased or reduced. The addition of most of the organic wastes to acidic soils is potentially a reliable strategy for increasing soil pH. Thus, besides the addition of target nutrients (mainly N, P and K), the magnitude of the pH increase and the waste lime value should also be considered when the waste agronomic rate is defined. If the waste capacity in neutralizing soil acidity is not taken into account, the high soil pH – in most cases above pH 7 – observed in some plots may severely affect the plant growth due to short-and long-term consequences of over liming on precipitation and micronutrient availability to crops (Abreu et al., 2007). Soil pH values above 7 are direct linked to the precipitation of P with Ca, losses of soil N as ammonia, and exhaustion of soil organic matter levels due to accelerated decomposition by microorganisms.

Exchangeable Al levels were low in the three studied soils (Figure 1), but they differed significantly among the treatments. Exchangeable Al was neutralized in the TH when chicken, pig, horse and quail manures, and limed compost were applied. In the RH, the levels of Al^{3+} were significantly higher for horse manure, sewage sludges 1 and 2, pine bark and peat, in comparison to the other wastes tested. The application of sewage



Legend

1 – Chicken manure	4 – Sewage sludge 1	7 – Plant substrate	10 – Cattle manure	13 – Coffee husk	16 – Control
2 – Pig manure	5 – Sewage sludge 2	8 – Coconut fiber	11 – Peat	14 – Compost	
3 – Horse manure	6 – Sawdust	9 – Pine bark	12 – Quail manure	15 – Biochar	

Figure 1. Soil acidity properties of *Latossolo Vermelho-Amarelo Distrófico* (Typic Haplustox-TH), *Latossolo Vermelho Distrófico* (Rhodic Hapludox-RH) and *Neossolo Quartzarênico* (Quartzipsamment-TQ) as influenced by the studied organic wastes. Means followed by the same letter do not differ significantly by the Scott-Knott test ($p<0.05$).

sludges 1 and 2 and biochar increased Al^{3+} values significantly in the TQ samples, showing the capacity of these wastes to increase the toxic levels of Al in plants grown in sandy soil. Neutralization of Al^{3+} is explained due to Al complexation by organic acids or complexing ligands (Mendonça et al., 2006; Tejada et al., 2010). In addition, an increase in the soil pH also explains the decrease in Al^{3+} when the soil pH in water is higher than 5.6 due to the precipitation of Al chemical species by OH^- (Souza et al., 2007). Aluminum detoxification due to the formation of organic matter-Al complexes is another process which lowers the activity of phytotoxic monomeric Al (Mokolobate and Haynes, 2002).

Compared to the control, the levels of Ca^{2+} in the TH samples were significantly higher for all the incubated wastes, with the exception of the soils treated with peat (Figure 1). For the RH samples, only the treatments with chicken and quail manures, substrate and compost significantly increased the Ca^{2+} levels in the RH samples, whereas, for the TQ, only compost and manure from chicken and quail resulted in higher availability of Ca^{2+}. Considering all the soil samples investigated, the waste Ca inputs poorly (R^2 from 0.13 to 0.41) explained the increase in the soil Ca^{2+} levels. In fact, the increase in soil Ca availability was only linked to the use of chicken and quail manures and limed compost. Levels of Mg^{2+} showed considerable variability in the three soils (Figure 1), again, mainly reflecting the inputs of Mg by poultry manure and compost. In general, the rates and types of investigated wastes were not suitable to increase the soil Mg available content to the level (0.8 $cmol_c$ dm^{-3}) considered adequate for plant growth.

Base saturation (V) levels were significantly higher in the TH, for most wastes, except for sludge 1 and peat. In the RH plots, only samples treated with compost and chicken, quail and cattle manures showed significantly higher values of V, while, in the soil treated with sewage sludge 1 and peat, V levels were significantly lower than the control (Figure 1). For the TQ samples, fertilization with horse manure, sludges 1 and 2, sawdust, plant substrate, peat and biochar significantly decreased the base saturation values, while V was higher in soils treated with chicken and quail manures, and with compost, in comparison to the other wastes added in soils. The increase in V values in most of the three soils treated with wastes can be explained by the increase in soil pH and cations (Ca^{2+}, Mg^{2+} and K^+), and it is also related to changes in soil CEC, waste type, the rate added to soil, waste basic cation inputs, and the waste lime or acidification value.

The C levels were only slightly modified in the TH samples due to the addition of wastes (Figure 2), with a significant increase in C levels in the samples treated with the plant substrate and a decrease in soil samples treated with chicken, pig and quail manures, pine bark, compost and biochar. Small or minor variations in soil C levels can be explained by the low amount (2 g kg^{-1}) of C added by the wastes in relation to the native C contents found in the RH (C content equal to 44,000 mg kg^{-1}), TH (C equal to 12,000 mg kg^{-1}), and TQ samples (C content equal to 9,000 mg kg^{-1}). Besides the amount of C added to the soil by the waste, the effective contribution of organic fertilization to increase SOM levels also relies on the chemical nature of the C in the waste. The addition of more humified or recalcitrant C by the plant substrate could explain the increase in C contents in the TH samples, however, the labile nature of most wastes added in the soil with the lowest SOM level (TH) could explain the reduction in the C level in comparison to the control plot. The use of wastes may improve the availability of nutrients and soil conditions (Hargreaves and Warman, 2008), enhancing the conditions for soil organic matter decomposition. The application of biochar could result in the consumption of all or part of the C added via the waste and part of the native soil C, due to, among other factors, the priming effect (Cely et al., 2014). An increase in the soil organic matter decomposition rate after the use of waste, as the soil treated with manures emitted larger quantities of $C\text{-}CO_2$ into the atmosphere than the non-fertilized soil, was reported by Fernandes et al. (2011). As the incubation time increased, the fractions of C that remained in soil were less labile, which reduced the organic matter decomposition rate. During decomposition, a large part of C is lost to the air in the form of $C\text{-}CO_2$; thus, the added C via waste is partially incorporated into the microbial biomass and soil humus (Reis and Rodella, 2002).

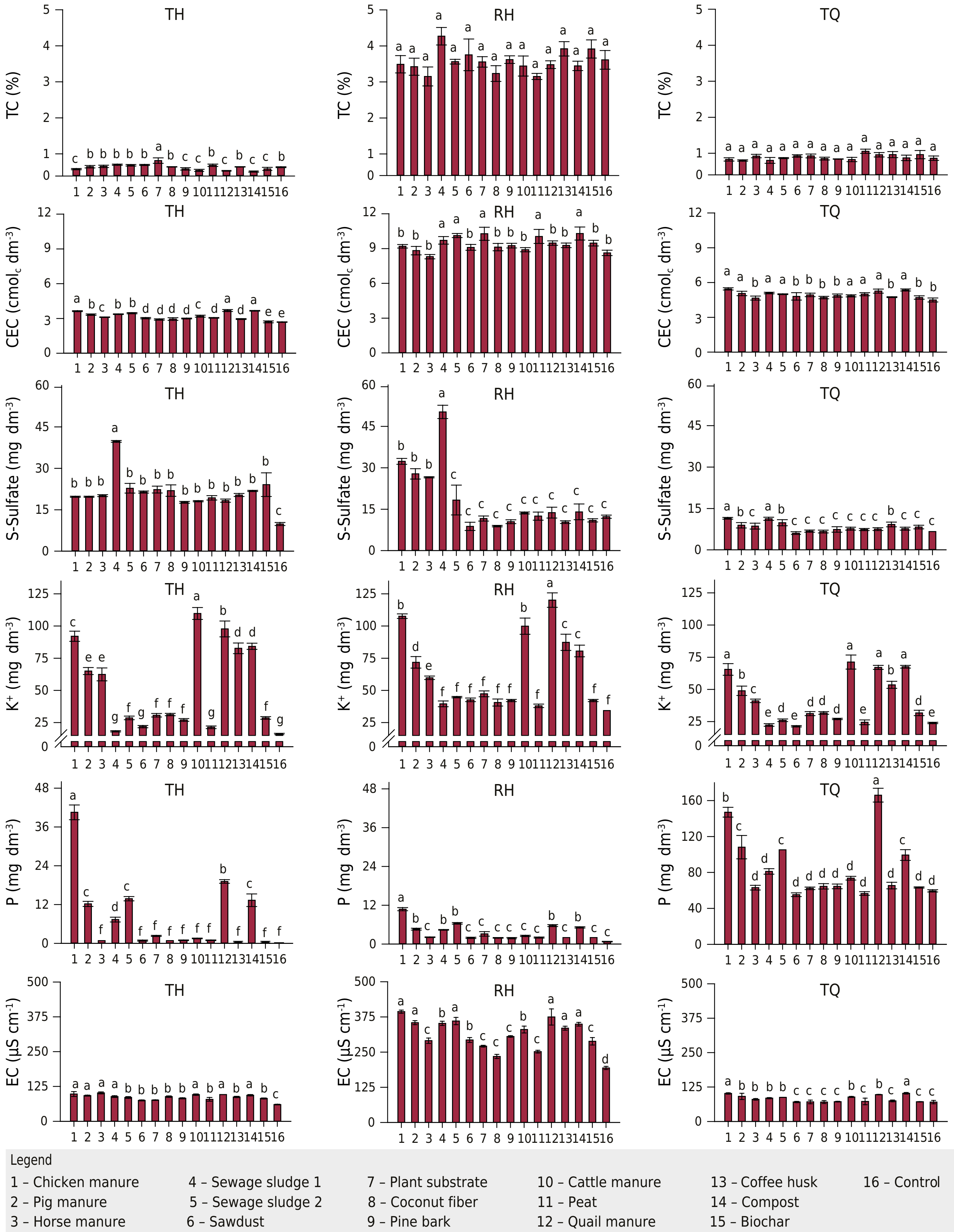


Figure 2. Fertility properties of soils [*Latossolo Vermelho-Amarelo Distrófico* (Typic Haplustox-TH), *Latossolo Vermelho Distrófico* (Rhodic Hapludox-RH) and *Neossolo Quartzarênico* (Quartzipsamment-TQ)] fertilized with different organic wastes. Means followed by the same letter do not differ significantly by the Scott-Knott test ($p<0.05$), considering each soil separately. CEC: cation exchange capacity at pH 7; TC: Total carbon; P and K: extracted by Mehlich-1 solution; EC: electrical conductivity.

Cation exchange capacity at pH 7 increased in all TH plots treated with wastes, with the exception of the samples treated with biochar. Quail and chicken manures and compost stood out with higher CEC at pH 7, in comparison to the control plots. In the RH samples, only sewage sludges 1 and 2, substrate, peat and compost – the most humified organic wastes used in this study – increased the soil CEC to values higher than those measured in the control plot. TQ samples treated with chicken, pig, cattle, and quail manures, sewage sludges 1 and 2, peat and compost showed significantly had higher values of CEC than the non-fertilized samples. Changes in the CEC of soils with variable charges, among other factors, are directly linked to variations in the soil C content and to the generation of negative charges in the SOM and in the humified compounds found in the wastes. The density of negative charges associated with soil colloids is also dependent on the soil pH (Oorts et al., 2003; Raij, 2010). Similarly, increased charge density at carboxylic and phenolic groups of SOM may be linked to an increase in soil CEC, again, influenced by the increase in soil pH, which was caused by most of the wastes investigated. In this study, the waste C contents poorly (R^2<0.45) explained the changes in soil CEC. The soil negative charge density measured at pH 7 was also not correlated to soil pH values and C contents, considering all the soil-waste mixtures investigated. Probably, the CEC changes observed for the waste-treated TH plots can be explained when soil C contents, pH values and the chemical nature and humification degree of the waste OM, and their cumulative effects on soil CEC, are considered together.

Levels of S-sulfate were significantly increased in all TH waste-treated plots, in comparison to non-fertilized soil. In the RH samples, only the treatments with chicken, pig and horse manures and sewage sludge 1 showed significantly higher available S than the control. In the TQ samples, treatments with chicken and pig manures, sludges 1 and 2, and coffee husk increased the availability of available S in soil. The contents of S-sulfate were above the critical level (10 mg dm^{-3}) in soil adequate for most crops, mainly in the plots fertilized with sewage sludge 1. The increase in the soil S-sulfate levels reflects a combination of factors related to waste S input, as was observed in this study, since a positive relationship between soil S-sulfate contents and waste S input was found for the three soils, with the coefficients of determination (R^2) ranging from 0.38 to 0.71. The increases in SOM and waste mineralization, mainly for those rich in S, are another source of S-sulfate in soils. Additionally, the increase in soil pH may decrease the adsorption of SO_4^{2-} in soil. It is likely that the increased availability of S-sulfate in medium and sandy textured soils is better explained by the increase in SOM decomposition and waste S input rather than the reduction in sulfate adsorption due to soil pH changes.

The application of chicken, cattle and quail manures, coffee husk and compost significantly increased the levels of K^+ in soil, whose contents ranged from 83 to 110 mg dm^{-3} in the TH samples (K^+ in the control equal to 16 mg dm^{-3}). For the RH samples, soil K^+ contents were also regulated by the waste tested, and the available K ranged from 80 to 120 mg dm^{-3} (K^+ in the control equal to 34 mg dm^{-3}). In the TQ samples, K^+ levels were increased, ranging from 54 to 71 mg dm^{-3}, in comparison to K^+ equal to 24 mg dm^{-3} in the control plot. The K available contents determined in the waste-treated TH and RH samples were considered high and they were enclosed in the same soil fertility class (high level) for both soils. The levels of K^+ measured in the sandy (TQ) samples were classified as medium, taking into account the K soil fertility classes adopted for Minas Gerais soils (Alvarez V et al.,1999). The increase in soil K levels positively correlated with the waste K inputs (Table 3), with a coefficient of determination around 0.6 for this relationship. Thus, the increase in soil K^+ levels relies on the type of waste added to the soil and the correct choice of the waste assures, for most soil-waste mixtures, suitable levels of available K to meet the nutritional requirements of most crops.

Phosphorus levels were significantly higher for the soil samples fertilized with chicken, pig and quail manures, sewage sludges 1 and 2 and compost, with the exception of TQ samples treated with sewage sludge 1. The differences in soil available P contents among the soil-waste mixtures investigated may be related to low molecular weight organic acids and other complexants produced during the waste decomposition, which have the potential to block the fixation of P on clay minerals and Fe and Al^{3+} oxide surfaces (Mkhabela and Warman, 2005; Novais et al., 2007). Changes in soil pH allegedly promote the precipitation of Fe and Al, reducing the formation P-Fe and P-A1 precipitates; the generation of negative charges in colloids repels the phosphate ion from soil P retention sites (McBride, 1994). In addition, some wastes can add organic P to the soil in labile forms, compared to less available P associated with the mineral phase of most Brazilian soils (Eberhardt et al., 2008). The high correlation of soil available P and waste P input (R^2 ranging from 0.77 to 0.90) is also another reliable explanation for the increased availability of P in the soils investigated in this study. The manures, sludges and compost tested in this study provided in all soils investigated adequate levels of available P for growing most crops.

Electrical conductivity values (Figure 2) was significantly increased in the waste-treated TH (from 75 to 102 $\mu S\ cm^{-1}$) and RH (from 251 a 394 $\mu S\ cm^{-1}$) samples, in comparison to the EC values determined in the control plots (EC values of 60 and 199 $\mu S\ cm^{-1}$, respectively, for the TH and RH control plots). In the TQ samples, the addition of chicken, pig, horse, cattle and quail manures, sewage sludges 1 and 2 and compost increased significantly the EC (from 70 to 102 $\mu S\ cm^{-1}$) to values higher than those EC level measured in the untreated soil (EC=51 $\mu S\ cm^{-1}$). The EC values found in this work are below the established critical range (750 to 3,490 $\mu S\ cm^{-1}$) for proper plant growth, according to Abad et al. (2001). The changes in the soil EC measured in this study were both soil and waste-dependent. The increase in the soil EC values can be explained by the inputs of nutrients and salts contained in the wastes. In the soil system, the amount of salts and ions found in the liquid phase are in equilibrium with their levels in the solid phase. Thus, in soil, it is very plausible that the factors governing solubilization, sorption and mineralization/immobilization processes exert a great influence on the amounts of ions governing soil EC. The addition of waste to soil markedly changed the magnitude of all soil processes as mentioned above. The pH change is a key factor regulating the solubility and availability of nutrients in soil. The waste and soil organic matter mineralization rates are other key factors which strongly regulate the amounts of ions in the liquid phase as well as the soil EC values.

Available Zn levels were significantly higher for the three soils treated with chicken, pig, and quail manures, compost, and especially with sludges 1 and 2 (Figure 3), in which the treated soil presented Zn^{2+} levels in the range of 8-12 mg dm^{-3}, while the maximum soil Zn values achieved by the other wastes did not reach 4 mg dm^{-3} of Zn^{2+}. This result can be explained due to the high levels of trace elements found in the sludges (Table 2) which, according to Lopes et al. (2004), may raise the levels of Zn to toxic levels in soil, thus increasing the possibility of nutrient transference to the entire food chain (Alloway, 1995).

Levels of Fe^{2+} in the soil were significantly higher for the treatments with cattle and quail manures, coffee husk and compost, when the TH samples were considered, whereas, for the RH samples, no difference was observed among the treatments. For the TQ samples, treatment of soil with pig, horse and cattle manures, sludge 1 and 2 and pine bark significantly increased the soil Fe levels, whereas the treatments with chicken manures and substrate led to significantly lower levels of Fe^{2+} as compared to the control (Figure 3). The decreased availability of Fe in the chicken and substrate-treated soils was probably due to the increase in pH to levels above those considered optimum (5.5-6.3) for plant growth. As the soil pH increases, the availability of Fe is markedly reduced; in the pH alkaline range reached in the chicken manure-treated soils, severe Fe deficiency in cultivated plants is anticipated. The available Fe^{2+} contents determined in all the waste-treated soils were far above the established critical value (30 mg dm^{-3}) for adequate plant growth in the Minas Gerais soils (Abreu et al., 2007).

Levels of Mn^{2+} were variable for each soil (Figure 3), and most waste applications resulted in high nutrient availability, with the exception of sawdust, coffee husk and biochar in the TH samples, and pine bark in the RH samples. The addition of chicken, cattle and quail manures,

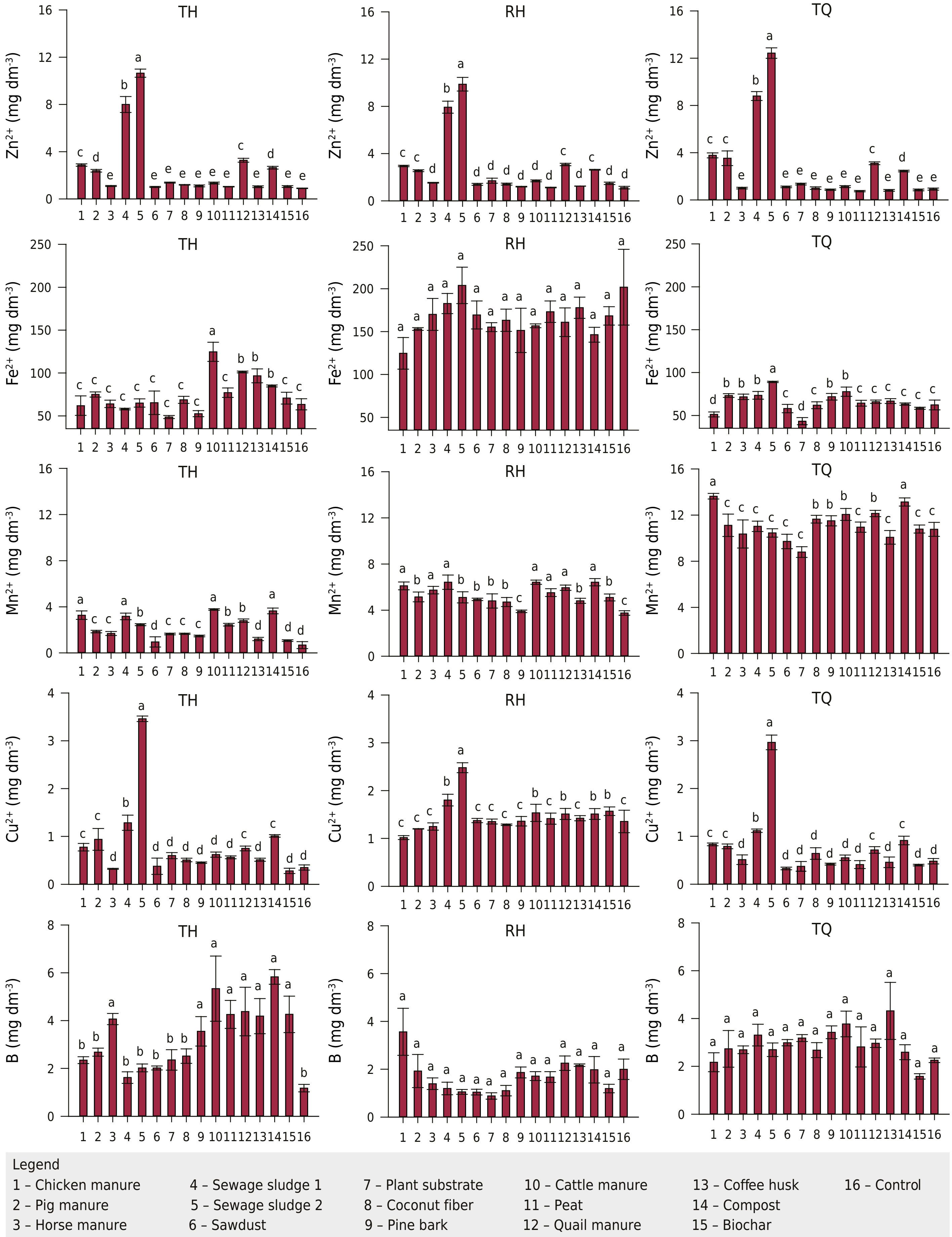


Figure 3. Contents of available micronutrients in soils [*Latossolo Vermelho-Amarelo Distrófico* (Typic Haplustox-TH), *Latossolo Vermelho Distrófico* (Rhodic Hapludox-RH) and *Neossolo Quartzarênico* (Quartzipsamment-TQ)] treated with organic wastes. Means followed by the same letter do not differ significantly by the Scott-Knott ($p<0.05$) test.

coconut fiber, pine bark and compost caused significantly higher levels of Mn^{2+} in the TQ samples, in comparison to the soil not treated with waste (control). The increase in soil Mn^{2+} contents could be explained, among other factors, by the dissolution and mineralization of Mn organic forms found in the waste (Hue et al., 2001), along with the waste Mn input. The formation of soluble organo-metallic complexes and the effect of the waste on soil pH along with the consequences of these changes on the balance of precipitated and soluble Mn forms in soil cannot be excluded. The input of Mn by peat was the highest amongst the wastes investigated, but such a high level of Mn added into the soil by peat did not increase the soil Mn availability. In soil, available Mn levels are regulated by the pH, the intensity of sorption processes and the redox potential (McBride, 1994). In acidic soils, the Mn availability tends to be maximum, compared to alkaline soil conditions (Hue et al., 2001). An increase in the amount of Mn sorbed onto clay and oxide surfaces reduces the amounts of readily available Mn to plants (Moreira et al., 2016).

Levels of Cu^{2+} varied according to the waste added to the soil, but increased availability Cu^{2+} was noted in the three soils when sludges 1 and 2 were used, with Cu^{2+} levels ranging from 1.1 to 3.5 mg dm^{-3} (Figure 3), which represents levels up to three times above the critical level established for Brazilian soils. Among other conditioning factors, the increase in Cu availability was mainly due to the input of Cu supplied via the waste. However, other factors (soil pH, CEC, and clay content and OM, and the effects of the waste on these soil attributes) that exert an influence on the soil Cu reactions such as adsorption/desorption, precipitation/dissolution, complexation and redox processes, as well as on the availability of copper in soil, cannot be excluded (McBride et al., 1997; Oliveira and Mattiazzo, 2001). As the soil pH and base saturation levels increase, the content of Cu^{2+} is reduced. The values of pH and V found in the sludge-treated soils are among the lowest values observed in this study, in comparison to the other wastes. Copper adsorption is increased when the content of clay and the soil CEC are higher.

An increase in the level of B was only verified in the TH samples, mainly when this soil was treated with horse, cattle and quail manures, pine bark, peat, coffee husk, compost and biochar (Figure 3). The content of B, and its input by the wastes, was low; however, the dynamics of this nutrient in soil is complex and controlled by many factors, such as texture, pH, OM and soil mineralogy (Azevedo et al., 2001). The availability of B in soil is directly associated with the soil organic matter (SOM) content. Any condition that regulates the SOM decomposition rate may interfere in the soil available B content. Although total B levels tend to be higher in clayey rather than in sandy soils, the content of available B, in general, is lower in finely textured soils because of increased B adsorption on clay minerals and Fe and Al oxide surfaces abundantly found in weathered soils (Alleoni and Camargo, 2000). A boron concentration in soil above 3 mg dm^{-3} is considered toxic to most crops (Alloway, 1995; Abreu et al., 2005); thus, for some of the wastes applied to the TH samples, it was necessary to monitor the levels of available B, since they were above this threshold level.

CONCLUSIONS

Animal manures, compost and alkalinized wastes have excellent potential to increase soil pH to levels above of those considered optimal for plant growth. Over-liming of sandy and medium textured soils indicates that the waste rate, in addition to the target nutrient to be added to the soil, must be based on the soil acidity buffering capacity and in the waste liming and agronomic value.

Soil electrical conductivity was slightly increased in the Quartzarenic Neosol (TQ) and Typic Haplustox (TH); however, it was sharply changed (from 195 to 394 µS cm^{-1}) by the addition of organic wastes in the Oxisol (RH) samples, mainly when the soil was incubated with chicken and pig manures, sewage sludge, coffee husk and compost. Regardless of the magnitude of the soil electrical conductivity change, the soil EC values found in this study were below the range considered safe for plant growth.

Fixing the amount of C (2 g kg^{-1}) added to soils required a large variation in the waste rates, but an increase in the waste rate is not a guarantee of higher nutrient input and, in most cases, did not assure improvements in soil fertility attributes.

The use of chicken, cattle and quail manures, coffee husk and compost significantly increased the levels of K^+ in the three soils, and the addition of chicken, pig and quail manures, sewage sludge 2 and compost significantly increased soil P levels, with the highest contents found for the soil with the lowest C content (TH).

Regardless of the applied rate, animal manure, sewage sludge and compost are wastes that had the greatest effect on the soil fertility attributes analyzed in the present study, but the magnitude of the changes promoted by each waste was soil-dependent.

Changes in the soil availability of P, K^+, Ca^{2+} and Zn^{2+} were highly related to the inputs of these nutrients provided by the wastes. Most of the wastes tested were not capable of providing the adequate levels of exchangeable Mg required by crops.

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