

Coffee processing residues as a soil potassium amendment

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Abstract

Introduction Total coffee production in the world in 2013 was 8.7 million Mg of coffee beans. Coffee must be processed after harvest to separate beans from the husk, and the post-harvest process can generate different types of residues. Knowing that 50 % of the harvested coffee is husk, it is important to consider that these by-products can contribute to environmental problems if not disposed of properly. There is a need to find alternatives to the piling of coffee husk as a means of disposal at coffee farms. The objectives in this experiment were to characterize five types of coffee processing residues and assess their value as potassium (K) fertilizer by examining K release.

Results Chemical characteristics of coffee residues varied with processing method, such as wet and dry processes. Application of residues to soil columns followed by 40 weeks of simulated leaching increased total K content

in the soil for all treatments based on application rate, except for enriched and three-year composted coffee husk ($3y_{comp}$). Coffee processing residues had higher concentrations of K leached compared with the control with no K application, but only $3y_{comp}$ was higher than other coffee processing residues. Total K released from coffee residues increased linearly with application rate, but the decomposition of the coffee residues was low, which suggest that K release from coffee processing residues is not related to decomposition.

Conclusion Post-harvest coffee processes impacted concentrations of K, nitrogen, carbon, cellulose, hemicellulose, lignin, phenol, pH, and electrical conductivity among the coffee processing residues. The K release was high (over 90 %), but it did not depend on the type of coffee processing residue, and thus, the residues can be a substitute for a mineral source of K applied to soils. The use of coffee processing residues as source of K did not prevent K losses by leaching. Some coffee residues resulted in greater K leaching than mineral KCl applied at the same rate.

Keywords Coffee husk · Coffee hulls · Potassium · Composting · Gypsum · Leaching

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Introduction

Total coffee bean production in 2013 was 8.7 million Mg (Ico 2014). Beans are separated from the husk through a variety of possible processing methods after harvest. According to Garcia et al. (2004), 50 % of the coffee fruit are beans and another 50 % are husk (by weight). The large amount of coffee husk generated in coffee processing has caused environmental concerns, and there is a need to find alternative uses for these residues (Felfi et al. 2010).

Coffee husk characteristics vary with the method of coffee processing. When the coffee is processed by the “wet” method, the coffee fruits are separated into three different groups: cherry coffee, green coffee, and buoy coffee. Cherry coffee is the newly mature coffee fruit, while buoy coffee is coffee fruit that has dried on the coffee tree before harvest and floats during the wet processing method. Green coffee is non-ripened coffee fruit. Further processing of cherry coffee produces residues known as coffee hull (parchment) and coffee pulp. For green and buoy coffee, the residue produced is known as “green coffee husk” and “buoy coffee husk,” respectively. When a combination of cherry, buoy, and green coffee fruits are processed by the “dry” method, the residue is known as “common” coffee husk (Matiello 1991; Bartholo et al. 1989).

The considerable range in the coffee processing residues characteristics was shown by Matiello et al. (2005), Bresnani (1979), Brum (2007), Castro (1960), and Paes et al. (1996). Characteristics have been reported to range from 23 to 93 % in dry mass, 95–200 g L⁻¹ in density, 0.4–3.7 % in K content, and 24:1–63:1 in C:N ratio.

Santinato et al. (2008) compared coffee production in soil amended with coffee husk and chemical fertilizer N, P, K, and S. They observed that yield was greater for coffee husk amendments applied between 2.5 and 20 Mg ha⁻¹ compared to chemical fertilizer applications that added equivalent nutrients. The yield increase provided by the coffee husk varied from 15 to 33 %. Increased yields resulting from coffee husk application compared to only N–P–K chemical fertilizer amendment were also observed by Bragança (1985). Garcia et al. (1983) showed that application of coffee husk based on plant K requirements and supplementing with P and N increased coffee production 20 % compared with chemical fertilization only.

Coffee processing residues are rich in several nutrients, the dominant of which is K, which will vary in concentration with the type of coffee husk (Garcia et al. 2004). Although coffee processing residues are known to be a good source of organic fertilizer for coffee production (Garcia et al. 2004; Rena et al. 1986; Matiello et al. 2005), less is known about the release and mineralization of the nutrients from coffee processing residues.

Potassium is the second most required mineral nutrient for plants (Marschner 1995). Since K does not have any structural function in plants and because it is not incorporated into any carbon chain, K can readily return to the soil

in a plant available form after harvest or plant senescence. This characteristic makes husk a potential K source for plants in a no-till system (Rosolem et al. 2003). Reuse of coffee processing residues as soil amendments can reduce fertilization costs and prevent environmental degradation by recycling the nutrients that would be lost by leaching or runoff from the stored residues. Knowing the total K content of coffee husk and the amount that can be released as assessed by a “release” curve, coffee husk could be utilized as an effective and predictable soil K amendment.

The objectives of this experiment were to characterize five types of coffee processing residues, assess their value as a K fertilizer, and investigate nutrient release after application to soil.

Materials and methods

An incubating-leaching column study was designed to quantify the potential for different coffee residues to serve as a K fertilizer. Laboratory analyses were conducted at Oklahoma State University (OSU), Stillwater, OK, USA, and also at Sao Paulo State University (UNESP), Botucatu, SP, Brazil. Experimental units were established in a greenhouse at UNESP consisting of 88 soil columns. The soil used was a sandy loam Rhodic Hapludox. The columns were made of polyvinyl chloride (PVC) pipes with 0.10 m diameter and 0.40 m in length. Pipe was cut every five cm, stacked on top of another, with each piece attached with plastic tape for a total of eight pieces per column. Folding the plastic tape, a one-cm-wide shelf was inserted between each section of pipe to prevent preferential flow along the walls of the entire column. The bottom of the columns consisted of fine sand, glass wool, and a screen with 0.16 cm² openings.

The soil utilized in the column experiment was amended with calcium carbonate (lime) 60 days before column construction. The moisture was adjusted to approximately 80 % of the soil retention capacity during the incubation. After 60 days of incubation, the soil was analyzed (Table 1). The analyses were conducted according to Raij and Quaggio (1983). Calcium, Mg, K, and P were extracted with resin and analyzed by Atomic Absorption Spectrometer (AA 6300, Shimadzu, Japan). Soil pH was measured in 0.01 M CaCl₂; H + Al were analyzed by adding SMP buffer solution to the same suspension used to determine pH, shaking for 15 min, and allowed to idle undisturbed for

Table 1 Soil characterization before application of coffee processing residues

pH (CaCl ₂)	SOM (g kg ⁻¹)	P (mg dm ⁻³)	H + Al (mmol _c dm ⁻³)	K (mmol _c dm ⁻³)	Ca (mmol _c dm ⁻³)	Mg (mmol _c dm ⁻³)	CEC (mmol _c dm ⁻³)
5.3	21	7.2	40	1.2	20	18	80



1 h before readings with a pH meter. There is correlation ($r = 0.98$) between the pH of soil suspension with SMP buffer solution and the H + Al (Raij and Quaggio 1983). Soil organic matter (SOM) was analyzed by colorimetric oxi-reduction method. Soil cation exchange capacity (CEC) is the sum of bases and H + Al.

Before receiving amendments, soil columns received excess water and were allowed to drain for 24 h to equalize the moisture of all treatments. Treatments consisted of five surface applied coffee processing residues at four rates of K (75, 150, 300, and 600 kg ha⁻¹ of K₂O equivalent) including a control with no amendment and an inorganic fertilizer (KCl) applied at 300 kg ha⁻¹ K₂O equivalent. Columns were maintained for 40 weeks. Coffee processing residues were applied on surface of the soil columns, and 30 mm of simulated rainfall (using deionized water) was applied weekly. Leachate was collected 24 h after each simulated rainfall event, and pH, EC, and K were analyzed directly in the collected solution. Potassium was determined using a Flame Emission (Micronal, Model B462); pH and EC were measured using a benchtop pH and EC meter. After 40 weeks, the coffee processing residues remaining on the surface were collected, dried, ground, and analyzed. The soil profile was divided into 4 slices (0–5 cm, 5–10 cm, 10–15 cm, and 15–40 cm). The soil K was extracted with resin (Raij and Quaggio 1983). The K released by the residues was calculated by subtracting total K mass (i.e., concentration * mass residue) measured in coffee processing residues after 40 weeks from the initial mass of K applied.

Five types of coffee processing residues were evaluated: coffee pulp from cherry coffee (Pulp), buoy coffee husk (Buoy), common coffee husk (combination of cherry, buoy, and green fruits processed dry; Husk_{com}), coffee husk composted for 1 year (1y_{comp}), and coffee husk enriched and composted for 3 years (3y_{comp}). The 1y_{comp} coffee husk was obtained from a coffee farm in Sao Paulo that had mixed all types of coffee husk from dry and wet processing and composted in a pile for 1 year. The same farm provided the 3y_{comp} coffee husks, which additionally received gypsum, lime, and poultry litter during the three-year composting process (percentages of each material used are not known).

Moisture content (weight basis) of coffee residues was determined by drying in an oven at 60 °C for 72 h. Samples were then ground and analyzed for total K by total digestion (Malavolta et al. 1997); 250 mg of sample was weighed and combined with 6 mL of a HNO₃ and HClO₄ 2:1 (v/v) solution. Samples were then digested in a block with an increase in temperature until 160 °C and maintained for 40 min, followed by another temperature increase to 210 °C for 20 min. Extracts were allowed to cool down and brought up to 50 mL with DI water. The

final solution was analyzed by flame emission (Micronal, Model B462) for K. The K content was used to calculate the rate of coffee processing residues to be applied per column.

Coffee processing residues were extracted for water soluble K (adapted from Stoner et al. 2012); 1:10 soil:DI water ratio equilibrated for 1 h (low-speed reciprocating shaker) followed by filtration with a 0.45 μm filter and analysis for K by ICP-AES. Total nitrogen and total carbon were analyzed with a LECO analyzer (LECO Corporation, St. Joseph, Michigan). Total phenols were measured by the Folin–Ciocalteu (FC) method cited by Singleton and Rossi (1965), which is based on the chemical reduction of tungsten and molybdenum oxides. The phenols were extracted from 0.4 g of coffee processing residues with 10 mL of DI water in 50-mL centrifuge tubes and shaken for 2 h (low-speed reciprocating shaker). Samples were then centrifuged for 5 min at 2000 RPM. 0.2 mL of the coffee processing residue extracted solution was combined with 15.8 mL of DI water, 1 mL of Folin–Ciocalteu (FC) reagent, and 3 mL of sodium carbonate in a 40-mL test tube. A phenol standard curve was made with tannic acid (concentrations between 1 and 15 mg L⁻¹); both standards and samples were analyzed in a spectrophotometer (Spectronic 21D, Milton Roy) set to 765 nm, and therefore, total phenolics are reported as tannic acid equivalents. Residues pH and EC were analyzed from a 1:40 solid/solution ratio on a benchtop pH and EC meter. Celluloses, hemicelluloses, and lignin were analyzed through acid and neutral detergent digestion, followed by titration, according to Van Soest and Wine (1967).

Results of the characterization of coffee processing residues were compared using the unpaired *t* test ($p < 0.05$). Leachate K, pH, and EC were examined with time by using regression. Soil K content and K released from coffee processing residues were analyzed by regression according to the K rate applied (K₂O) and compared among coffee processing residues using an unpaired *t* test ($p < 0.05$).

Results and discussion

Coffee processing residues characteristics

The five coffee residues varied in total K content (Table 2), which is likely a result of different post-harvest processing. The lowest total K concentrations observed in the composted treatments likely were due to K leaching during the composting process in the field (El-Fadel et al. 2002). Water soluble K concentrations of coffee pulp (Pulp), buoy coffee husk (Buoy), common coffee husk (Husk_{com}), and 1 year composted coffee husk (1y_{comp}) ranged between



Table 2 Characterization of coffee processing residues used in this study

	Pulp	Husk _{com}	3y _{comp}	Buoy	1y _{comp}
Total K (g kg ⁻¹)	38.9 a	23.0 c	6.1 e	34.7 b	17.8 d
Soluble K (g kg ⁻¹)	17.7 a	7.4 c	5.6 d	10.9 b	7.4 c
Total N (g kg ⁻¹)	26.7 a	14.8 bc	12.0 c	15.6 b	17.5 b
Total C (g kg ⁻¹)	427.0 a	447.0 a	150.0 b	447.0 a	400.0 a
C:N Ratio	16.0 c	30.0 a	13.0 c	29.0 a	23.0 b
Lignin (g kg ⁻¹)	20.9 b	21.0 b	31.3 a	20.7 b	30.5 a
Cellulose (g kg ⁻¹)	25.9 d	33.5 c	10.9 e	41.5 a	35.8 b
Hemicellulose (g kg ⁻¹)	3.8 d	10.8 b	BD§§	15.7 a	7.6 c
pH	5.7 c	5.9 c	6.7 b	7.2 b	8.2 a
EC (μS cm ⁻¹)	1612 a	1156 b	1586 a	858 c	621 d
Total Phenols (g kg ⁻¹)	23.5 a	14.5 b	4.4 c	14.9 b	15.2 b
DM (%)	20.0 c	96.0 a	85.0 b	92 a	93 a

DM = dry mass; Pulp = coffee pulp; Husk_{com} = common coffee husk; 3y_{comp} = enriched and composted for 3 years coffee husk; Buoy = buoy coffee husk; 1y_{comp} = 1 year composted coffee husk; different lower case letters represent significant differences between materials by *t* test ($p < 0.05$); BD = below detection

Table 3 Corresponding application of nutrients with application of 300 kg ha⁻¹ K₂O from coffee residues

	Pulp	Husk _{com}	3y _{comp}	Buoy	1y _{comp}
DM applied residues (kg ha ⁻¹)	6402	10826	40816	7177	13992
FM applied residue (kg ha ⁻¹)	32010	11227	48019	7801	15045
K ₂ O (kg ha ⁻¹)	300	300	300	300	300
Total N (kg ha ⁻¹)	170	160	490	112	245
Total C (kg ha ⁻¹)	2734	4839	6122	3208	5597
Total phenols (kg ha ⁻¹)	150	157	180	107	213
Lignin (kg ha ⁻¹)	134	227	1278	149	427

DM = dry mass; FM = fresh mass; Pulp = coffee pulp; Husk_{com} = common coffee husk; 3y_{comp} = enriched and composted for 3 years coffee husk; Buoy = buoy coffee husk; 1y_{comp} = 1 year composted coffee husk

32.2 and 45.5 % of the total K content. However, the percentage of total K that was water soluble was much greater for the enriched and three-year composted coffee husk (3y_{comp}) at 91.8 %, which suggests greater plant availability. The lower C:N ratio and phenols content in this material compared to the other treatments may have resulted greater K solubility.

Lignin, a relatively recalcitrant polysaccharide, was high in the 3y_{comp} coffee husk. This suggests that lignin remained somewhat intact during the 3 years of composting. On the other hand, celluloses and hemicelluloses appeared to be degraded. Although this treatment contained the lowest C content among all materials, much of the remaining C was in the form of lignin due to its relatively high resistance to degradation (Kiehl 1998).

The highest EC was observed in Pulp and 3y_{comp}, which cannot be attributed to K content only as K content was lowest in the 3y_{comp} (Table 2). The coffee processing residues displayed an appreciable range in pH. Part of this variation is due to the degradation process and also additional amendments.

The 1y_{comp} had the highest pH measured compared to the fresh residues, which was expected since during the

degradation process the microbial activity increases the pH of the organic material (Bidone and Povinelli 1999; Smars et al. 2002). The high pH observed in Buoy may also be due to microbial activity. This is because coffee plants have different maturity times, and commercially, all the fruits are harvested at the same time. Some fruits such as the early matured (Buoy) remain on the vine for a longer time period and are therefore more subject to microbial activity (Matiello et al. 2005).

The lowest phenol content was measured in the 3y_{comp} material (Table 2). This may be due to the leaching and degradation that often occurs during the composting process (El-Fadel et al. 2002). Phenols are somewhat volatile compounds (Chatonnet et al. 1993); some may be lost when the temperature increases during the composting process. The effluent generated by the compost pile can also possess phenols. The Pulp had the highest phenol content because this material is the husk from ripe coffee fruit (coffee cherry), and when the fruits are ripe, the seed and the husk have the highest phenol content. Before this point, when the fruits are still green they have not produced enough phenol to increase the husk content, and later, after ripening, the phenols decrease because they can translocate

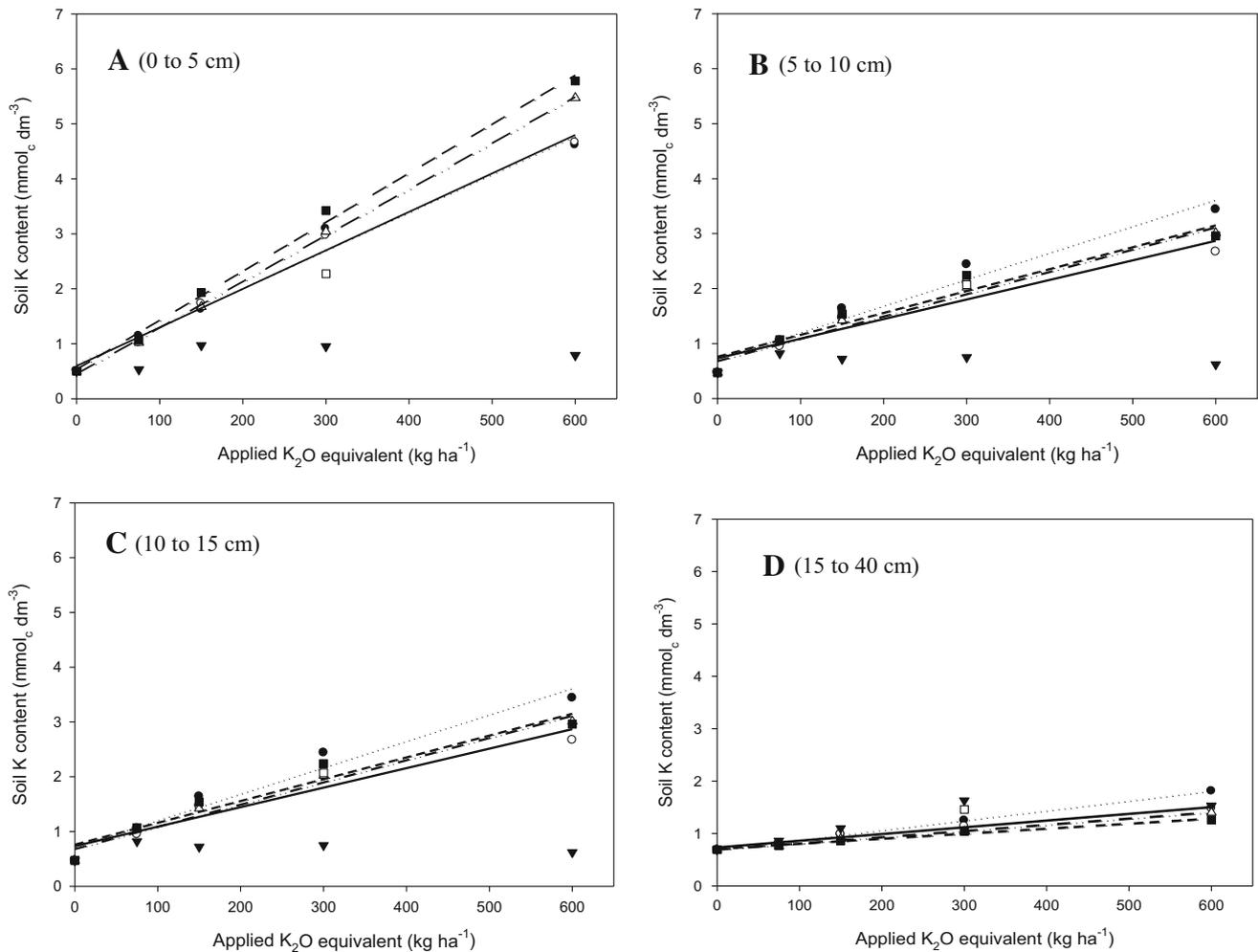


Fig. 1 Soil potassium (K) content at 40 weeks after amendment of coffee residues and simulated leaching. 0–5 (a), 5–10 (b), 10–15 (c), and 15–40 (d) cm, filled circle coffee pulp (Pulp); circle common coffee husk (Husk_{Com}); filled inverted triangle enriched and

composted for 3 years coffee husk (3y_{comp}); triangle buoy coffee husk (Buoy); filled square 1 year composted coffee husk (1y_{comp}); square mineral fertilizer (300 kg K₂O ha⁻¹). Regression equations are shown in Table 4

Table 4 Regression equations for correlations shown in Fig. 1

	Analyzed soil depth			
	a (0–5 cm)	b (5–10 cm)	c (10–15 cm)	d (15–40 cm)
Pulp	$y = 0.76 + 0.0057x$ $R^2 = 0.72^{**}$	$y = 0.73 + 0.0048x$ $R^2 = 0.95^{**}$	$y = 0.70 + 0.0036x$ $R^2 = 0.94^{**}$	$y = 0.69x + 0.0019x$ $R^2 = 0.85^{**}$
Husk _{com}	$y = 0.59 + 0.0070x$ $R^2 = 0.97^{**}$	$y = 0.74 + 0.0035x$ $R^2 = 0.90^{**}$	$y = 0.74 + 0.0026x$ $R^2 = 0.87^{**}$	$y = 0.73 + 0.0013x$ $R^2 = 0.85^{**}$
3y _{comp}	NS	NS	NS	NS
Buoy	$y = 0.45 + 0.0084x$ $R^2 = 0.98^{**}$	$y = 0.68 + 0.0040x$ $R^2 = 0.91^{**}$	$y = 0.69 + 0.0026x$ $R^2 = 0.87^{**}$	$y = 0.65 + 0.0012x$ $R^2 = 0.86^{**}$
1y _{comp}	$y = 0.54 + 0.0089x$ $R^2 = 0.98^{**}$	$y = 0.76 + 0.0040x$ $R^2 = 0.92^{**}$	$y = 0.75 + 0.0028x$ $R^2 = 0.86^{**}$	$y = 0.71 + 0.0010x$ $R^2 = 0.88^{**}$

Regression equations describe relationship between potassium (K) application rate (x) and soil K content (y), shown in Fig. 1, after 40 weeks of simulated leaching. Pulp = coffee pulp; Husk_{Com} = common coffee husk; 3y_{comp} = enriched and composted for 3 years coffee husk; Buoy = buoy coffee husk; 1y_{comp} = 1 year composted coffee husk; NS = no significant regression; ** Significant at (p < 0.01)

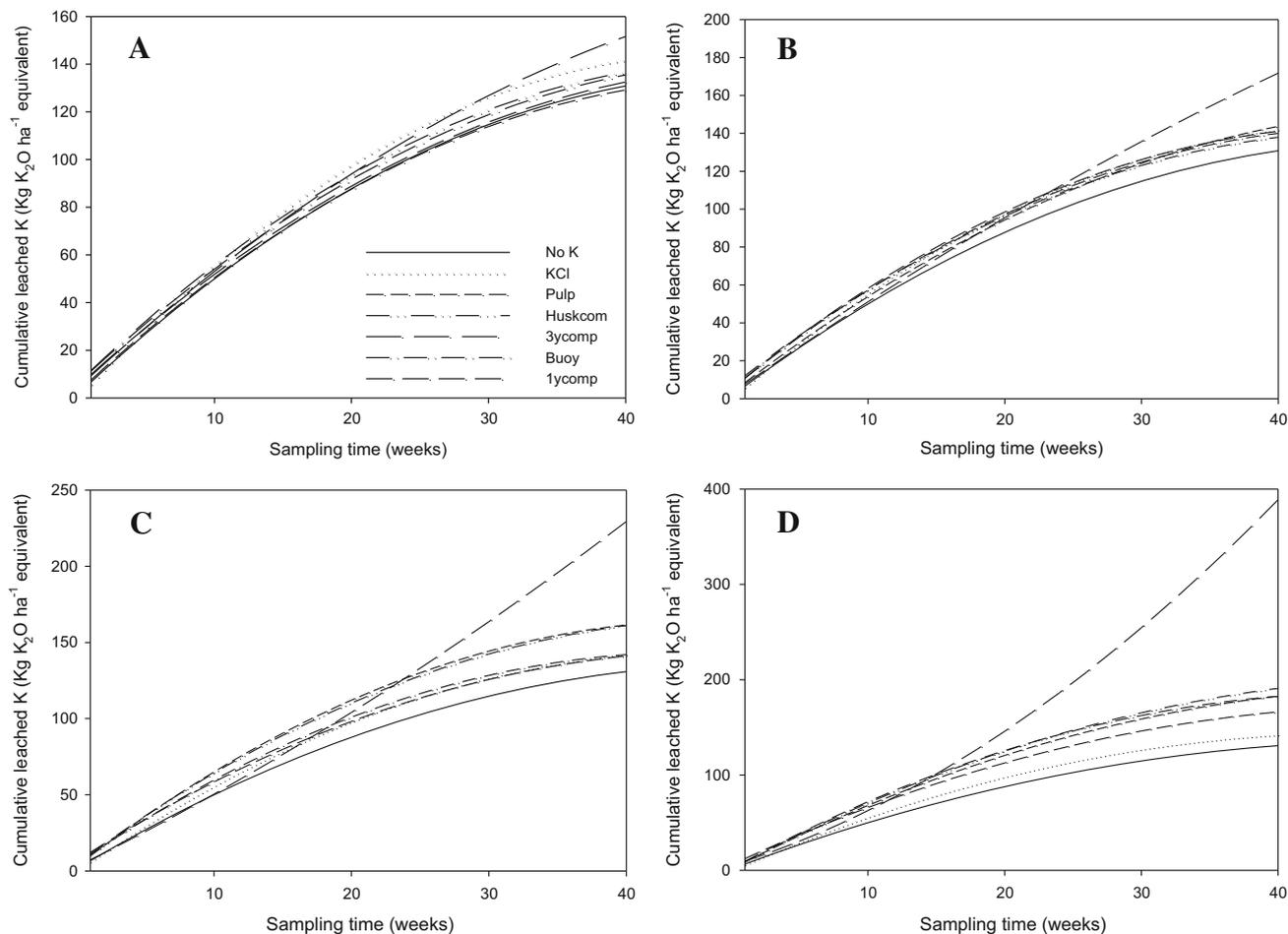


Fig. 2 Cumulative potassium (K) leached from the amended columns over 40 weeks. **a, b, c, d**, are, respectively, equivalent to 75, 150, 300, and 600 kg ha⁻¹ of applied K₂O. “No K” = control with no K added; “KCl” = mineral K control (300 kg ha⁻¹ of K₂O);

Pulp-coffee pulp; Husk_{Com}-common coffee husk; Buoy-buoy coffee husk; 1y_{comp}-1 year composted coffee husk; 3y_{comp}-enriched and composted for 3 years coffee husk. Regression equations shown in Table 5

from husk to the seeds and also be degraded by microorganisms (Rossetti 2007).

The dry matter content of Pulp was the lowest among all residues (Table 2). The other residues consisted of coffee husks that were harvested dry, or dried before coffee processing; mature coffee is peeled before the drying process. The low (20 %) dry mass could increase the transportation and application costs in the field when Pulp is used compared to other coffee processing residues as a K source (Table 3).

Based on a desired application rate of 300 kg K₂O ha⁻¹, the composted treatments, either 1y_{comp} or 3y_{comp}, would provide the highest input of carbon to the soil. However, the 3y_{comp} would add 3.0–9.5 times more lignin than others residues (Table 3), which is relatively resistant to degradation. The amount of N applied with the 3y_{comp} would be the highest of all residues for this scenario, while buoy coffee husk applications would result in the lowest N.

Because the 3y_{comp} has C:N ratio of 13, the N will likely be released rapidly (Kiehl 1985). Due to the low K content, the 3y_{comp} would require 1.5, 3.2, 4.3, and 6.2 times greater application rates than Pulp, 1y_{comp}, Husk_{Com}, and Buoy, respectively, to meet the desired K₂O rate of 300 kg ha⁻¹. This suggests that the 3y_{comp} husk has the lowest feasibility as a K source.

Changes in soil potassium with coffee processing residue applications

After application of residues to the soil columns followed by 40 weeks of simulated leaching, the resulting soil K content increased with increasing residue application rate ($p < 0.01$); one exception was the 3y_{comp} (Fig. 1; Table 4). The fact that soil K content did not increase with application rates for that treatment can be explained by the increased K leaching (Fig. 2). The high solubility of the K



Table 5 Regression equations for correlations shown in Fig. 2

No K	$y = 1.3206 + 5.4059x - 0.0542x^2$	$R^2 = 0.94^{**}$
KCl	$y = -0.4772 + 6.2702x - 0.0679x^2$	$R^2 = 0.97^{**}$
<i>Rate 1</i>		
Pulp	$y = 2.2155 + 5.3655x - 0.0548x^2$	$R^2 = 0.94^{**}$
Husk _{com}	$y = 6.1004 + 5.5039x - 0.0560x^2$	$R^2 = 0.96^{**}$
3y _{comp}	$y = 4.0472 + 5.3010x - 0.0403x^2$	$R^2 = 0.93^{**}$
Buoy	$y = 5.9070 + 5.3354x - 0.0524x^2$	$R^2 = 0.87^{**}$
1y _{comp}	$y = 4.6969 + 5.2154x - 0.0505x^2$	$R^2 = 0.98^{**}$
<i>Rate 2</i>		
Pulp	$y = 2.9076 + 5.6189x - 0.0525x^2$	$R^2 = 0.90^{**}$
Husk _{com}	$y = 6.5280 + 5.6850x - 0.0600x^2$	$R^2 = 0.99^{**}$
3y _{comp}	$y = 2.7244 + 5.0465x - 0.0205x^2$	$R^2 = 0.95^{**}$
Buoy	$y = 5.0099 + 5.8400x - 0.0616x^2$	$R^2 = 0.89^{**}$
1y _{comp}	$y = 5.1643 + 5.9346x - 0.0634x^2$	$R^2 = 0.92^{**}$
<i>Rate 3</i>		
Pulp	$y = 2.9607 + 6.9475x - 0.0746x^2$	$R^2 = 0.95^{**}$
Husk _{com}	$y = 4.6522 + 6.6426x - 0.0683x^2$	$R^2 = 0.97^{**}$
3y _{comp}	$y = 2.8049 + 4.4571x + 0.0302x^2$	$R^2 = 0.95^{**}$
Buoy	$y = 4.5654 + 6.1995x - 0.0691x^2$	$R^2 = 0.98^{**}$
1y _{comp}	$y = 6.4527 + 5.8011x - 0.0609x^2$	$R^2 = 0.87^{**}$
<i>Rate 4</i>		
Pulp	$y = 1.3661 + 7.3782x - 0.0711x^2$	$R^2 = 0.97^{**}$
Husk _{com}	$y = 1.6880 + 7.6100x - 0.0720x^2$	$R^2 = 0.93^{**}$
3y _{comp}	$y = 4.9605 + 4.4950x + 0.1275x^2$	$R^2 = 0.91^{**}$
Buoy	$y = 1.5471 + 7.8808x - 0.0839x^2$	$R^2 = 0.98^{**}$
1y _{comp}	$y = 5.6697 + 6.6848x - 0.0668x^2$	$R^2 = 0.96^{**}$

Regression equations describe relationship between sampling time (x) and cumulative potassium (K) leached (y), shown in Fig. 2, during 40 weeks of simulated leaching. No K = non-amended soil; KCl = mineral potassium application as KCl (300 kg K₂O ha⁻¹ equivalent); Pulp = coffee pulp; Husk_{com} = common coffee husk; 3y_{comp} = enriched and composted for 3 years coffee husk; Buoy = buoy coffee husk; 1y_{comp} = 1 year composted coffee husk; rate 1, rate 2, rate 3, and rate 4 are equivalent to 75, 150, 300, and 600 kg K₂O ha⁻¹ applied; ** Significant at ($p < 0.01$)

in the 3y_{comp} is evident by the higher proportion of total K in the form of water soluble K (Table 2). However, the excessive K leaching (thus low resulting soil K) from this material cannot be attributed to high K solubility alone. For example, the mineral K treatment (KCl) is 100 % soluble, yet resulted in less leached K (and therefore greater soil K) than the 3y_{comp} residue (Figs. 1, 2) after 40 weeks. It appears that the gypsum amended to the 3y_{comp} during the composing process may have had an impact on K mobility after this residue was applied to the columns due to the addition of sulfate (Ernani 1986; Ernani and Barber 1993; Dias et al. 1994).

Santinato et al. (2008) observed that coffee trees fertilized with coffee husk plus mineral fertilizer had equal or higher yields than exclusive mineral fertilization. Due to the fact that the 3y_{comp} was unable to increase soil K as

much as the other residues and resulted in greater K leaching, this material has less potential for meeting crop K demands when used as a fertilizer. On the other hand, Pulp, Husk_{com}, Buoy, and 1y_{comp} increased the soil K content in a manner similar to the mineral K source (KCl) (Fig. 1; Table 4).

Column leachate

Cumulative leaching of K as a function of time (Fig. 2; Table 5) for all treatments was fitted to a polynomial curve ($p < 0.01$), including the control which received no K. Werle et al. (2008) observed that the source of K leached through soil columns can be from the native soil K, not only from recently applied K. At an application rate of 300 kg K₂O ha⁻¹, the least amount of total K leached was observed with the application of mineral K, 1y_{comp}, and Buoy (Fig. 2c). Pulp and Husk_{com} had intermediate values of K leaching, while the 3y_{comp} had the highest K leaching ($p < 0.05$).

Higher K leaching can result in less K uptake efficiency of applied K since it can move deeper into the soil profile beyond the reach of plant roots. According to Werle et al. (2008), K leaching increases as the rate of K applied in the soil increases. Total leached K increased linearly with K application rate for Pulp, Husk_{com}, and 3y_{comp}. However, Buoy and 1y_{comp} did not present the same behavior.

The application of 75 kg ha⁻¹ of K₂O in the form of Pulp, Husk_{com}, Buoy, and 1y_{comp} showed no significant differences between the controls which received no K. The 3y_{comp} leached a high amount of K between week 27 and 40 at an application rate of 75 kg K₂O ha⁻¹ (Fig. 2a). However, the application rate of 75 kg K₂O ha⁻¹ was not enough to increase K leaching beyond the non-amended control when the potassium sources were Pulp, Husk_{com}, Buoy, and 1y_{comp}.

At an applied K₂O rate of 150 kg ha⁻¹ (Fig. 2b), K leaching became significantly greater than the no K control for 3y_{comp} at week 24. For 1y_{comp} and Pulp, K leaching became greater than the no K control after week 36. Except for the 3y_{comp}, this rate was not enough to provide significant differences in K leaching between the coffee processing residue treatments.

Differences in K leaching among treatments became apparent with application of 300 kg K₂O ha⁻¹. For example, when 300 kg ha⁻¹ of K₂O was applied in the form of Pulp and Husk_{com}, the cumulative K leached was significantly different from the no K control by week 8 (Fig. 2c). The 3y_{comp}, Buoy, and 1y_{comp} began to show significant differences in cumulative K leached after week 20, 11, and 38, respectively. At an application rate of 600 kg ha⁻¹ of K₂O, the K leaching from Husk_{com}, Buoy, Pulp, 3y_{comp}, and 1y_{comp} were significantly higher than the

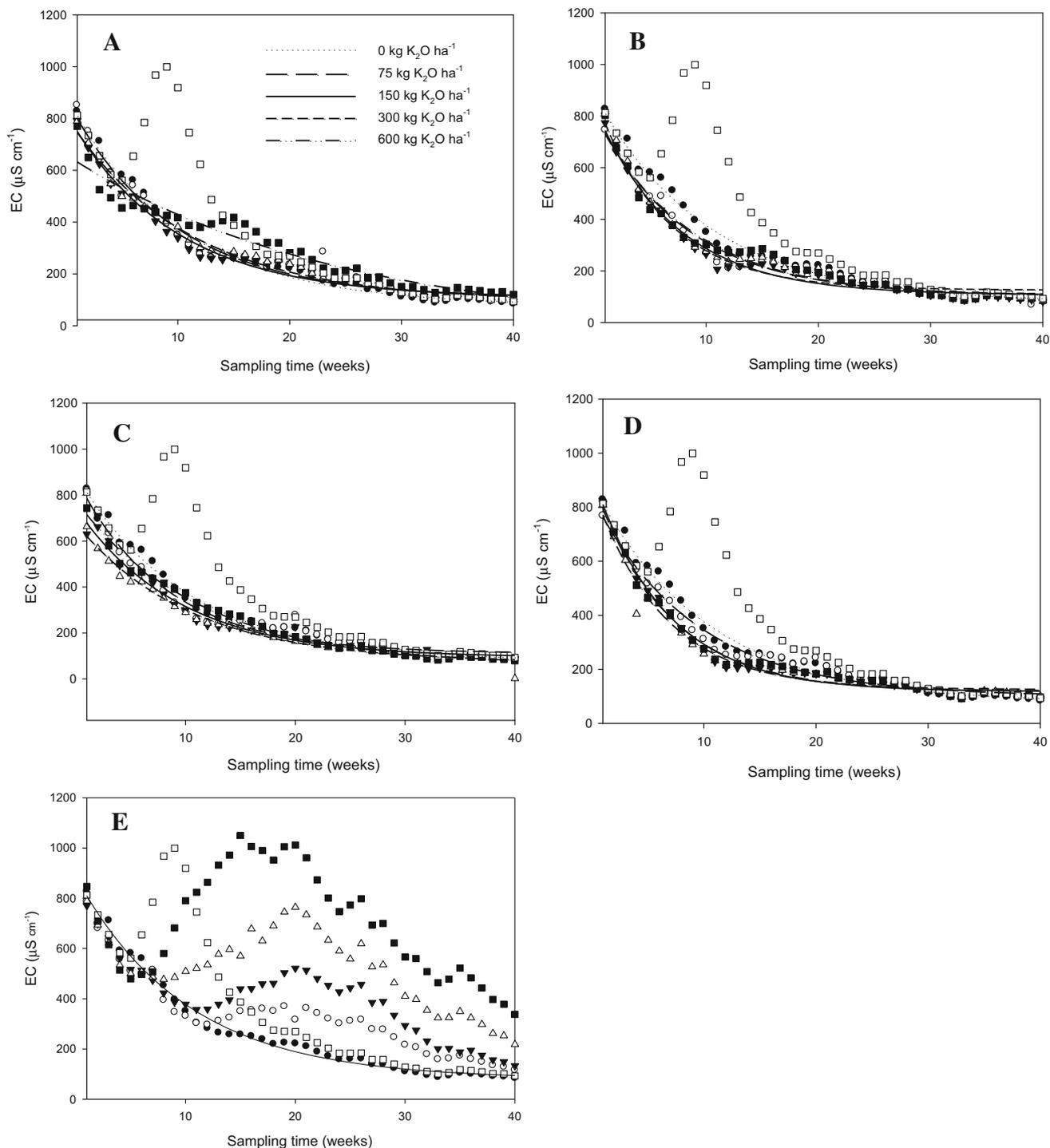


Fig. 3 Electrical conductivity of leachate from amended columns over 40 weeks. A-coffee pulp (Pulp); B-common coffee husk ($Husk_{com}$); C-buoy coffee husk (Buoy); D-1 year composted coffee husk ($1y_{comp}$); E-enriched and composted for 3 years coffee husk

($3y_{comp}$). Rates equivalent to: filled circle 0; circle 75; filled inverted triangle 150; triangle 300; filled square 600 kg K_2O ha $^{-1}$; square mineral fertilizer (300 kg K_2O ha $^{-1}$). Regression equations shown in Table 6

no K control after week 11, 11, 13, 14, and 17, respectively (Fig. 2d).

Among the residues tested, $1y_{comp}$ displayed the least K leaching during the beginning of the simulated leaching,

although final cumulative leached K was not significantly different from the other residues, except for $3y_{comp}$ (Fig. 2; Table 5). Note that this material also had the highest pH and lowest EC compared to the other residues (Table 2).



The elevated pH may have impacted the underlying soil by increasing soil pH and thereby increasing negative charge on the surfaces of variable charged minerals, which are abundant in oxisols. Such an increase in negative charge would improve retention of cations. Also, the low EC of the material may have prevented some K leaching; anion movement through the soil will cause the cation held with the least strength to be leached in order to maintain charge balance. Potassium is very low on the lyotropic series and therefore relatively weakly held onto the soil CEC.

At application rates of 75 and 150 kg ha⁻¹ of K₂O, the rate of K leaching as indicated by the change in slope of cumulative leached K (Fig. 2a, b; Table 5) decreased with time for all treatments. However, at application rates of 300 and 600 kg ha⁻¹ of K₂O, the rate of K leaching actually increased with time for the columns treated with 3y_{comp} residue. The elevated K leaching rates that occurred initially for soils amended with the coffee residues are indicative of the high K solubility in these materials (Fig. 2; Table 2). In fact, the cumulative K leached after 40 weeks was similar to the inorganic KCl fertilizer, except for the 3y_{comp} (Fig. 2). The 3y_{comp} had the highest concentration of water soluble K and as a percentage of total K (Table 2). The initial low K leaching rate followed by an increase in leaching for the 3y_{comp} (Fig. 2) may be explained by the lignin content. Note that the 3y_{comp} residue possessed the largest amount of total lignin (Table 2) and resulted in an application rate of lignin 3–9.6 times greater than other residues (Table 3). Lignin can act as a physical barrier against water due to its hydrophobic character (Santos et al. 2012). It is possible that the applied water could not completely moisten 3y_{comp} residue initially, thereby delaying the loss of K from the interior of residue aggregates. The initial leached K would have occurred from the outside layer of each aggregate. Gradually, the water could have penetrated into the interior of the 3y_{comp} and allowed for K to dissolve in solution. At that point, the sulfate and Ca (from gypsum) could have increased the rate of K leaching as previously described. This ultimately resulted in the greatest amount of K leached after 40 weeks from the 3y_{comp} compared to the other residues.

Malavolta (1980) reported that nutrient leaching and dissolution from plant leaves by water depended on factors such as wax content, wettability, and cuticle status. Rosolem et al. (2003), studying K leaching from different cover crop residues, reported that the differences between K leached from residues were dependent on the plant tissue composition of each plant species such as cellulose and lignin content and also morphological differences of the plant shoot organs and leaf hairiness.

The leachate EC displayed a pattern (Fig. 3; Table 6) similar to K for the coffee residues where leaching was

Table 6 Regression equations for correlations shown in Fig. 3

Treatments	Equations
Pulp—0	$R^2 = 0.94^{**}$ $y = 78.89 + 805.50e^{-0.0988x}$
Pulp—75	$R^2 = 0.93^{**}$ $y = 103.08 + 778.48e^{-0.1066x}$
Pulp—150	$R^2 = 0.85^{**}$ $y = 107.87 + 714.77e^{-0.1062x}$
Pulp—300	$R^2 = 0.94^{**}$ $y = 94.78 + 716.08e^{-0.0929x}$
Pulp—600	$R^2 = 0.88^{**}$ $y = -19.0765 + 678.50e^{-0.0400x}$
Husk _{com} —0	$R^2 = 0.94^{**}$ $y = 78.89 + 805.50e^{-0.0988x}$
Husk _{com} —75	$R^2 = 0.93^{**}$ $y = 107.34 + 712.19e^{-0.1254x}$
Husk _{com} —150	$R^2 = 0.89^{**}$ $y = 107.32 + 733.34e^{-0.1408x}$
Husk _{com} —300	$R^2 = 0.93^{**}$ $y = 110.81 + 733.35e^{-0.1418x}$
Husk _{com} —600	$R^2 = 0.94^{**}$ $y = 101.60 + 707.22e^{-0.1186x}$
Buoy—0	$R^2 = 0.94^{**}$ $y = 78.89 + 805.50e^{-0.0988x}$
Buoy—75	$R^2 = 0.90^{**}$ $y = 110.71 + 763.75e^{-0.1231x}$
Buoy—150	$R^2 = 0.84^{**}$ $y = 107.79 + 744.67e^{-0.1321x}$
Buoy—300	$R^2 = 0.91^{**}$ $y = 82.12 + 602.76e^{-0.1028x}$
Buoy—600	$R^2 = 0.97^{**}$ $y = 60.96 + 715.12e^{-0.0893x}$
1y _{comp} —0	$R^2 = 0.94^{**}$ $y = 78.89 + 805.50e^{-0.0988x}$
1y _{comp} —75	$R^2 = 0.93^{**}$ $y = 100.63 + 742.15e^{-0.1110x}$
1y _{comp} —150	$R^2 = 0.95^{**}$ $y = 117.78 + 806.22e^{-0.1527x}$
1y _{comp} —300	$R^2 = 0.96^{**}$ $y = 122.64 + 780.82e^{-0.1566x}$
1y _{comp} —600	$R^2 = 0.96^{**}$ $y = 119.92 + 785.29e^{-0.1510x}$
3y _{comp} —0	$R^2 = 0.94^{**}$ $y = 78.89 + 805.50e^{-0.0988x}$
3y _{comp} —75	NS
3y _{comp} —150	NS
3y _{comp} —300	NS
3y _{comp} —600	NS
KCL	NS

Regression equations describe relationship between sampling time (x) and leachate electrical conductivity (EC; y), shown in Fig. 3, during 40 weeks of simulated leaching. Pulp = coffee pulp; Husk_{com} = common coffee husk; 3y_{comp} = enriched and composted for 3 years coffee husk; Buoy = buoy coffee husk; 1y_{comp} = 1 year composted coffee husk; NS = no significant regression; KCL = mineral potassium application as KCl (300 kg K₂O ha⁻¹ equivalent); ** significant at ($p < 0.01$); 0, 75, 150, 300, 600 means Kg K₂O ha⁻¹ equivalent applied using coffee processing residues as source

initially high and then decreased with time and continued leaching. The 300 kg K₂O ha⁻¹ application of KCl fertilizer is shown in every graph within Fig. 3. The KCl treatment clearly displays a large spike in ion leaching at around week nine; this spike in ion leaching is dissimilar to all coffee residue materials except for the 3y_{comp} (Fig. 3e). Total ion leaching as indicated by EC was similar among all treatments and the no K control except for the KCl treatment and 3y_{comp}. This suggests for all coffee residues except 3y_{comp} that native soil ions, rather than applied residue ions, contributed the majority of the leached ions. The similarity of leached ion patterns between KCl and 3y_{comp} is likely due to the fact this residue contained a highly soluble salt (gypsum; CaSO₄), similar to KCl.

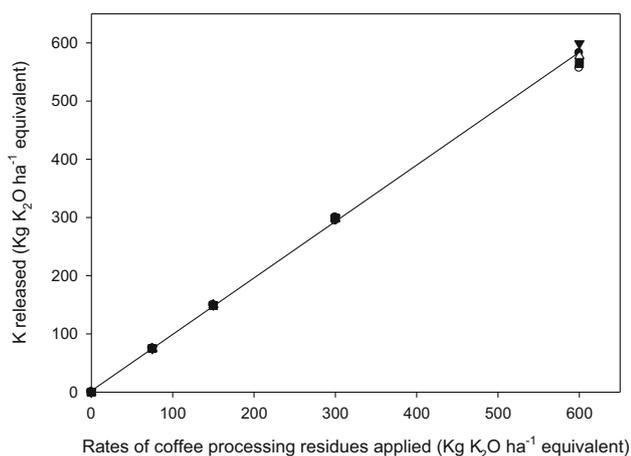


Fig. 4 Total potassium (K) released from coffee processing residues after 40 weeks of simulated leaching. **Significant difference at $p < 0.01$; *filled circle* coffee pulp (Pulp); *circle* common coffee husk (Husk_{com}); *filled inverted triangle* enriched and composted for 3 years coffee husk (3y_{comp}); *triangle* buoy coffee husk (Buoy); *filled square* 1 year composted coffee husk (1y_{comp}); *square* mineral fertilizer (300 kg K₂O ha⁻¹). Regression equations shown in Table 7

Table 7 Regression equations for data shown in Fig. 4

Treatments	Equations	R ²
Pulp	$y = 5.7341 + 0.9411x$	0.99**
Husk _{com}	$y = 6.4985 + 0.9262x$	0.99**
3y _{comp}	$y = -0.0197 + 0.9981x$	1.00**
Buoy	$y = 3.5433 + 0.9622x$	0.99**
1y _{comp}	$y = 5.7341 + 0.9144x$	0.99**

Regression equations describe relationship between potassium (K) application rate (x) and total K released from residues (y), shown in Fig. 4, after 40 weeks of simulated leaching. Pulp = coffee pulp; Husk_{com} = common coffee husk; 3y_{comp} = enriched and composted for 3 years coffee husk; Buoy = buoy coffee husk; 1y_{comp} = 1 year composted coffee husk; ** significant at ($p < 0.01$)

Coffee processing residues applied at soil surface

As expected, total K released from coffee residues increased linearly ($p < 0.01$) with application rate (Fig. 4; Table 7). The total K released from coffee residues was not significantly related to decomposition (data not shown). In addition, K release was >92 % for all coffee residues, and no significant difference was observed ($p < 0.05$) between coffee residues and the mineral K control. These results suggest that K found in coffee residues is not bound up in organic forms. The high release, or solubility, of this nutrient from plant residues occurs because K is not metabolized in the plant and it forms only easily reversible links with organic complexes (Rosolem et al. 2003). The results for this study are similar to Crusciol et al. (2005) who demonstrated that K contents were near zero when measured in cover crop residues 50 days after knife roller (crimper) management and glyphosate application.

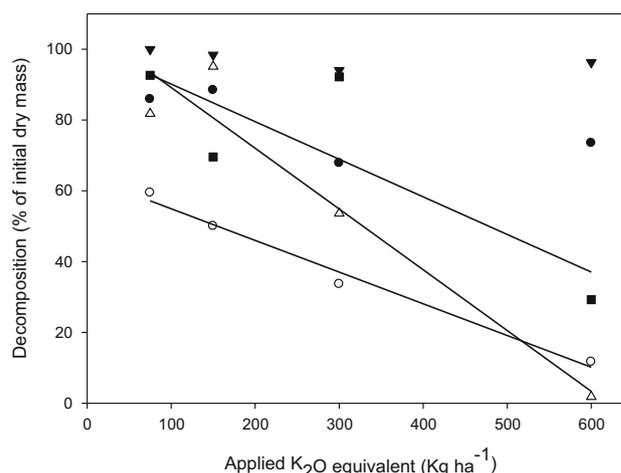


Fig. 5 Decomposition of surface applied coffee processing residues after 40 weeks of simulated leaching. *filled circle* Coffee pulp (Pulp); *circle* common coffee husk (Husk_{com}); *filled inverted triangle* enriched and composted for 3 years coffee husk (3y_{comp}); *triangle* buoy coffee husk (Buoy); *filled square* 1 year composted coffee husk (1y_{comp}). Significant regression at $p < 0.01$ for Husk_{com} ($y = 63.9109 - 0.0896x$; $R^2 = 0.38^{**}$), Buoy ($y = 106.37 - 0.1717x$; $R^2 = 0.81^{**}$), and 1y_{comp} ($y = 100.7932 - 0.1063x$; $R^2 = 0.46^{**}$)

The coffee processing residues applied on the soil surface generally had lower decomposition (Fig. 5) at the highest application rate for 1y_{comp}, Husk_{com}, and Buoy. The decrease in decomposition at the high application rates is likely due to less surface contact between the residues and the soil (Martins et al. 1999). The decomposition of Pulp and the 3y_{comp} was higher than the others treatments and did not decrease with application rate. The higher decomposition for Pulp may be explained by possession of the largest initial N content and a relatively low C:N ratio (Table 2). The 3y_{comp} possessed the smallest particle size based on visual observation and may have had better contact with the soil surface as a result. This material also possessed the lowest C:N ratio. A C:N ratio less than 30 generally indicates greater potential for C decomposition by microorganisms (Ranells and Waggener 1992; Da Ros 1993).

Conclusions

Different post-harvest coffee processing methods impact potassium, nitrogen, carbon, celluloses, hemicelluloses, lignin, phenols, pH, and electrical conductivity in the coffee processing residues. The K release is high (over 90 %) for coffee residues, but does not depend on the type of coffee processing residue, and thus, the residues can substitute for a mineral source of soil K amendment.

The use of coffee processing residues as a source of K did not reduce K leaching loss. The enriched and

composted for 3 years coffee husk, coffee pulp, and common coffee husk displayed higher K leaching than the mineral K source.

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