Environmental Challenges 15 (2024) 100893

Contents lists available at ScienceDirect

Environmental Challenges

journal homepage: www.elsevier.com/locate/envc

Potential of organic wastes typical of the Brazilian Amazon for fertilizer use in agriculture

Alysson Roberto Baizi e Silva [a,*], Vinícius Ide Franzini [b]

[a] Embrapa Amazônia Oriental, Belém 66095-903, Pará, Brazil
[b] Embrapa Uva e Vinho, Bento Gonçalves 95701-008, Rio Grande do Sul, Brazil

ARTICLE INFO

Keywords:
Charcoal
Manure
Nutrient
Oil palm waste
Organic fertilizer
Wood sawdust

ABSTRACT

Characterization of different organic wastes is essential to reveal alternative nutrient sources useful for agriculture. The objective of this work was to characterize a variety of organic wastes generated in the Brazilian Amazon in order to identify nutrient sources for potential use as organic fertilizers. Samples of nine different organic wastes from agricultural, livestock and forestry activities were collected in the state of Pará, Amazon region, Brazil. These samples were characterized using reference methods for analyses of organic fertilizers. Palm oil mill boiler ash was highly concentrated in P, K, Ca, and Mg and also highly alkaline, being considered a promising material for use as fertilizer and lime in acid soils. Palm oil mill decanter cake was the best N source; it also contained relevant amounts of K, S, and Zn. Cattle manure was more concentrated in N and oil palm empty fruit bunch in K. Residual eucalyptus charcoal was high in Ca but also in Na and Al. Oil palm fruit fiber, oil palm fruit shell, wood sawdust of the pile top, and wood sawdust of the pile slope were consistently poor in nutrients. All wastes presented low concentrations of As, Ba, Cd, Cr, Hg, Pb, and Se. This study identified organic wastes differing in prevalent nutrients for potential use as organic fertilizers. Such a difference could be explored in further studies by combining two or more wastes with complementary prevalent nutrients in order to better meet the nutritional requirements of different crops in the Brazilian Amazon.

Introduction

Soils of the Brazilian Amazon are mostly acid and poor in mineral plant nutrients (Rodrigues, 1996; Quesada et al., 2011; Schaefer et al., 2017). Therefore, lime and fertilizers are essential to develop agriculture in the Amazon and thus to ensure food security for the local population. However, the prices of mineral fertilizers in this region are normally very high. With the Covid-19 pandemic (USDA, 2022) and the Russia-Ukraine war (Arndt et al., 2023), they became even higher. Because of these high prices, the use of fertilizers in Amazonian agriculture has been restricted, mainly in family farming. Thus, the search for alternative sources of mineral nutrients is a need.

Organic wastes can be used as alternatives to mineral fertilizers because they contain appreciable amounts of plant nutrients (Sharma et al., 2019), mainly nitrogen (N), phosphorus (P), and potassium (K). Results from long-term experiments have shown equivalence between organic wastes, such as manures, and mineral fertilizers in terms of crop yields (Johnston, 1997; Edmeades, 2003), indicating that organic wastes are able to supply sufficient amounts of nutrients to plants. In addition to providing nutrients, organic wastes also improve soil structure (Haynes and Naidu, 1998; Sharma et al., 2019) and increase soil biological activity (Mandal et al., 2007; Chakraborty et al., 2011; Sharma et al., 2019), resulting in additional benefits to the agricultural production environment.

The most abundant organic wastes in the Brazilian Amazon are those generated in the state of Pará. Generation of cattle manure in this state is enormous. It is estimated at 17.2 million t per year, considering a herd of 23.9 million animals (IBGE, 2021a) and a daily feces production of 1.97 kg per animal (dry basis) (Braz et al., 2002). Residual eucalyptus charcoal is another important organic waste. This material consists of charcoal fragments remaining on the kiln floor after the removal of the commercial charcoal. What leads one to believe that this waste is generated in a considerable amount in Pará is that the state needs to produce a lot of commercial charcoal to sustain its large production of pig iron, estimated around 500 thousand t per year according to Sindifer (2022). The palm oil industry also generates large amounts of organic wastes. The processing of 1 t fresh fruit bunches results in approximately 230 kg empty fruit bunch, 140 kg fiber, 55 kg shell, 32 kg decanter cake,

* Corresponding author.
E-mail address: alysson.silva@embrapa.br (A.R.B. Silva).

https://doi.org/10.1016/j.envc.2024.100893
Received 12 December 2023; Received in revised form 1 February 2024; Accepted 6 March 2024
Available online 7 March 2024

and 50 kg boiler ash (wet basis) (Chavalparit et al., 2006). Considering a production of 2.8 million t fresh fruit bunches per year in Pará (IBGE, 2021b), the amounts of oil palm wastes generated annually in the state are estimated to be (× 1000 t): 644 empty fruit bunch, 392 fiber, 154 shell, 89.6 decanter cake, and 140 boiler ash (wet basis). Wood sawdust is also an abundant waste in Pará. It is estimated that something like 4 million m^3 of this material are generated per year in the state (Ramos et al., 2017).

These large amounts of organic wastes could be employed as nutrient sources for agriculture. However, the use of such wastes as organic fertilizers is normally ignored in the region. In cases where wastes are added to soils, this is simply a way of disposal of these materials, without any intention of substituting mineral fertilizers. The main reason for this low interest in agricultural recycling is the lack of knowledge about the composition of these wastes. Thus, to overcome this challenge, the composition of the wastes needs be characterized. This characterization should be performed in order to determine the content of nutrients. In addition, the presence of undesirable elements should be investigated as well. Among these elements are sodium (Na), aluminum (Al), arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), mercury (Hg), lead (Pb), and selenium (Se). Such elements are undesirable due to problems they may cause. Excess Na may salinize soils (Shahid et al., 2018), Al may induce toxicity in cultivated plants (Foy et al., 1978; Kochian et al., 2015), and As, Ba, Cd, Cr, Hg, Pb, and Se as potentially toxic elements may contaminate the environment and harm the human health when in excess (Adriano, 2001; Peana et al., 2021).

Characterization is a key factor for valorization of organic wastes as nutrient sources. In addition, it helps to identify wastes that are more suitable for use as organic fertilizers, increasing the chance of finding better substitutes for mineral fertilizers. It also provides information for a more efficient use of wastes as organic fertilizers for direct application to soils (Schnug et al., 1996; Schröder, 2005) or as raw materials for production of organomineral fertilizers (Ngo et al., 2022), biofertilizers (Ezemagu et al., 2021), and bio-based fertilizers (Chojnacka et al., 2020). Organic wastes used more efficiently due to the knowledge of their characteristics are capable of providing nutrients to plants without contaminating soil and water, protecting the environment in agricultural ecosystems. Therefore, characterization is essential for the responsible use and better management of organic wastes in agriculture.

The objective of this work was to characterize a variety of organic wastes generated in the Brazilian Amazon in order to identify nutrient sources for potential use as organic fertilizers.

Materials and methods

Wastes

Samples of (i) cattle manure, (ii) residual eucalyptus charcoal, (iii) oil palm empty fruit bunch, (iv) oil palm fruit fiber, (v) oil palm fruit shell, (vi) palm oil mill decanter cake, (vii) palm oil mill boiler ash, (viii) wood sawdust of the pile top, and (ix) wood sawdust of the pile slope were collected in the state of Pará, Amazon region, Brazil. The collection of each type of waste followed a particular procedure, based on characteristics of generation of the material. The adopted procedures are described below.

Cattle manure samples were collected in five small family farms, where unlimed, unfertilized, and poorly managed *Urochloa* sp. (syn. *Brachiaria* sp.) pastures were grazed by non-supplemented Zebu cattle. In each selected farm, three patches of dry bovine feces were randomly picking up from the pasture surface and then mixed to form a composite sample. This collection generated five composite samples, one from each farm, obtained in May-June 2016 (end of the rainy season).

Collection of residual eucalyptus charcoal samples was performed in two of ten kilns built in a eucalyptus farm. In each selected kiln, random portions of the residual charcoal on the floor were collected and then mixed to form a composite sample. From this procedure, two composite samples, one from each kiln, were obtained in November 2016 (end of the dry season).

Oil palm wastes were collected at three different times in the same mill. Collection was performed at November 2017 (dry season), January 2018 (rainy season), and August 2018 (rainy-dry season transition), when the oil palm yield in the region is typically high, low, and medium, respectively. At each of these times, one sample of empty bunch, fiber, shell, decanter cake, boiler ash was randomly collected. These samples were derived from recently processed fresh fruit bunches, harvested in African oil palm (*Elaeis guineensis*) and oil palm interspecific hybrids (*E. oleifera* × *E. guineensis*) plantations. As one sample was collected at each time, three samples were obtained for each type of oil palm waste.

Samples of wood sawdust from different native tree species were collected in a representative uncovered pile with basal area of approximately 0.4 ha and height around 4 m. The collection was performed separately in two distinct parts of the pile: top and slope. This procedure was adopted because the sawdust from the top was a material more recent than the sawdust from the slope, and this difference could result in materials with contrasting nutrient concentrations. In each part of the pile, 20 random samples were taken from the 0–20, 20–40, 40–60, 60–80, and 80–100-cm depths using a Dutch auger for soil sampling as also was used later by Miller et al. (2019). This sampling scheme was implemented because there was no guarantee that the material within each part of the pile was homogeneous in nutrient concentrations. The auger was inserted perpendicularly to the top and slope surface. Samples from each depth were mixed to form one composite sample. As a result, five composite samples, one from each depth, were obtained for each part of the pile. This collection was carried out in September-October 2016 (dry season).

Chemical analysis

Each waste sample was separated into two parts. One part was used to determine the pH in water [1:5 (w/v) waste:deionized water ratio] of sample weighed *in natura*. The other part was oven-dried at 65 °C until constant weight for moisture determination (Brasil, 2017). The dry samples were ground in a Wiley-type mill, passed through a 500-µm sieve (Brasil, 2017), and analyzed as follows. Organic carbon (OC) was determined by the dichromate oxidation method (Abreu et al., 2006), and the cation exchange capacity (CEC) by the titration method (Brasil, 2017). N was determined by the Kjeldahl method (Abreu et al., 2006). Mineral N forms were also quantified. NH_4^+–N and NO_3^-–N were extracted with KCl and determined by the MgO method and the Devarda alloy method, respectively (Abreu et al., 2006). P, K, calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), zinc (Zn), Na, Al, As, Ba, Cd, Cr, Hg, Pb, and Se were extracted with HNO_3 in a microwave oven (CEM Mars 5, USA) and determined by inductively coupled plasma optical emission spectrometry (ICP-OES | Varian Vista-MPX, USA), except for K and Na, which were determined by flame photometry. This procedure, which is known as the method 3051A (USEPA, 1995), has been accredited according to the ABNT NBR ISO/IEC 17025:2017 in the laboratory where it was performed. C/N ratio and CEC/C ratio were calculated for each waste sample.

Statistical analysis

Residuals of each variable were checked for normality, by the Shapiro-Wilk test, and homogeneity of variances, by the Bartlett's test. As at least one of these assumptions was not met for all variables, we used the nonparametric Kruskal-Wallis test and the Fisher's least significant difference (LSD) computed on ranks (Conover, 1999) to detect differences between wastes. All statistical analyses were performed in R (Version 4.1.1) (R Core Team, 2021) at $P < 0.05$ using the *easyanova* package (Arnhold, 2013).

Results and discussion

Moisture, acidity, organic carbon, and cation exchange capacity

The wastes differed in moisture at the time of collection (Table 1). Oil palm empty fruit bunch and palm oil mill decanter cake had the highest mean moisture contents (> 60 %), whereas the lowest mean contents (< 10 %) were observed in residual eucalyptus charcoal, oil palm fruit shell, and palm oil mill boiler ash. The other wastes (cattle manure, oil palm fruit fiber, wood sawdust of the pile top, and wood sawdust of the pile slope) had intermediate mean levels (between 22 % and 45 %). Excess moisture impacts handling, storage, transport, and land application of organic wastes. These operations are expected to be more difficult and/or expensive for empty fruit bunch and decanter cake because of their high moisture contents.

The wastes also differed in acidity (Table 1). Oil palm empty fruit bunch, oil palm fruit fiber, oil palm fruit shell, palm oil mill decanter cake, wood sawdust of the pile top, and wood sawdust of the pile slope were acid materials (pH < 7), cattle manure and residual eucalyptus charcoal were nearly neutral (pH ~ 7), and palm oil mill boiler ash was highly alkaline (pH 11). High alkalinity of this same type of boiler ash was observed in a previous study (Oliveira et al., 2006). The alkaline reaction of plant biomass ash has been attributed to the presence of acid-neutralizing anions in the material. These anions are basically carbonates, bicarbonates, and hydroxides (Etiégni and Campbell, 1991; Mahmood and Kamal, 2022). Because of its high alkalinity, likely related to such anions, palm oil mill boiler ash is believed to be a promising material for liming acid soils.

The organic C concentration was different between wastes (Table 1). Oil palm empty fruit bunch, oil palm fruit fiber, oil palm fruit shell, and the wood sawdust of the pile slope had the highest mean organic C concentrations. In contrast, the lowest mean concentration was observed in the palm oil mill boiler ash. Cattle manure, residual eucalyptus charcoal, palm oil mill decanter cake, and wood sawdust of the pile top had intermediate mean concentrations. Despite these differences, all wastes were relatively rich in organic C (306–497 g kg^{-1}), except the boiler ash, which was very poor (36 g kg^{-1}). This boiler ash was very low in organic C probably due to the C loss from the original plant biomass occurred during combustion of the material. Throughout this process, C is oxidized and transformed into gaseous substances (Demeyer et al., 2001), mainly CO_2, according to the following simplified reaction, adapted from Etiégni and Campbell (1991):

$$\text{Plant biomass–C} + O_2 \rightarrow \text{ash} + CO_2 \quad (1)$$

This low organic C concentration becomes the palm oil mill boiler ash a material with limited efficiency in increasing the soil C content. Such a limitation has been revealed to be a common characteristic to plant biomass ashes (Augusto et al., 2008).

The CEC also was different between wastes (Table 1). Palm oil mill decanter cake had the highest mean CEC value. The lowest mean values were observed in oil palm fruit shell and palm oil mill boiler ash. The other wastes had intermediate mean values. These differences, however, may not be reflected in the CEC of soils amended with these wastes. This is because the increase in soil CEC does not seem to depend only on the waste CEC. It may also depend on the increase in soil pH, as shown by Rodella et al. (1995) for an acid sandy soil treated with different organic materials. In addition, multiple waste applications may be required to increase the soil CEC (Zebarth et al., 1999).

Table 1
Moisture, pH (H_2O), organic C content, and CEC in organic wastes typical of the Brazilian Amazon. Each value is a mean ± standard deviation.

Waste	Moisture (%)	pH (H_2O)	Organic C (g kg^{-1})	CEC ($mmol_c$ kg^{-1})
Cattle manure ($n = 5$)	31.1 ± 17.8 bc†	7.10 ± 0.22 b	306.4 ± 86.0 de	343.4 ± 77.1 bc
Residual eucalyptus charcoal ($n = 2$)	5.4 ± 0.2 e	7.19 ± 0.08 ab	399.0 ± 36.8 cd	302.5 ± 75.7 cd
Oil palm empty fruit bunch ($n = 3$)	60.4 ± 7.6 a	6.55 ± 0.92 bc	467.0 ± 14.9 ab	456.3 ± 61.5 ab
Oil palm fruit fiber ($n = 3$)	22.7 ± 9.0 cd	5.23 ± 0.34 d	495.3 ± 39.6 a	305.3 ± 43.9 cd
Oil palm fruit shell ($n = 3$)	8.0 ± 1.2 de	5.29 ± 0.32 de	496.7 ± 21.1 a	156.3 ± 64.9 e
Palm oil mill decanter cake ($n = 3$)	77.6 ± 3.3 a	4.10 ± 0.06 e	427.7 ± 41.5 bc	642.7 ± 58.4 a
Palm oil mill boiler ash ($n = 3$)	0.3 ± 0.2 e	11.49 ± 1.02 a	35.5 ± 8.1 e	46.5 ± 16.8 e
Wood sawdust (pile top) ($n = 5$)	44.6 ± 3.9 b	5.45 ± 0.35 d	435.8 ± 20.4 c	283.8 ± 36.0 cd
Wood sawdust (pile slope) ($n = 5$)	38.4 ± 14.2 b	6.26 ± 0.20 c	470.4 ± 16.9 a	263.2 ± 64.2 d
P-value (Kruskal-Wallis test)	< 0.001	0.001	0.001	0.002

†Different letters within a column indicate significant difference between wastes according to the Fisher's LSD computed on ranks ($P < 0.05$).

Macronutrients

There were differences between wastes for all macronutrients (Table 2). The wastes followed this order for mean N concentration: palm oil mill decanter cake > cattle manure = oil palm fruit fiber = oil palm empty fruit bunch > oil palm fruit shell = residual eucalyptus charcoal > wood sawdust of the pile top > wood sawdust of the pile slope > palm oil mill boiler ash (Table 2). This boiler ash had the lowest mean N concentration (1.5 g kg^{-1}) probably due to the loss of N in the gaseous form during combustion of plant biomass. Such a loss has been suggested by Demeyer et al. (2001) as an explanation for the low levels

Table 2
Concentration of macronutrients in organic wastes typical of the Brazilian Amazon. Each value is a mean ± standard deviation.

Waste	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})	S (g kg^{-1})
Cattle manure ($n = 5$)	12.26 ± 2.30 b†	1.03 ± 0.34 b	2.23 ± 1.78 d	2.48 ± 1.31 c	1.66 ± 0.58 d	1.16 ± 0.46 b
Residual eucalyptus charcoal ($n = 2$)	4.95 ± 0.64 c	0.56 ± 0.04 c	5.62 ± 0.54 c	26.55 ± 2.33 ab	1.75 ± 0.07 cd	1.06 ± 0.17 bc
Oil palm empty fruit bunch ($n = 3$)	10.17 ± 2.11 b	1.02 ± 0.15 b	23.17 ± 9.42 b	3.40 ± 0.26 b	2.27 ± 0.38 bc	0.81 ± 0.22 bc
Oil palm fruit fiber ($n = 3$)	10.90 ± 0.44 b	0.85 ± 0.14 b	5.24 ± 0.96 c	3.40 ± 0.20 b	1.63 ± 0.23 d	1.17 ± 0.12 b
Oil palm fruit shell ($n = 3$)	5.83 ± 0.46 c	0.42 ± 0.18 c	2.91 ± 0.87 d	1.10 ± 0.44 d	0.78 ± 0.27 e	0.63 ± 0.15 cd
Palm oil mill decanter cake ($n = 3$)	31.17 ± 1.50 a	2.63 ± 0.42 a	17.44 ± 5.33 b	12.17 ± 1.45 ab	3.87 ± 0.85 ab	2.73 ± 0.55 a
Palm oil mill boiler ash ($n = 3$)	1.47 ± 0.15 f	23.87 ± 2.49 a	57.08 ± 8.26 a	61.77 ± 5.33 a	38.93 ± 4.59 a	1.48 ± 0.94 b
Wood sawdust (pile top) ($n = 5$)	3.54 ± 0.48 d	0.03 ± 0.01 d	0.25 ± 0.12 f	1.68 ± 0.43 cd	0.31 ± 0.07 f	0.39 ± 0.04 de
Wood sawdust (pile slope) ($n = 5$)	2.88 ± 0.44 e	0.03 ± 0.01 d	0.54 ± 0.08 e	2.08 ± 0.38 c	0.37 ± 0.05 f	0.28 ± 0.04 e
P-value (Kruskal-Wallis test)	< 0.001	< 0.001	< 0.001	0.001	< 0.001	0.001

†Different letters within a column indicate significant difference between wastes according to the Fisher's LSD computed on ranks ($P < 0.05$).

of N normally found in boiler ashes. On the other hand, the high content of N in the decanter cake (31 g kg^{-1}) may have resulted from a concentration of nitrogenous compounds from the oil palm fresh fruit bunch in the final stage of the crude oil extraction. Such a possibility is supported by the fact that no N additive is used in this industrial process (Chew et al., 2021) and therefore the N in the decanter cake could only come from the fresh fruit bunch. Cattle manure was much less concentrated in N than the palm oil mill decanter cake but it still had a relevant mean concentration (12 g kg^{-1} N). This value is similar to that found by Melo et al. (2008) (11 g kg^{-1} N), however, lower than those found by Prochnow et al. (2001) (23 g kg^{-1} N) and Kirchmann and Witter (1992) ($\geq$ 23 g kg^{-1} N). Such differences could be primarily attributed to variations in N intake by the animals that excreted the feces evaluated in these studies, since N intake and fecal N excretion are interrelated processes (Pagliari et al., 2019). Mean N concentrations in oil palm empty fruit bunch (10 g kg^{-1} N) and oil palm fruit fiber (11 g kg^{-1} N) can also be considered relevant because they are equivalent to that of the cattle manure. In the case of the empty fruit bunch, its mean N concentration was slightly above of the upper limit of the range of N concentrations often found in this waste (6.5–9.4 g kg^{-1} N; Pardon et al., 2016), suggesting that the empty fruit bunch evaluated in the present work is one of the richest in N. Mean N concentrations in charcoal (5.0 g kg^{-1} N) and fruit shell (5.8 g kg^{-1} N) were slightly lower than half of that of the cattle manure. Mean N concentrations of wood sawdust of the pile top (3.5 g kg^{-1} N) and wood sawdust of the pile slope (2.9 g kg^{-1} N) were even lower, less than one third of that of the cattle manure. Thus, residual eucalyptus charcoal, oil palm fruit shell, and wood sawdust, in addition to the palm oil mill boiler ash, seem to have low potential as N sources.

Ammonium-N (NH_4^+–N) and nitrate-N (NO_3^-–N) were determined as mineral N in addition to the total N above. Mean concentrations of both forms varied between wastes (Table 3), but these concentrations were very low compared to those of total N (Table 2). Mean mineral N (NH_4^+–N + NO_3^-–N) concentrations did not exceed 1 % of those of total N. This indicates that N in the wastes was predominantly in organic forms.

The order followed by the wastes in terms of P concentration was this: palm oil mill boiler ash = palm oil mill decanter cake > cattle manure = oil palm empty fruit bunch = oil palm fruit fiber > residual eucalyptus charcoal = oil palm fruit shell > wood sawdust of the pile top = wood sawdust of the pile slope (Table 2). Such a sequence is very different of that for N concentration. The main difference occurred with the boiler ash. This waste had the lowest mean N concentration and the highest mean P concentration (24 g kg^{-1} P). As mentioned above, the low N content was associated with the N loss. The high P content, on the other hand, seems to have been caused by a concentration effect. Experimental results have shown P being concentrated in plant biomass ashes as a result of combustion (Etiégni and Campbell, 1991). In addition, this increase in concentration is generally accompanied by a decrease in P solubility, due to the formation of apatite and other calcium phosphates (Steenari and Lindqvist, 1997; Vassilev et al., 2013; Brod et al., 2015). Consequently, the efficiency of ashes in releasing P rapidly tends to be low. Thus, for a more complete evaluation of the potential of palm oil mill boiler ash as a P source, further studies on mineralogy and solubility are needed. Although there was no statistical difference, mean P concentration in the decanter cake (2.6 g kg^{-1} P) was almost one tenth lower than that of the boiler ash. Like N, P in the decanter cake may have been concentrated, since this P came from fresh fruit bunch, which contain less P (1.5 g kg^{-1} P; Siang et al., 2022). Mean P concentrations in cattle manure (1.0 g kg^{-1} P), empty fruit bunch (1.0 g kg^{-1} P), and fruit fiber (0.9 g kg^{-1} P) were even lower than that of the decanter cake. This cattle manure had less P than those previously evaluated in other works (9.0–10.4 g kg^{-1} P in Kirchmann and Witter, 1992; 2.2–18.5 g kg^{-1} P in Dagna and Mallarino, 2014) probably due to lower P intake by cattle, since the fecal P is a reflection of dietary P (Pagliari et al., 2019). P level in the empty fruit bunch was similar to that of a previous report (1.1 g kg^{-1} P; Ferreira et al., 1998). On the other hand, mean P concentration in the fruit fiber was less than half of that reported in the same work (1.9 g kg^{-1} P; Ferreira et al., 1998), suggesting a pronounced variability for P in this waste. Lower mean P concentrations were observed in eucalyptus charcoal (0.6 g kg^{-1} P) and fruit shell (0.4 g kg^{-1} P). Finally, P was negligible in the two types of wood sawdust (0.03 g kg^{-1} P), indicating low potential of these wastes as P sources.

The sequence of the wastes for K concentration was the following: palm oil mill boiler ash > oil palm empty fruit bunch = palm oil mill decanter cake > residual eucalyptus charcoal = oil palm fruit fiber > cattle manure = oil palm fruit shell > wood sawdust of the pile slope > wood sawdust of the pile top (Table 2). Boiler ash had the highest mean K concentration (57.1 g kg^{-1} K) probably due to a relative concentration effect, i.e., loss of K lower than that of other elements such as C and N during combustion. In addition, K present in this boiler ash is believed to be released rapidly, because studies have generally shown that most of the K contained in plant biomass ashes is highly soluble in water (Etiégni and Campbell, 1991; Ulery et al., 1993; Khanna et al., 1994). This high solubility is due to the presence of K combined with chloride, sulfate, and carbonate, which are soluble salts (Steenari and Lindqvist, 1997; Steenari et al., 1999). Mean K concentrations in empty fruit bunch (23.2 g kg^{-1} K) and decanter cake (17.4 g kg^{-1} K) were less than half that of the boiler ash. However, mean K concentration in the empty fruit bunch was higher than that found by Ferreira et al. (1998) (16.4 g kg^{-1} K). Such a difference may be related to variations in K supply to oil palm plants. As already mentioned for N and P, K present in the decanter cake has its origin in the fresh fruit bunch. Eucalyptus charcoal and fruit fiber had mean K concentrations (5.6 and 5.2 g kg^{-1} K, respectively) lower than those of the previous wastes. Cattle manure and fruit shell had even lower mean K concentrations (2.2 and 2.9 g kg^{-1} K, respectively). Higher K concentrations in cattle manure have been found by Kirchmann and Witter (1992) (7.3–14.4 g kg^{-1} K) and Dagna and Mallarino (2014) (5.0–90.0 g kg^{-1} K), probably due to higher K intake by cattle. Wood sawdust of the pile top had half the mean K concentration of the wood sawdust of the pile slope but both wastes were the lowest in K.

The wastes also differed in Ca and Mg concentrations (Table 2). Palm oil mill boiler ash had the highest mean concentrations for both nutrients (61.8 g kg^{-1} Ca and 38.9 g kg^{-1} Mg). This result is consistent with other studies showing large amounts of Ca and Mg in different plant biomass ashes (Etiégni and Campbell, 1991; Ulery et al., 1993; Someshwar, 1996). Although abundant, Ca and Mg seem to be less soluble in water than K in such ashes (Khanna et al., 1994; Vassilev et al., 2013). This could suggest a low efficiency of these materials in supplying Ca e Mg to plants. However, such nutrients occur in ashes principally as oxides and carbonates (Misra et al., 1993; Steenari and Lindqvist, 1997; Vassilev et al., 2013; Maresca et al., 2017). These compounds, when reacted with acid soils, are dissolved (Keiblinger et al., 2016). Therefore, ashes applied to this type of soil release Ca and Mg (Khanna et al., 1994),

Table 3
Concentration of NH_4^+–N and NO_3^-–N in organic wastes typical of the Brazilian Amazon. Each value is a mean ± standard deviation.

Waste	NH_4^+–N (g kg^{-1})	NO_3^-–N (g kg^{-1})
Cattle manure ($n = 5$)	0.0826 ± 0.0150 a†	0.0060 ± 0.0047 bcd
Residual eucalyptus charcoal ($n = 2$)	0.0118 ± 0.0134 bc	0.0023 ± 0.0013 cd
Oil palm empty fruit bunch ($n = 3$)	0.0201 ± 0.0094 b	0.0196 ± 0.0060 a
Oil palm fruit fiber ($n = 3$)	0.0615 ± 0.0294 a	0.0228 ± 0.0131 a
Oil palm fruit shell ($n = 3$)	0.0164 ± 0.0006 b	0.0092 ± 0.0066 ac
Palm oil mill decanter cake ($n = 3$)	0.1237 ± 0.0462 a	0.0109 ± 0.0039 ab
Palm oil mill boiler ash ($n = 3$)	0.0013 ± 0.0010 c	0.0122 ± 0.0070 ab‡
Wood sawdust (pile top) ($n = 5$)	0.0145 ± 0.0077 b	0.0020 ± 0.0013 d
Wood sawdust (pile slope) ($n = 5$)	0.0112 ± 0.0091 b	0.0034 ± 0.0021 cd
P-value (Kruskal-Wallis test)	0.001	0.014

†Different letters within a column indicate significant difference between wastes according to the Fisher's LSD computed on ranks ($P < 0.05$).
‡$n = 2$, since the NO_3^-–N concentration in one of the three samples was below the limit of quantification of the analytical method (< 0.0001 g kg^{-1}).

which can then be absorbed by plant roots. Residual eucalyptus charcoal, another material obtained from plant biomass burning, and palm oil mill decanter cake had lower mean Ca concentrations (26.6 and 12.2 g kg^{-1}, respectively), but they were still relevant. The other wastes were very low in Ca ($\leq$ 3.4 g kg^{-1}). Wastes other than palm oil mill boiler ash had low mean Mg concentrations (< 3.9 g kg^{-1}).

Similarly to N, the highest mean S concentration (2.7 g kg^{-1}) occurred in the palm oil mill decanter cake (Table 2). This suggests that at least some of the nitrogenous compounds from the fresh fruit bunch that were accumulated in the decanter cake also contained S. In fact, in plants, certain amino acids and proteins contain both N and S in their composition (Hawkesford et al., 2023). In contrast to the decanter cake, the two types of wood sawdust had the lowest mean S concentrations (< 0.4 g kg^{-1}), and the other wastes were in intermediate positions (Table 2).

Micronutrients

Unlike macronutrients, some of the micronutrients were below the limit of quantification (LOQ) of the analytical method in a relevant number of wastes (Table 4). This was the case of B (LOQ = 16.7 mg kg^{-1}) in cattle manure, residual eucalyptus charcoal, oil palm fruit fiber, oil palm fruit shell, wood sawdust of the pile top, and wood sawdust of the pile slope. It was also the case of Cu (LOQ = 5.4 mg kg^{-1}) in cattle manure, eucalyptus charcoal, and wood sawdust of both top and slope of the pile. In addition, Zn was below the LOQ (5.4 mg kg^{-1}) in fruit shell and wood sawdust from the two parts of the pile. Mo and Ni were below their LOQs (1.3 and 3.2 mg kg^{-1}, respectively) in almost all wastes. Mo was quantified only in two samples of palm oil mill boiler ash (1.5 and 1.3 mg kg^{-1}) and Ni in one sample of palm oil mill decanter cake (6.3 mg kg^{-1}), three of boiler ash (4.2, 4.7, and 6.6 mg kg^{-1}), and one of fruit shell (20.2 mg kg^{-1}). Although Ni is a plant micronutrient (Cakmak et al., 2023), it is considered a contaminant in organic fertilizers by the Brazilian legislation. The maximum limit of Ni allowed in these fertilizers is 70 mg kg^{-1} (Brasil, 2016). No waste evaluated in the present study reached this value.

Table 4
Concentration of micronutrients in organic wastes typical of the Brazilian Amazon. Each value is a mean ± standard deviation.

Waste	B (mg kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})
Cattle manure (*n* = 5)	< 16.7†	< 5.4	971 ± 377 b	98.3 ± 45.1 ac	32.32 ± 13.81 b
Residual eucalyptus charcoal (*n* = 2)	< 16.7	< 5.4	3029 ± 1742 a	109.3 ± 16.6 ab	6.50 ± 4.67 c
Oil palm empty fruit bunch (*n* = 3)	28.0 ± 17.6	12.37 ± 3.32 c‡	379 ± 213 c	47.3 ± 17.8 bd	25.60 ± 1.56 b
Oil palm fruit fiber (*n* = 3)	< 16.7	15.90 ± 1.06 c	899 ± 391 b	30.8 ± 15.7 de	11.47 ± 1.53 c
Oil palm fruit shell (*n* = 3)	< 16.7	7.40 ± 1.71 d	315 ± 165 cd	16.6 ± 9.5 e	< 5.4
Palm oil mill decanter cake (*n* = 3)	32.2 ± 11.6	70.13 ± 44.92 b	2442 ± 1465 a	75.3 ± 9.7 bc	37.93 ± 1.97 ab
Palm oil mill boiler ash (*n* = 3)	67.4 ± 16.6	175.33 ± 38.19 a	6026 ± 3914 a	745.0 ± 155.7 a	74.00 ± 22.26 a
Wood sawdust (pile top) (*n* = 5)	< 16.7	< 5.4	245 ± 124 cd	18.2 ± 2.2 e	< 5.4
Wood sawdust (pile slope) (*n* = 5)	< 16.7	< 5.4	157 ± 61 d	22.7 ± 8.9 e	< 5.4
P-value (Kruskal-Wallis test)	0.061	0.011	< 0.001	0.001	0.014

†Limit of quantification of the analytical method.
‡Different letters within a column indicate significant difference between wastes according to the Fisher's LSD computed on ranks ($P < 0.05$).

There were differences between wastes for micronutrients whose concentrations were above the LOQs, except for B, which did not differ in concentration between oil palm empty fruit bunch, decanter cake, and boiler ash (Table 4). The highest mean Cu concentration (175.3 mg kg^{-1}) occurred in the boiler ash. However, this waste may not be a rapid-release Cu source due to a probable low Cu solubility, which is a common characteristic in plant biomass ashes (Steenari et al., 1999). But, as this solubility increases with increasing acidity (Maresca et al., 2017), application of boiler ash to a very acid soil could increase the release of Cu from the waste. On the other hand, this soil acidity effect could be neutralized by an increase in soil pH induced by the boiler ash alkalinity (see the high pH of this waste in Table 1), decreasing the Cu availability to plants (Fageria et al., 2002). This possible antagonistic effect, however, need to be further investigated. Decanter cake in turn could be a better Cu source because it has a relevant mean Cu concentration (70.1 mg kg^{-1}) and low pH (see in Table 1). Cu-rich acid organic waste seems to be more efficient in supplying Cu to plants than the same type of waste with an alkaline reaction (Pires and Mattiazzo, 2003). Empty fruit bunch, fruit fiber, and fruit shell were very low in Cu (< 16 mg kg^{-1}), therefore they have limited potential as Cu sources. Fe concentration varied greatly between wastes. The highest mean values were observed in eucalyptus charcoal (3029 mg kg^{-1} Fe), decanter cake (2442 mg kg^{-1} Fe), and boiler ash (6026 mg kg^{-1} Fe) and the lowest mean values in the wood sawdust of both top and slope of the pile (245 and 157 mg kg^{-1}, respectively). The other wastes had intermediate mean concentrations, but not higher than 1000 mg kg^{-1} Fe. Despite these large differences, use of these wastes as Fe sources for crops in the Brazilian Amazon is of secondary importance, due to the lack of records on Fe deficiency in crops in this region. Boiler ash also had the highest mean Mn concentration (745 mg kg^{-1}), possibly caused by a concentration effect during combustion. Increase in Mn concentration has been observed with the burning of plant biomass (Etiégni and Campbell, 1991). The other wastes had less than 110 mg kg^{-1} Mn, which reduces their potential as Mn sources. Similarly to Cu, Fe, and Mn, the highest mean Zn concentration (74 mg kg^{-1}) occurred in the boiler ash. However, Zn solubility in this waste tends to be low, since various plant biomass ashes have shown such characteristic (Steenari et al., 1999). Decanter cake had half the mean Zn concentration of the boiler ash (38 mg kg^{-1}). However, Zn in the decanter cake is believed to be more soluble than that in the boiler ash, since Zn solubility has been higher in wastes derived from fresh plant tissues (Rodríguez-Espinosa et al., 2023) than in material resulting from plant biomass combustion (Steenari et al., 1999). Thus, Zn from the decanter cake may be released into the soil more rapidly. Furthermore, the high acidity of this waste (Table 1) tends to maintain the soil-released Zn in forms available to plants. Therefore, decanter cake seems to be a promising source of Zn. Cattle manure and empty fruit bunch could be considered other interesting options as Zn sources since they contained appreciable amounts of Zn (32 and 26 mg kg^{-1}, respectively). However, these wastes had mean pH values close to neutrality (Table 1), which could result in low Zn solubility. Consequently, cattle manure and empty fruit bunch seems to have limited potential to provide Zn to plants. Eucalyptus charcoal and fruit fiber were very low in Zn (< 12 mg kg^{-1}), which reduces their potential as Zn sources.

Na, Al, and potentially toxic elements

There were differences between wastes for Na concentration (Table 5). Eucalyptus charcoal had the highest mean Na concentration (1489 mg kg^{-1}), while the lowest one occurred in the fruit fiber (55 mg kg^{-1} Na). The other wastes had intermediate mean concentrations ranging from 102 to 657 mg kg^{-1} Na. Although Na is considered a beneficial element for plants (Ma et al., 2023), addition of excess Na can salinize the soil and thus cause salt stress in plants limiting the crop production (Subbarao et al., 2003; Kronzucker et al., 2013). Therefore, eucalyptus charcoal, which contains a high Na concentration, should be used carefully in order to avoid soil salinization, since this process

Table 5
Concentration of Na, Al, and potentially toxic elements in organic wastes typical of the Brazilian Amazon. Each value is a mean ± standard deviation (n).

Waste	Na (mg kg^{-1})	Al (mg kg^{-1})	Ba (mg kg^{-1})	Cr (mg kg^{-1})
Cattle manure	628.4 ± 313.9 (5) ab†	2005.6 ± 459.2 (5) a	8.08 ± 3.70 (5) a	1.46 ± 0.60 (5) d
Residual eucalyptus charcoal	1489.0 ± 72.1 (2) a	5159.5 ± 3380.7 (2) a	6.40 ± 0.57 (2) a	3.75 ± 2.62 (2) bc
Oil palm empty fruit bunch	129.9 ± 52.5 (3) cd	111.0 ± 56.9 (3) cd	< 1.0‡	2.60 ± 1.77 (3) cd
Oil palm fruit fiber	55.1 ± 14.2 (3) d	231.0 ± 179.0 (3) bc	< 1.0	4.83 ± 2.01 (3) bc
Oil palm fruit shell	279.6 ± 418.5 (3) cd	40.5 ± 31.4 (3) d	< 1.0	7.13 ± 2.75 (3) ab
Palm oil mill decanter cake	255.0 ± 128.7 (3) bc	625.3 ± 561.0 (3) ab	< 1.0	7.77 ± 2.79 (3) ab
Palm oil mill boiler ash	657.0 ± 296.4 (3) ab	3959.3 ± 6373.2 (3) ab	4.20 ± 1.98 (2) ab	10.40 ± 4.16 (3) a
Wood sawdust (pile top)	101.7 ± 54.7 (5) cd	95.3 ± 64.6 (5) cd	1.65 ± 0.47 (4) b	< 0.6
Wood sawdust (pile slope)	172.4 ± 43.7 (5) c	66.0 ± 16.3 (5) d	< 1.0	< 0.6
P-value (Kruskal-Wallis test)	0.005	0.003	0.032	0.014

†Different letters within a column indicate significant difference between wastes according to the Fisher's LSD computed on ranks ($P < 0.05$).
‡Limit of quantification of the analytical method.

causes serious negative impacts on agriculture and also on the environment (Shahid et al., 2018).

There were differences between wastes also for Al concentration, despite the high variability of the data (Table 5). The highest mean Al concentrations occurred in eucalyptus charcoal (5160 mg kg^{-1}), boiler ash (3959 mg kg^{-1}), and cattle manure (2006 mg kg^{-1}). These concentrations were much higher than those of other wastes, whose means ranged from 41 to 625 mg kg^{-1}. Applications of high-Al wastes in soils can be harmful to growth and production of crops, since Al is highly toxic to many cultivated plants (Foy et al., 1978; Kochian et al., 2015). Therefore, fertilizer use of the wastes evaluated in the present work, particularly those more concentrated in Al, should be accompanied by adequate monitoring of Al availability in the soil and Al status in plants.

The potentially toxic elements As, Cd, Hg, and Pb were below their LOQs (< 1.0, < 0.2, < 1.0, and < 2.9 mg kg^{-1}, respectively) in all wastes. Se was also below the LOQ (< 1.0 mg kg^{-1}) in almost all wastes. It was quantified only in two samples of fruit shell (6.6 and 11.6 mg kg^{-1} Se), one sample of fruit fiber (5.7 mg kg^{-1} Se), and one sample of boiler ash (3.2 mg kg^{-1} Se). Ba and Cr were below the LOQ (< 1.0 and < 0.6 mg kg^{-1}, respectively) in some wastes and above in others (Table 5). In these latter wastes, the mean Ba concentrations in cattle manure (8.1 mg kg^{-1}) and eucalyptus charcoal (6.4 mg kg^{-1}) were similar to that in the boiler ash (4.2 mg kg^{-1}) and higher than that in the wood sawdust of the pile top (1.7 mg kg^{-1}). In the other wastes, Ba was below the LOQ. The mean Cr concentration in the boiler ash (10.4 mg kg^{-1}) was similar to those in fruit shell (7.1 mg kg^{-1}) and decanter cake (7.8 mg kg^{-1}) and higher than those in cattle manure (1.5 mg kg^{-1}), eucalyptus charcoal (3.8 mg kg^{-1}), empty fruit bunch (2.6 mg kg^{-1}), and fruit fiber (4.8 mg kg^{-1}). Cr was below the LOQ in wood sawdust of both top and slope of the pile. The concentrations of As, Cd, Hg, Pb, and Se in the wastes evaluated in this study are below the maximum limits allowed for organic fertilizers in Brazil (20, 3, 1, 150, 80 mg kg^{-1}, respectively) (Brasil, 2016). The concentrations of Ba and Cr are in turn well below the maximum limit allowed for high-quality biosolids generated in Brazilian sewage treatment plants (1300 and 1000 mg kg^{-1}, respectively) (Brasil, 2020). Therefore, the wastes evaluated here present a low risk of soil contamination with these potentially toxic elements.

Sum and ratio of macronutrients

Fig. 1A shows the sum of the concentration of all macronutrients in the wastes. Palm oil mill boiler ash was the most concentrated in primary macronutrients (N, P, and K) (Fig. 1B), secondary macronutrients (Ca, Mg, and S) (Fig. 1C), and consequently in all macronutrients. The second most concentrated in macronutrients was palm oil mill decanter cake (Fig. 1A). In addition to concentration, these wastes also differed in proportion of primary and secondary macronutrients. Boiler ash was the most concentrated in secondary macronutrients (Fig. 1C), whereas the decanter cake had higher concentration of primary macronutrients (Fig. 1B). This difference may affect the valorization of these wastes as organic fertilizers, since more value is given to materials with a higher concentration of primary macronutrients.

The ratio among primary macronutrients is useful for comparing mineral fertilizers with different concentrations of N, P, and K (Hignett, 1985). We freely apply this concept to our wastes and the results in elemental and oxide basis are shown in Table 6. All wastes seem to be as NK fertilizers, except the palm oil mill boiler ash, which has characteristic of a PK fertilizer. The oil palm empty fruit bunch, although similar to a NK fertilizer, is more heavily loaded in K. These characteristics could be used to better indicate the use of wastes as organic fertilizers according to soil and crop needs.

C/N and CEC/C ratios

The wastes differed in C/N ratio (Fig. 2A) according to the following sequence: palm oil mill decanter cake (14) < palm oil mill boiler ash (24) = cattle manure (26) < residual eucalyptus charcoal (82) = and oil palm fruit shell (85) < wood sawdust of the pile slope (125) < wood sawdust of the pile top (167). None of these wastes had a mean C/N ratio below the maturity index established for organic materials (< 12; Bernal et al., 1998a). This suggests that, if applied to a soil, any waste above could induce N immobilization and consequently appearance of N deficiency in plants. This possibility is based on the fact that organic material with a high C/N ratio generally increases the amount of immobilized N, resulting in N-deficient plants (Bernal et al., 1998b).

CEC/C ratio is another index to assess the maturity of an organic material and its advantage is that it is not affected by high NH_4^+–N concentrations as is the C/N ratio (Roig et al., 1988). Concentrations of NH_4^+–N in the wastes included in this work were very low (Table 3). Even so, this index was used as an auxiliary criterion to assess the maturity of these wastes, since it is calculated using another measure (i.e., CEC) not included in the C/N ratio. Fig. 2B shows the differences between wastes for the CEC/C ratio. The results were the inverse of those of the C/N ratio. Wastes with low C/N ratio had high CEC/C ratio. Considering the maturity index for manures suggested by Roig et al. (1988), 1.7, no CEC/C ratio value was above this limit, corroborating the C/N ratio results.

Thus, to avoid possible immobilization of N in soil during plant growth by application of these wastes with high C/N ratio and low CEC/C ratio, at least two measures could be adopted. The first would be to apply the wastes well before sowing or planting (Bernal et al., 1998b). Alternatively, the wastes could be submitted to composting before being applied to the soil (Bernal et al., 1998b). Determination of other characteristics, e.g., water soluble organic C/organic N ratio (Bernal et al., 1998a) and biodegradable organic C/N ratio (Puyuelo et al., 2011), could provide further evidence for the need of composting or early application of the wastes, mainly those containing significant amounts of recalcitrant C. This more specific characterization should be explored in future studies.

Conclusions

To our knowledge, this is the first work that collectively evaluated the composition of different organic wastes typical of the Brazilian

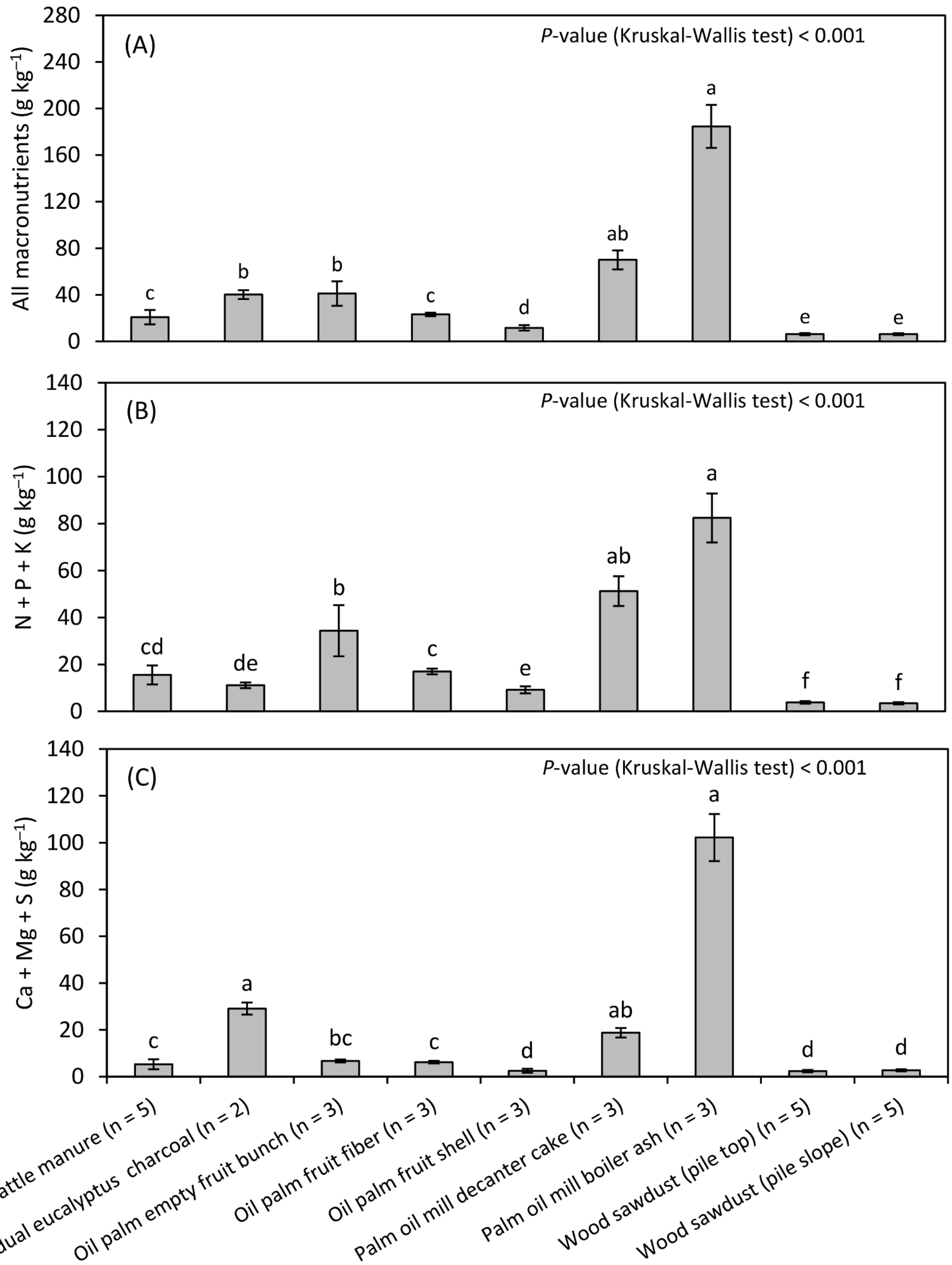

Fig. 1. Sum of the concentration of all macronutrients (A), N + P + K (B), and Ca + Mg +S (C) in organic wastes typical of the Brazilian Amazon. The vertical line on each bar represents the standard deviation. Different letters on the bars indicate significant difference between wastes according to the Fisher's LSD computed on ranks ($P < 0.05$).

Table 6
Ratio between nutrients in organic wastes typical of the Brazilian Amazon.

Waste	N:P:K ratio	$N:P_2O_5:K_2O$ ratio
Cattle manure	12:1:2	5:1:1
Residual eucalyptus charcoal	9:1:10	4:1:5
Oil palm empty fruit bunch	10:1:23	4:1:12
Oil palm fruit fiber	13:1:6	6:1:3
Oil palm fruit shell	14:1:7	6:1:4
Palm oil mill decanter cake	12:1:7	5:1:3
Palm oil mill boiler ash	1:16:39	1:37:47
Wood sawdust (pile top)	118:1:8	51:1:4
Wood sawdust (pile slope)	96:1:18	42:1:9

Amazon for potential use as organic fertilizers. The wastes collected in this region showed different characteristics. Palm oil mill boiler ash was highly concentrated in P, K, Ca, and Mg and also highly alkaline, being therefore considered a promising material for use as fertilizer and lime in acid soils. On the other hand, it had the lowest organic C content and CEC, which limits its potential to improve the soil fertility for a long term. Palm oil mill decanter cake was the best N source by combining higher N concentration and lower C/N ratio. It also had an appreciable K amount and the highest S concentration, as well as an interesting potential to provide Zn. Cattle manure was more concentrated in N and oil palm empty fruit bunch in K, i.e., the former being essentially considered a N source and the latter a typical K source. Residual eucalyptus charcoal

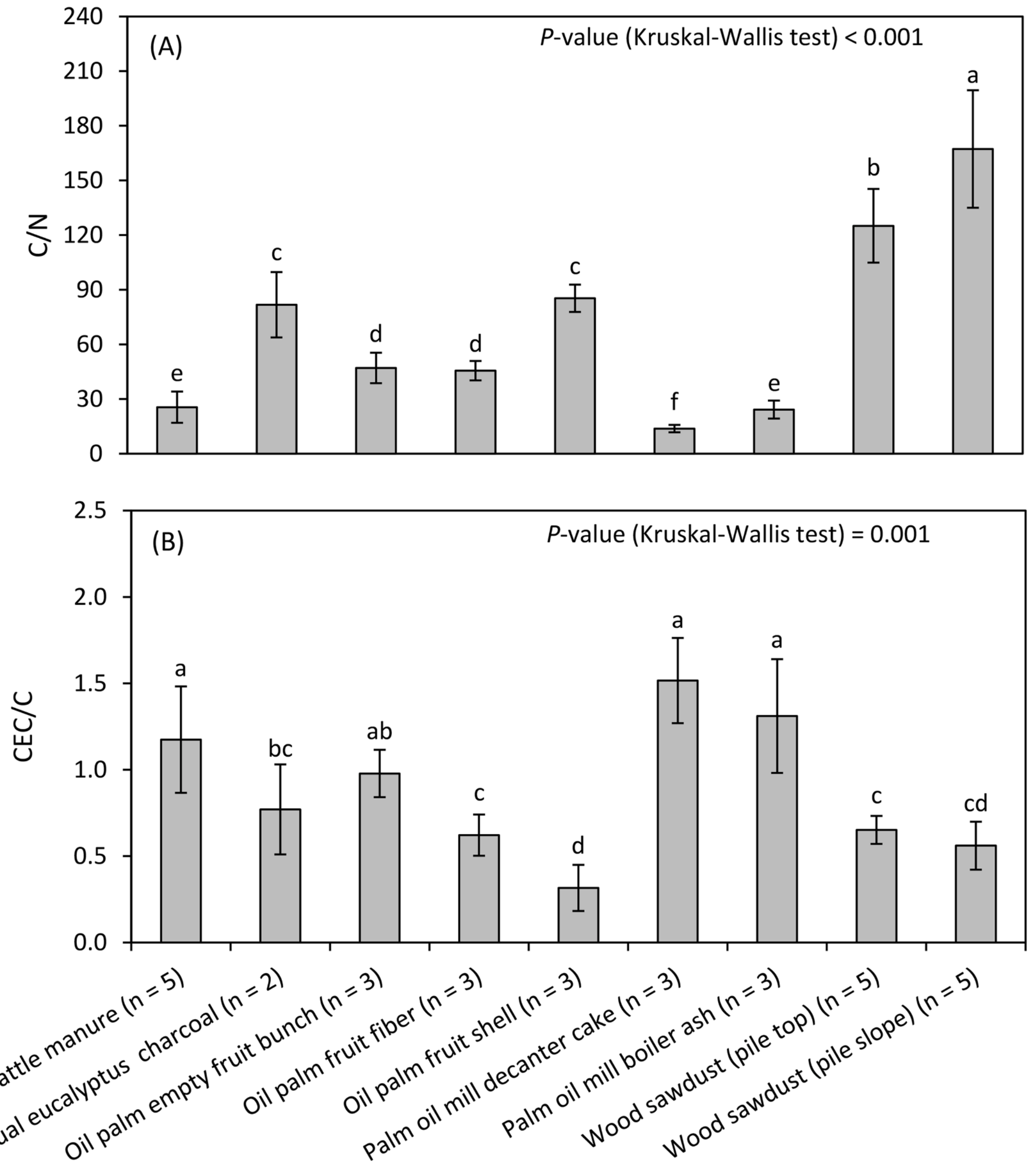

Fig. 2. C/N ratio (A) and CEC/C ratio (B) in organic wastes typical of the Brazilian Amazon. The vertical line on each bar represents the standard deviation. Different letters on the bars indicate significant difference between wastes according to the Fisher's LSD computed on ranks ($P < 0.05$).

in turn was a Ca-rich material but on the other hand it had high Na and Al concentrations, which restricts its use as an organic fertilizer in situations where addition of at least one of these two elements may be harmful to plants. Oil palm fruit fiber, oil palm fruit shell, wood sawdust of the pile slope, and wood sawdust of the pile top were consistently poor in nutrients, demonstrating low potential as organic fertilizers. All wastes presented low concentrations of As, Ba, Cd, Cr, Hg, Pb, and Se, indicating a low risk of soil contamination with potentially toxic elements. This study identified organic wastes differing in prevalent nutrients for potential use as organic fertilizers. Such a difference could be explored in further studies by combining two or more wastes with complementary prevalent nutrients in order to better meet the nutritional requirements of different crops in the Brazilian Amazon.

CRediT authorship contribution statement

Alysson Roberto Baizi e Silva: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Vinícius Ide Franzini:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

We thank all farmers who provided the wastes characterized in this study. We also thank Celso M. da Mota Brito for helping us with the collection of the waste samples. This work was supported by the Brazilian Agricultural Research Corporation (Embrapa) (ASQ Project, Activity 02.13.14.013.00.02.007).

References

Adriano, D.C., 2001. Trace Elements in Terrestrial Environments: Biogeochemistry, Bioavailability, and Risks of Metals. Springer, New York.

Arndt, C., Diao, X., Dorosh, P., Pauw, K., Thurlow, J., 2023. The Ukraine war and rising commodity prices: implications for developing countries. Glob. Food Secur. 36, 100680 https://doi.org/10.1016/j.gfs.2023.100680.

Arnhold, E., 2013. Package in the R environment for analysis of variance and complementary analyses. Braz. J. Vet. Res. Anim. Sci. 50, 488–492. https://doi.org/10.11606/issn.1678-4456.v50i6p488-492.

Augusto, L., Bakker, M.R., Meredieu, C., 2008. Wood ash applications to temperate forest ecosystems – potential benefits and drawbacks. Plant Soil 306, 181–198. https://doi.org/10.1007/s11104-008-9570-z.

Bernal, M.P., Paredes, C., Sánchez-Monedero, M.A., Cegarra, J., 1998a. Maturity and stability parameters of composts prepared with a wide range of organic wastes. Bioresour. Technol. 63, 91–99. https://doi.org/10.1016/S0960-8524(97)00084-9.

Bernal, M.P., Navarro, A.F., Sánchez-Monedero, M.A., Roig, A., Cegarra, J., 1998b. Influence of sewage sludge compost stability and maturity on carbon and nitrogen mineralization in soil. Soil Biol. Biochem. 30, 305–313. https://doi.org/10.1016/S0038-0717(97)00129-6.

Brasil, 2017. Manual de Métodos Analíticos Oficiais para Fertilizantes e Corretivos. MAPA, Brasília.

Brasil, 2016. Instrução Normativa SDA no. 7, 12 de abril de 2016, republicada em 02 de maio de 2016. https://pesquisa.in.gov.br/imprensa/jsp/visualiza/index.jsp?jornal=1&data=02/05/2016&pagina=9.

Brasil, 2020. Resolução do CONAMA no. 498, de 19 de agosto de 2020. Define critérios e procedimentos para aplicação de biossólido, e dá outras providências. https://conama.mma.gov.br/index.php?option=com_sisconama&task=arquivo.download&id=797.

Braz, S.P., Junior, Nascimento, do, D., Cantarutti, R.B., Regazzi, A.J., Martins, C.E., Fonseca, D.M.da, Barbosa, R.A., 2002. Aspectos quantitativos do processo de reciclagem de nutrientes pelas fezes de bovinos sob pastejo em pastagem de *Brachiaria decumbens* na Zona da Mata de Minas Gerais. Rev. Bras. Zootec. 31, 858–865. https://doi.org/10.1590/S1516-35982002000400008.

Brod, E., Øgaard, A.F., Hansen, E., Wragg, D., Haraldsen, T.K., Krogstad, T., 2015. Waste products as alternative phosphorus fertilisers part I: inorganic P species affect fertilisation effects depending on soil pH. Nutr. Cycl. Agroecosyst. 103, 167–185. https://doi.org/10.1007/s10705-015-9734-1.

Cakmak, I., Brown, P., Colmenero-Flores, J.M., Husted, M., Kutman, B.Y., Nikolic, M., Rengel, Z., Schmidt, S.B., Zhao, F.J., 2023. Micronutrients. In: Rengel, Z., Cakmak, I., White, P.J. (Eds.), Marschner's Mineral Nutrition of Plants. Academic Press, London, pp. 283–385.

Chakraborty, A., Chakrabarti, K., Chakraborty, A., Ghosh, S., 2011. Effect of long-term fertilizers and manure application on microbial biomass and microbial activity of a tropical agricultural soil. Biol. Fertil. Soils 47, 227–233. https://doi.org/10.1007/s00374-010-0509-1.

Chavalparit, O., Rulkens, W., Mol, A.P.J., Khaodhair, S., 2006. Options for environmental sustainability of the crude palm oil industry in Thailand through enhancement of industrial ecosystems. Environ. Dev. Sustain. 8, 271–287. https://doi.org/10.1007/s10668-005-9018-z.

Chew, C.L., Ng, C.Y., Hong, W.O., Wu, T.Y., Lee, Y.Y., Low, L.E., Kong, P.S., Chan, E.S., 2021. Improving sustainability of palm oil production by increasing oil extraction rate: a review. Food Bioprocess Technol 14, 573–586. https://doi.org/10.1007/s11947-020-02555-1.

Chojnacka, K., Moustakas, K., Witek-Krowiak, A., 2020. Bio-based fertilizers: a practical approach towards circular economy. Bioresour. Technol. 295, 122223 https://doi.org/10.1016/j.biortech.2019.122223.

Conover, W.J., 1999. Practical Nonparametric Statistics, 3rd ed. John Wiley & Sons, New York.

Dagna, N.E., Mallarino, A.P., 2014. Beef cattle manure survey and assessment of crop availability of phosphorus by soil testing. Soil Sci. Soc. Am. J. 78, 1035–1050. https://doi.org/10.2136/sssaj2013.06.0223.

Demeyer, A., Voundi Nkana, J.C., Verloo, M.G., 2001. Characteristics of wood ash and influence on soil properties and nutrient uptake: an overview. Bioresour. Technol. 77, 287–295. https://doi.org/10.1016/S0960-8524(00)00043-2.

de Abreu, M.F., de Andrade, J.C., de Arruda Falcão, A.de, 2006. Protocolos de análises químicas. Andrade, J.C. de, Abreu, M.F. de Análise Química De Resíduos Sólidos Para Monitoramento e Estudos agroambientais. Instituto Agronômico. Campinas, pp. 121–458.

Edmeades, D.C., 2003. The long-term effects of manures and fertilisers on soil productivity and quality: a review. Nutr. Cycl. Agroecosyst. 66, 165–180. https://doi.org/10.1023/A:1023999816690.

Etiégni, L., Campbell, A.G., 1991. Physical and chemical characteristics of wood ash. Bioresour. Technol. 37, 173–178. https://doi.org/10.1016/0960-8524(91)90207-Z.

Ezemagu, I.G., Ejimofor, M.I., Menkiti, M.C., Diyoke, C., 2021. Biofertilizer production via composting of digestate obtained from anaerobic digestion of post biocoagulation sludge blended with saw dust: physiochemical characterization and kinetic study. Environ. Chall. 5, 100288 https://doi.org/10.1016/j.envc.2021.100288.

Fageria, N.K., Baligar, V.C., Clark, R.B., 2002. Micronutrients in crop production. Adv. Agron. 77, 185–268. https://doi.org/10.1016/S0065-2113(02)77015-6.

Ferreira, W., de, A., Botelho, S.M., Vilar, R.R.L., 1998. Resíduos Da Agroindústria Do dendê: Caracterização e Equivalência Em Fertilizantes. Embrapa Amazônia Oriental, Belém. https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/375583/1/CPATUBP198.pdf.

Foy, C.D., Chaney, R.L., White, M.C., 1978. The physiology of metal toxicity in plants. Ann. Rev. Plant Physiol. 29, 511–566. https://doi.org/10.1146/annurev.pp.29.060178.002455.

Haynes, R., Naidu, R., 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. Nutr. Cycl. Agroecosyst. 51, 123–137. https://doi.org/10.1023/A:1009738307837.

Hawkesford, M., Cakmak, I., Coskun, D., De Kok, L.J., Lambers, H., Schjoerring, J.K., White, P.J., 2023. Functions of macronutrients. In: Marschner, P. (Ed.), Marschner's Mineral Nutrition of Higher Plants, Third ed. Academic Press, San Diego, pp. 201–281.

Hignett, T.P., 1985. Fertilizer Manual. Springer Science+Business Media, Dordrecht.

IBGE, 2021. Pesquisa pecuária municipal – PPM. https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9107-producao-da-pecuaria-municipal.html?=&t=resultados/(accessed 28 November 2022).

IBGE, 2021. Produção agrícola municipal – PAM. https://sidra.ibge.gov.br/tabela/1613#resultado (accessed 29 November 2022).

Johnston, A.E., 1997. The value of long-term field experiments in agricultural, ecological, and environmental research. Adv. Agron. 59, 291–333. https://doi.org/10.1016/S0065-2113(08)60057-7.

Keiblinger, K.M., Bauer, L.M., Deltedesco, E., Holawe, F., Unterfrauner, H., Zehetner, F., Peticzka, R., 2016. Quicklime application instantly increases soil aggregate stability. Int. Agrophys. 30, 123–128. https://doi.org/10.1515/intag-2015-0068.

Khanna, P.K., Raison, R.J., Falkiner, R.A., 1994. Chemical properties of ash derived from *Eucalyptus* litter and its effects on forest soils. For. Ecol. Manage. 66, 107–125. https://doi.org/10.1016/0378-1127(94)90151-1.

Kirchmann, H., Witter, E., 1992. Composition of fresh, aerobic and anaerobic farm animal dungs. Bioresour. Technol. 40, 137–142. https://doi.org/10.1016/0960-8524(92)90199-8.

Kochian, L.V., Piñeros, M.A., Liu, J., Magalhaes, J.V., 2015. Plant adaptation to acid soils: the molecular basis for crop aluminum resistance. Annu. Rev. Plant Biol. 66, 571–598. https://doi.org/10.1146/annurev-arplant-043014-114822.

Kronzucker, H.J., Coskun, D., Schulze, L.M., Wong, J.T., Britto, D.T., 2013. Sodium as nutrient and toxicant. Plant Soil 369, 1–23. https://doi.org/10.1007/s11104-013-1801-2.

Ma, J.F., Zhao, F.J., Rengel, Z., Cakmak, I., 2023. Beneficial elements. In: Rengel, Z., Cakmak, I., White, P.J. (Eds.), Marschner's Mineral Nutrition of Plants. Academic Press, London, pp. 387–418.

Mahmood, T., Kamal, A., 2022. Ash properties relevance to beneficial uses. Waste Manag. 141, 282–289. https://doi.org/10.1016/j.wasman.2021.11.018.

Mandal, A., Patra, A.K., Singh, D., Swarup, A., Masto, R.E., 2007. Effect of long-term application of manure and fertilizer on biological and biochemical activities in soil during crop development stages. Bioresour. Technol. 98, 3585–3592. https://doi.org/10.1016/j.biortech.2006.11.027.

Maresca, A., Hyks, J., Astrup, T.F., 2017. Recirculation of biomass ashes onto forest soils: ash composition, mineralogy and leaching properties. Waste Manag. 70, 127–138. https://doi.org/10.1016/j.wasman.2017.09.008.

Melo, L.C.A., Silva, C.A., de Oliveira Dias, B., 2008. Caracterização da matriz orgânica de resíduos de origens diversificadas. Rev. Bras. Cienc. Solo 32, 101–110. https://doi.org/10.1590/S0100-06832008000100010.

Miller, C.M.F., Heguy, J.M., Karle, B.M., Price, P.L., Meyer, D., 2019. Optimizing accuracy of sampling protocols to measure nutrient content of solid manure. Waste Manag 85, 121–130. https://doi.org/10.1016/j.wasman.2018.12.021.

Misra, M.K., Ragland, K.W., Baker, A.J., 1993. Wood ash composition as a function of furnace temperature. Biomass Bioenergy 4, 103–116. https://doi.org/10.1016/0961-9534(93)90032-Y.

Ngo, H.T.T., Watts-Williams, S.J., Panagaris, A., Baird, R., McLaughlin, M.J., Cavagnaro, T.R., 2022. Development of an organomineral fertiliser formulation that improves tomato growth and sustains arbuscular mycorrhizal colonization. Sci. Total Environ. 815, 151977 https://doi.org/10.1016/j.scitotenv.2021.151977.

Oliveira, R.F., de, Furlan, Júnior, J., Teixeira, L.B., 2006. Composição Química De Cinzas De Caldeira Da Agroindústria Do Dendê. Embrapa Amazônia Oriental, Belém. https://www.infoteca.cnptia.embrapa.br/bitstream/doc/408574/1/com.tec.155.pdf.

Pagliari, P.H., Wilson, M., Waldrip, H.M., He, Z., 2019. Nitrogen and phosphorus characteristics of beef and dairy manure. In: Waldrip, H.M., Pagliari, P.H., He, Z. (Eds.), Animal Manure: Production, Characteristics, Environmental Concerns, and Management. America Society of Agronomy and Soil Science Society of America, Madison, pp. 45–62.

Pardon, L., Bessou, C., Nelson, P.N., Dubos, B., Ollivier, J., Marichal, R., Caliman, J.P., Gabrielle, B., 2016. Key unknowns in nitrogen budget for oil palm plantations. A review. Agron. Sustain. Dev. 36, 20. https://doi.org/10.1007/s13593-016-0353-2.

Peana, M., Medici, S., Dadar, M., Zoroddu, M.A., Pelucelli, A., Chasapis, C.T., Bjørklund, G., 2021. Environmental barium: potential exposure and health-hazards. Arch. Toxicol. 95, 2605–2612. https://doi.org/10.1007/s00204-021-03049-5.

Pires, A.M.M., Mattiazzo, M.E., 2003. Biosolids conditioning and the availability of Cu and Zn for rice. Sci. Agric. 60, 161–166. https://doi.org/10.1590/S0103-90162003000100024.

Prochnow, L.I., Cunha, C.F., Kiehl, J.C., Alcarde, J.C., 2001. Controle da volatilização de amônia em compostagem, mediante adição de gesso agrícola e superfosfatos com diferentes níveis de acidez residual. Rev. Bras. Cienc. Solo 25, 65–70. https://doi.org/10.1590/S0100-06832001000100007.

Puyuelo, B., Ponsá, S., Gea, T., Sánchez, A., 2011. Determining C/N ratios for typical organic wastes using biodegradable fractions. Chemosphere 85, 653–659. https://doi.org/10.1016/j.chemosphere.2011.07.014.

Quesada, C.A., Lloyd, J., Anderson, L.O., Fyllas, N.M., Schwarz, M., Czimczik, C.I., 2011. Soils of Amazonia with particular reference to the RAINFOR sites. Biogeosciences 8, 1415–1440. https://doi.org/10.5194/bg-8-1415-2011.
Ramos, W.F., Ruivo, M.de L.P., Jardim, M.A.G., Porro, R., Castro, R.M.da S., Souza, L.M. de., 2017. Análise da indústria madeireira na Amazônia: gestão, uso e armazenamento de resíduos. Revista Brasileira de Ciências Ambientais 43, 1–16. https://doi.org/10.5327/Z2176-947820170057.
R Core Team, 2021. R: A language and Environment For Statistical Computing (Version 4.1.1). R Foundation for Statistical Computing.
Rodella, A.A., Fischer, K.R., Alcarde, J.C., 1995. Cation exchange capacity of an acid soil as influenced by different sources of organic litter. Commun. Soil Sci. Plant Anal. 26, 2691–2967. https://doi.org/10.1080/00103629509369500.
Roig, A., Lax, A., Cegarra, J., Costa, P., Hernandez, M.T., 1988. Cation exchange capacity as a parameter for measuring the humification degree of manures. Soil Sci 146, 311–316.
Rodrigues, T.E., 1996. Solos da Amazônia. Alvarez V., V.H., Fontes, L.E.F., Fontes, M.P.F. Solo Nos Grandes Domínios Morfoclimáticos do Brasil e o Desenvolvimento Sustentado. SBCS, UFV, DPS, Viçosa, pp. 19–60.
Rodríguez-Espinosa, T., Navarro-Pedreño, J., Gómez Lucas, I., Almendro Candel, M.B., Pérez Gimeno, A., Zorpas, A.A., 2023. Soluble elements released from organic wastes to increase available nutrients for soil and crops. Appl. Sci. 13, 1151. https://doi.org/10.3390/app13021151.
Schaefer, C.E.G.R., Lima, H.N de, Teixeira, W.G., Vale Jr., J.F., do, V., Souza, K.W.de, Corrêia, G.R., Mendonça, B.A.F.de, Amaral, E.F., Campos, M.C.C., Ruivo, M.de L.P., 2017. Solos da região amazônica. In: Curi, N., Ker, J.C., Novais, R.F., Vidal-Torrado, P., Schaefer, C.E.G.R. (Eds.), Pedologia – Solos dos Biomas Brasileiros. Sociedade Brasileira de Ciência do Solo, Viçosa, pp. 111–175.
Schnug, E., Oswald, P., Haneklaus, S., 1996. Organic manure management and efficiency: role of organic fertilizers and their management practices. In: Rodriguez-Barrueco, C. (Ed.), Fertilizers and Environment. Springer, Dordrecht, pp. 259–265.
Schröder, J., 2005. Revisiting the agronomic benefits of manure: a correct assessment and exploitation of its fertilizer value spares the environment. Bioresour. Technol. 96, 253–261. https://doi.org/10.1016/j.biortech.2004.05.015.
Shahid, S.A., Zaman, M., Heng, L., 2018. Introduction to soil salinity, sodicity and diagnostics techniques. Zaman, M., Shahid, S.A., Heng, L. Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques. Springer International Publishing, Cham, pp. 1–42.
Sharma, B., Vaish, B., Monika Singh, U.K., Singh, P., Singh, R.P., 2019. Recycling of organic wastes in agriculture: an environmental perspective. Int. J. Environ. Res. 13, 409–429. https://doi.org/10.1007/s41742-019-00175-y.
Siang, C.S., Wahid, S.A.A., Sung, C.T.B., 2022. Standing biomass, dry-matter production, and nutrient demand of tenera oil palm. Agronomy 12, 426. https://doi.org/10.3390/agronomy12020426.
Sindifer, 2022. Statistical Yearbook. http://sindifer.com.br/sndfr/anuario-estatistico/. accessed 28 November 2022.
Someshwar, A.V., 1996. Wood and combination wood-fired boiler ash characterization. J. Environ. Qual. 25, 962–972. https://doi.org/10.2134/jeq1996.00472425002500050006x.
Steenari, B.M., Karlsson, L.G., Lindqvist, O., 1999. Evaluation of the leaching characteristics of wood ash and the influence of ash agglomeration. Biomass Bioenergy 16, 119–136. https://doi.org/10.1016/S0961-9534(98)00070-1.
Steenari, B.M., Lindqvist, O., 1997. Stabilisation of biofuel ashes for recycling to forest soil. Biomass Bioenergy 13, 39–50. https://doi.org/10.1016/S0961-9534(97)00024-X.
Subbarao, G.V., Ito, O., Berry, W.L., Wheeler, R.M., 2003. Sodium–a functional plant nutrient. Crit. Rev. Plant Sci. 22, 391–416. https://doi.org/10.1080/07352680390243495.
Ulery, A.L., Graham, R.C., Amrhein, C., 1993. Wood-ash composition and soil pH following intense burning. Soil Sci. 156, 358–364.
USDA, 2022. Impacts and Repercussions of Price Increases On the Global Fertilizer Market. https://www.fas.usda.gov/data/impacts-and-repercussions-price-increases-global-fertilizer-market. accessed 28 November 2022.
USEPA, 1995. Test Methods For Evaluating Solid waste, Physical/Chemical methods, EPA Publication SW-846, Third ed. EPA, Washington.
Vassilev, S.V., Baxter, D., Andersen, L.K., Vassileva, C.G., 2013. An overview of the composition and application of biomass ash. Part 1. Phase–mineral and chemical composition and classification. Fuel 105, 40–76. https://doi.org/10.1016/j.fuel.2012.09.041.
Zebarth, B.J., Neilsen, G.H., Hogue, E., Neilsen, D., 1999. Influence of organic waste amendments on selected soil physical and chemical properties. Can. J. Soil Sci. 79, 501–504. https://doi.org/10.4141/S98-074.