

Effects of Household Waste Compost and Wood Ash on the Physico-Chemical Properties of A Tropical Sandy Soil: Case of A Ferralitic Soil from Brazzaville (Congo)

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Abstract The ferralitic sandy soils of peri-urban Brazzaville (Republic of Congo) are acidic, poor in organic matter (OM) and have a low cation exchange capacity (CEC). This study evaluated, after a 14-day incubation and before any crop cultivation, the effects of seven treatments on the physico-chemical properties of such a soil: T0 (control); T1-T4, wood ash at 125, 250, 500 and 1,000 g per 5-kg pot (2.5-20% of soil mass); T5, household waste compost (100 g/pot); T6, a 1:1 (w/w) mixture of T1 and T5 soils (≈ 61 g ash + 49 g compost per 5 kg). Pots were arranged in a randomized complete block design with four replicates, and 18 variables were analysed by ANOVA (Tukey HSD) and principal component analysis (PCA). The unamended soil was moderately acid (pH 5.52), with low OM (2.17%), total N (994 mg/kg) and CEC (6.37 cmol(+)/kg). Wood ash (pH 11.0; Ca 15.5%) raised soil pH to 10.21-10.28 (T3-T4), strongly increased Ca, Mg and K, and raised EC up to 1,816 μ S/cm, while TME contents decreased, mainly through dilution. Compost increased total N (up to 1,159 mg/kg in T5) and MWRC. T6 showed the most balanced measured profile: pH 7.86, MWRC 28.8% (highest value), OM 4.40%, CEC 12.11 cmol(+)/kg and N 1,093 mg/kg, with EC (1,311 μ S/cm) lower than in T3-T4. All TME remained below the NF U 44-041 soil limit values. PCA retained three components (89.17% of variance): PC1 (62.85%) opposed the ash-driven mineral enrichment (Ca, Mg, K, pH, EC) to native Fe, Al and TME; PC2 (19.27%) reflected the compost-driven organic gradient (N, MWRC, OM). T6 lay between both gradients, consistent with a complementary effect of the two amendments; this should be validated by crop-response trials.

Keywords: household waste compost, wood ash, ferralitic sandy soil, physico-chemical properties, PCA, Brazzaville, Congo

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1. Introduction

Ferralitic soils represent one of the dominant pedological units of humid intertropical Africa. Characterized by advanced ferralitic weathering of parent material, they are distinguished by accumulation of iron and aluminium as oxides and hydroxides, advanced desilicification, and progressive depletion of basic cations (Ca^{2+} , Mg^{2+} , K^{+}) through leaching under tropical rainfall [1,2]. In the Brazzaville department (Republic of Congo), these soils predominantly display a sandy texture from the Pool Malebo alluvio-aeolian formations, combining structural constraints of sands with chemical limitations of ferrallitization (acidity, reduced CEC, macronutrient deficiency) [3,4].

This convergence of pedological limitations directly

affects the productivity of peri-urban market-gardening systems, essential for food security in Brazzaville [5,6]. Correcting acidity and enriching organic matter are urgent agronomic priorities, but the economic accessibility of mineral fertilizers and agricultural lime remains limited for small producers [7,8]. Organic and mineral amendments from local residues, namely household solid waste compost and domestic wood ash, constitute abundant, accessible alternative inputs [9,10,11].

Wood ash, rich in calcium, magnesium and potassium oxides and carbonates, exerts a strong alkalizing effect on acid soils through the release of hydroxyl ions upon dissolution [9,12,13], as confirmed on acid tropical and hydromorphic soils [14,15]. Household waste compost enriches soil with stable organic matter and mineralizable nitrogen, and improves CEC [10,11,16]. Their effects are expected to be distinct and complementary ash acting primarily on the mineral and acid-base dimension,

compost on the organic and biological dimension and their combined use has been proposed to ameliorate acid tropical soils [17,18].

This study addresses a gap in the local literature by evaluating, through PCA on 18 physico-chemical variables, the comparative and combined effects of seven amendment treatments on ferralitic sandy soils of Brazzaville, before any crop establishment. Three specific objectives were pursued: (i) to characterize the amendments and the reference soil; (ii) to measure the changes induced by seven treatments before crop cultivation; (iii) to identify, through PCA and Pearson correlation matrix, the gradients of variation associated with both amendments.

2. Materials and Methods

2.1. Study Soil and Experimental Site

The study was conducted at the Plant and Life Chemistry Unit (UC2V), Faculty of Science and Technology, Marien NGOUABI University, Brazzaville (4°16'S, 15°17'E, altitude 320 m). The experimental soil, a ferralitic sandy soil representative of peri-urban market garden sites, was collected from the arable layer (0-20 cm), sieved to 2 mm and homogenized before amendment incorporation. This soil falls into the Oxisols (USDA) or Ferralsols (WRB) category, from the alluvio-sandy Pool Malebo geological formations [19,20].

2.2. Amendments Used

Household waste compost (HWC) was prepared in three batches (C1, C2, C3) from organic household biowaste and organic adjuvants (poultry, rabbit and sheep manure, eggshells), stabilized to physico-chemical maturity. Compost characteristics are reported as mean $\pm$ SD of the three batches ($n = 3$). Wood ash (WA) was collected from urban households burning untreated wood (mainly *Eucalyptus* spp. and *Cassia siamea*). Both amendments were sieved to 2 mm, air-dried and physico-chemically analyzed before incorporation.

2.3. Experimental Design

The experimental unit was a pot containing 5 kg of air-dried soil. Seven pre-cropping treatments were applied: T0 (unamended control); T1 (125 g WA/pot, 2.5% w/w); T2 (250 g WA/pot, 5% w/w); T3 (500 g WA/pot, 10% w/w); T4 (1,000 g WA/pot, 20% w/w); T5 (100 g HWC/pot, 2% w/w); T6, a 1:1 (w/w) mixture of 2.5 kg of T1 soil and 2.5 kg of T5 soil, i.e. ≈ 61 g WA + 49 g HWC per 5-kg pot (WA:HWC mass ratio $\approx 55:45$, half of the T1 and T5 doses). Field-equivalent rates were calculated as: rate (t/ha) = [amendment mass (g) / soil mass (kg)] $\times 10^{-3} \times M$, where M is the mass of soil per hectare in the 0-20 cm layer ($M = 10^4 \text{ m}^2 \times 0.20 \text{ m} \times \text{pb}$). With a soil bulk density $\text{pb} = 1.46 \text{ g/cm}^3$ ($M = 2,920 \text{ t/ha}$), T1-T4 correspond to ≈ 73 , 146, 292 and 584 t/ha, T5 to ≈ 58 t/ha and T6 to ≈ 36 t/ha WA + 29 t/ha HWC. The high doses (T3-T4) exceed usual agronomic practice and were included to describe

the dose-response range. The 28 pots (7 treatments $\times$ 4 replicates) were arranged in a randomized complete block design with four blocks (B1-B4), each block containing one pot of each treatment randomly assigned. Amendments were thoroughly mixed with the soil, and pots were maintained at 60% of MWRC and incubated for 14 days at room temperature ($\approx 25^\circ\text{C}$) before sampling. One composite sample was collected per pot ($n = 4$ per treatment).

2.4. Analytical Methods

pH (NF X 31-103; ISO 10390) and EC (NF X 31-113; ISO 11265) were measured in a 1:5 (w/v) soil:water suspension (10 g of soil in 50 mL of distilled water, stirred for 1 h, left to settle for 30 min and filtered). MWRC was determined by the funnel drainage method: 100 mL of distilled water (V_i) were added to 100 g of soil placed on filter paper in a funnel and allowed to drain for 5 h; the drained volume (V_f) was recorded and MWRC was calculated as $V_i - V_f$ and expressed as % (w/w) [21]. OM was determined by loss on ignition (LOI): 4 g of oven-dried soil were ignited at $1,100^\circ\text{C}$ for 2 h in a muffle furnace (Thermolyne F48055) and OM (%) was calculated from the mass loss relative to the initial dry mass; this procedure may overestimate OM in carbonate-bearing materials [22]. Total Kjeldahl N was determined after sulphuric acid digestion in the presence of a catalyst, distillation and titration (NF ISO 11261). Available P was extracted by the Olsen method (0.5 M NaHCO_3 , pH 8.5) and determined colorimetrically with the molybdate-ascorbic acid reagent (Murphy & Riley; NF EN ISO 6878) at $\lambda = 660 \text{ nm}$. Exchangeable K and Na were extracted with 1 M ammonium acetate (pH 7) and determined by flame emission spectrometry (NF X 31-108). Pseudo-total Ca and Mg were determined in the aqua regia digest (see below) by EDTA complexometric titration: Ca + Mg at pH 10 ($\text{NH}_3/\text{NH}_4\text{Cl}$ buffer, Eriochrome Black T indicator), Ca alone at pH 12-13 (NaOH, murexide/calcon indicator, Mg being precipitated as $\text{Mg}(\text{OH})_2$), and Mg by difference. HCl-extractable Al and Fe were obtained by cold extraction with concentrated HCl (Al: 10 g of soil, 4 $\times$ 25 mL HCl; Fe: 5 g of soil, 15 mL HCl; 15 min contact) and determined spectrophotometrically with Eriochrome cyanine R at 535 nm (Al) and o-phenanthroline at 490 nm (Fe); this procedure does not measure exchangeable Al. CEC was determined at pH 7 by successive percolation with 1 N CaCl_2 , 0.1 N CaCl_2 and 1 N KNO_3 , followed by titration of the displaced Ca^{2+} (EDTA) and Cl^- (AgNO_3), and is expressed in $\text{cmol}(+)/\text{kg}$. Particle size was determined by the Robinson pipette method (NF X 31-107). TME (Cr, Cu, Ni, Pb, Se, Zn) were determined as pseudo-total contents after aqua regia digestion (HCl 37% : HNO_3 65%, 3:1; 1.0 g of sample, 24 h at room temperature then 2 h at 150°C ; NF X 31-415, ISO 11466), by flame atomic absorption spectrometry (Skyscan AAS6000; ISO 11047), Se being determined by hydride generation (Thermo Scientific VP100). A reagent blank was included in each analytical series, calibration used multi-level standard solutions, and the analytical error did not exceed 10% of reference values. Soil limit values refer to NF U 44-041 and compost limit values to NF U 44-051 [23].

2.5. Statistical Analysis

Results are expressed as mean $\pm$ standard deviation (SD) of the four replicate pots ($n = 4$). Treatment effects were tested by one-way analysis of variance (ANOVA), followed by Tukey's HSD test ($\alpha = 0.05$); means sharing the same letter are not significantly different. The block effect, tested in a two-way model (treatment + block), was not significant for 16 of the 18 variables ($p > 0.05$; significant only for OM and K) and did not change the conclusions, so one-way ANOVA results are reported. Normality of residuals and homogeneity of variances were checked with the Shapiro–Wilk and Levene/Brown–Forsythe tests; for variables showing heterogeneous variances, the treatment effect was confirmed by the non-parametric Kruskal–Wallis test ($p < 0.01$ for all variables). PCA was performed on the correlation matrix (variables standardized to zero mean and unit variance) of the 28×18 data matrix (7 treatments $\times$ 4 replicate pots; variables: pH, EC, CEC, MWRC, OM, Al, Fe, N, P, K, Ca, Mg, Cr, Cu, Ni, Pb, Se and Zn); components with eigenvalues > 1 (Kaiser criterion) were retained [24]; sampling adequacy was checked with the Kaiser–Meyer–Olkin (KMO) index and Bartlett's test of sphericity. The overall treatment effect on the 18 variables was tested by a permutational multivariate analysis of variance (PERMANOVA; Euclidean distance on standardized variables, 9,999 permutations). Pearson correlation coefficients were computed on the same 28 observations (critical $|r| = 0.374$ at $p = 0.05$ and 0.479 at $p = 0.01$). Given the limited number of observations relative to variables, PCA was used as a

descriptive tool. ANOVA and mean comparisons were performed with OriginPro 2024 (OriginLab Corporation, Northampton, MA, USA) and checked, together with the PCA, KMO, Bartlett and PERMANOVA analyses, in Python 3.11 (NumPy 2.4, SciPy 1.17, statsmodels 0.15) [25]. The full data matrix and PCA outputs are provided as Supplementary Tables S1–S3.

3. Results and Discussion

3.1. Physico-Chemical Characteristics of the Reference Ferralitic Soil

The reference soil (Table 1) shows the typical properties of a degraded ferralitic sandy soil of the Pool Malebo department. Its sandy texture (88.6% sand) results from advanced ferrallitization concentrating quartz resistant to hydrolysis [1,19,20], and the low clay content (7.58%), mainly kaolinite, is consistent with advanced ferralitic pedogenesis [2]. The moderately acid pH (5.52) reflects the leaching of basic cations and clay mineral hydrolysis [26,27]; at this pH, phosphorus tends to be retained on Fe/Al oxides [28,29]. The very low Ca (15 mg/kg), Mg (10 mg/kg) and exchangeable K (16.0 mg/kg), together with low OM (2.17%) and CEC (6.37 cmol(+)/kg), are characteristic of ferralitic soils cultivated without organic restitution [19]. TME contents are all below the NF U 44-041 soil limit values, indicating a natural pedogeochemical background without anthropogenic contamination.

Table 1. Physico-Chemical Characteristics Of The Reference Ferralitic Sandy Soil Of Brazzaville

Parameter	Measured value	Pedological interpretation
pH	5.52 $\pm$ 0.57	Moderately acid; limits availability of P, Ca, Mg and K
EC (μ S/cm)	148 $\pm$ 9	Very low; no salinity risk
TDS (ppm)	78	Very low soluble ionic reserve
MWRC (%)	12.0 $\pm$ 0.8	Low water retention, sandy soil
Total Kjeldahl N (mg/kg)	994 $\pm$ 13	Low total N ($\approx$ 0.10%)
Available P (Olsen, mg/kg)	105.3 $\pm$ 1.7	P retention by Fe/Al oxides expected in acid medium
Exchangeable K (mg/kg)	16.0 $\pm$ 1.4	Very low exchangeable K ($\approx$ 0.04 cmol(+)/kg)
Ca, pseudo-total (mg/kg)	15 $\pm$ 1	Very low Ca reserve
Mg, pseudo-total (mg/kg)	10 $\pm$ 1	Very low Mg reserve
HCl-extractable Al (mg/kg)	30.5 $\pm$ 3.1	Exchangeable (toxic) Al not measured
HCl-extractable Fe (mg/kg)	4,413 $\pm$ 175	Fe-rich ferralitic matrix
OM (%; LOI)	2.17 $\pm$ 0.26	Low ($< 4\%$); poor structural stability
CEC (cmol(+)/kg)	6.37 $\pm$ 0.99	Very low; high risk of nutrient leaching
Clay (%)	7.58	Very low clay fraction
Silts (FS + CS) (%)	3.83	Negligible silt fraction
Fine sand (%)	42.90	Dominant fraction
Coarse sand (%)	45.70	Total sands = 88.60% $\rightarrow$ sandy texture
Chromium Cr (mg/kg)	15.35 $\pm$ 0.28	$<$ NF U 44-041 standard (150), natural background
Copper Cu (mg/kg)	14.06 $\pm$ 0.26	$<$ 100 mg/kg, unpolluted
Nickel Ni (mg/kg)	4.90 $\pm$ 0.07	$<$ 50 mg/kg, compliant
Lead Pb (mg/kg)	14.13 $\pm$ 0.48	$<$ 100 mg/kg, natural pedogeochemical background
Selenium Se (mg/kg)	6.98 $\pm$ 0.59	$<$ 10 mg/kg, compliant
Zinc Zn (mg/kg)	22.64 $\pm$ 0.11	$<$ 300 mg/kg, unpolluted

Values are means $\pm$ SD of the four unamended control pots (T0, $n = 4$). TDS and particle-size distribution were determined on the initial soil before treatment application.

3.2. Physico-Chemical Characteristics of Wood Ash

Table 2. Physico-Chemical Characteristics Of Wood Ash

Parameter	Measured value	Implications for soil properties
pH	11.0	Strong alkalizing effect, neutralizes acidity
EC ($\mu\text{S}/\text{cm}$)	9,270	Very high, salinization risk at high dose
TDS (ppm)	4,620	High soluble ionic load
MWRC (%)	95	Improves water retention of sandy soil
N (mg/kg)	7	Nearly zero, N volatilized during combustion
P (mg/kg)	443	Enriches soil in available phosphorus
K (mg/kg)	1,469	Increases soil K content
Ca (mg/kg)	155,300 (15.5%)	Major constituent, raises soil pH
Mg (mg/kg)	49,600 (5.0%)	Enriches soil in exchangeable magnesium
Na (mg/kg)	2,100	Moderate contribution to soil EC
Chromium Cr (mg/kg)	2.87 ± 0.14	< soil (soil/ash ratio = 5.3)
Copper Cu (mg/kg)	3.67 ± 0.71	< Swiss threshold (100); soil/ash ratio = 3.8
Nickel Ni (mg/kg)	1.66 ± 0.64	< Swiss threshold (30); soil/ash ratio = 3.0
Lead Pb (mg/kg)	6.28 ± 0.71	< Swiss threshold (120); soil/ash ratio = 2.2
Selenium Se (mg/kg)	3.27 ± 0.92	< soil (soil/ash ratio = 2.1)
Zinc Zn (mg/kg)	6.87 ± 0.07	< Swiss threshold (400); soil/ash ratio = 3.3

Wood ash (Table 2) has a pH of 11.0, characteristic of tropical woody biomass ash, resulting from dissolution of oxides (CaO , MgO) and carbonates (K_2CO_3) formed during domestic combustion at 400-700°C [12,30]. The exceptional richness in Ca (155,300 mg/kg) and Mg (49,600 mg/kg) reflects the species used primarily *Eucalyptus spp.* and *Cassia siamea*, known for their high divalent cation content [31]. This is consistent with African data for similar hardwood ashes [32]. Near-zero N content results from volatilization during combustion [13]. The high EC of the ash (9,270 $\mu\text{S}/\text{cm}$) indicates a potential salinity risk at high application rates; salinity is generally considered limiting for sensitive crops when the EC of the saturated paste extract exceeds 4 dS/m (4,000 $\mu\text{S}/\text{cm}$), a value not directly comparable with 1:5 extracts [33]. TME are systematically below receiving soil levels [34,35].

3.3. Physico-Chemical Characteristics of Household Waste Compost

The mean C/N ratio of 18.52 (FAO: 15-20) is compatible with progressive N mineralization, although values approaching 20 may cause temporary N immobilization [36]. The $\text{NO}_3^-/\text{NH}_4^+$ ratio (5.88) approaches but remains slightly below the maturity threshold of 6.25 [37], whereas the low COD (211 mgO_2/l) indicates a largely stabilized organic matter [36]. Total N (1.03%) is the only significant nitrogen source in this system: ash contains practically none (7 mg/kg). The two amendments are therefore complementary in composition:

ash provides Ca, Mg, K and alkalizing power; compost provides N, OM and organic CEC. TME conform to NF U 44-051 [23,38].

Table 3. Composition Of Household Waste Compost (Mean Values C1, C2, C3)

Parameter	Mean	Standards	Implications for soil properties
pH	7.96 ± 0.78	NF U44-051: 6-9	Near-neutral pH, moderately raises acid soil pH
Corg (%)	18.35 ± 2.57	FAO: 10-17	Source of humified carbon, enriches soil OM
Ntot (%)	1.03 ± 0.26	FAO: 0.4-0.5	Only significant nitrogen source for soil
C/N ratio	18.52 ± 3.37	FAO: 15-20	Progressive mineralization; temporary N immobilization possible
OM (%)	31.56 ± 4.43	NF: > 20	Improves OM, structure and CEC of soil
CEC ($\text{cmol}(+)/\text{kg}$)	21.84 ± 2.11	> 20 (Mustin, 1987)	Increases sandy soil CEC through humified OM input
$\text{NO}_3^-/\text{NH}_4^+$ ratio	5.88 ± 0.42	Maturity threshold > 6.25*	Close to, but below, the maturity threshold
COD (mgO_2/l)	211 ± 14.89	< 1,220**	Stable OM, active fermentation absent
Phosphorus P (%)	0.35 ± 0.16	NF: > 0.3	Improves soil P availability
Calcium Ca (%)	2.46 ± 1.22	-	Complementary calcium input
Magnesium Mg (%)	0.29 ± 0.06	NF: < 1	Compliant, improves exchangeable Mg
Potassium K (%)	0.30 ± 0.08	FAO: 0.4-2.3	Complementary K input to ash
Chromium Cr (mg/kg)	4.33 ± 2.30	NF: < 100	Compliant
Copper Cu (mg/kg)	14.67 ± 3.20	NF: < 300	Compliant
Nickel Ni (mg/kg)	3.91 ± 0.66	NF: < 60	Compliant
Lead Pb (mg/kg)	13.67 ± 4.03	NF: < 180	Compliant
Zinc Zn (mg/kg)	109.3 ± 27.2	NF: < 600	Compliant
Selenium Se (mg/kg)	1.08 ± 0.51	NF: < 12	Compliant

3.4. Effects of Amendments on Physico-Chemical Properties of the Ferralitic Soil

3.4.1. Texture and Particle Size Distribution

Table 4. Particle size characteristics of ferralitic soil according to treatments (before cultivation)

Treat.	Clay (%)	Fine silt (%)	Coarse silt (%)	Fine sand (%)	Coarse sand (%)	Texture	Total
T0	7	6	5	40	42	Sandy	100
T1	9	6	5	38	42	Sandy	100
T2	11	5	4	37	43	Sandy	100
T3	9	5	6	37	43	Sandy	100
T4	10	5	5	38	41	Sandy	100
T5	8	6	5	39	41	Sandy	100
T6	7	6	5	39	42	Sandy	100

3.4.2. Effect On Soil pH And Electrical Conductivity

Table 5. pH And Electrical Conductivity (EC, 1:5) Of Amended Ferrallitic Soils (Before Crop Establishment)

	T0	T1	T2	T3	T4	T5	T6
pH	5.52 ± 0.57 ^c	8.07 ± 0.32 ^b	8.40 ± 0.80 ^b	10.28 ± 0.96 ^a	10.21 ± 0.83 ^a	6.18 ± 0.35 ^c	7.86 ± 0.63 ^b
EC (µS/cm)	148 ± 9 ^g	736 ± 11 ^f	1,128 ± 21 ^e	1,706 ± 8 ^b	1,816 ± 39 ^a	1,190 ± 14 ^d	1,311 ± 15 ^c

Means ± SD (n = 4); within a row, means followed by the same letter are not significantly different (one-way ANOVA, Tukey HSD, α = 0.05).
pH: F(6,21) = 28.9, p < 0.001; EC: F(6,21) = 3,507, p < 0.001.

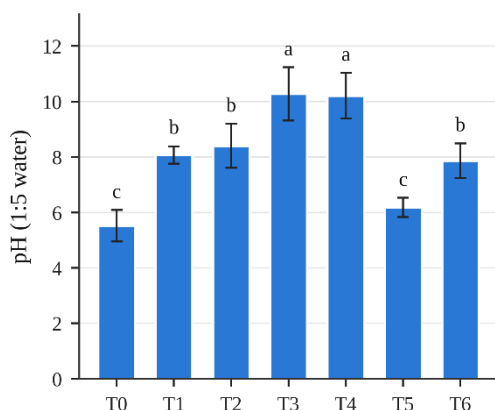


Figure 1. Effect of wood ash and compost on soil pH (means ± SD, n = 4; different letters indicate significant differences, Tukey HSD, α = 0.05)

Wood ash induced a dose-dependent pH increase (F(6,21) = 28.9, p < 0.001), from 5.52 (T0) to 8.07–8.40 in T1–T2 and 10.21–10.28 in T3–T4 (Table 5; Figure 1). This is attributed to the dissolution of the oxides and carbonates contained in the ash, e.g. $\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + 2\text{OH}^-$ and $\text{CO}_3^{2-} + \text{H}_2\text{O} \rightleftharpoons \text{HCO}_3^- + \text{OH}^-$ [9,12]. The response levelled off above T3 (T3 and T4 not significantly different), consistent with Rolka et al. [39], Ohno & Erich [40] and Perkiömäki & Fritze [35], and with studies on acid soils in which wood or biomass ash raised pH and basic cations in a dose-dependent manner, up to pH 9.1 at the highest rates [14,15]. T1–T2 reached moderately alkaline values, whereas T3–T4 (pH > 10) are over-alkaline, which is detrimental to micronutrient availability and microbial activity [41]; in a pot trial on an acid soil, biomass-ash rates above 1.25% (w/w) inhibited maize growth through combined alkaline and saline stress [14]. Compost alone (T5, pH 6.18) did not differ significantly from T0. T6, which contains half of the ash of T1 and half of the compost of T5, reached pH 7.86, within the 6.5–8.0 range generally considered favourable for market-garden crops [42,43]; it did not differ significantly from T1 (8.07) and was well above T5, showing that a moderate ash dose is sufficient to correct acidity in the mixture. A specific buffering effect of compost cannot be inferred from these data.

Soil EC increased with ash dose (F(6,21) = 3,507, p < 0.001), from 148 µS/cm (T0) to 1,816 µS/cm (T4), in line with the high EC of the ash (Table 2). Compost also raised EC (T5: 1,190 µS/cm), and T6 reached 1,311 µS/cm. These values were measured in 1:5 extracts, which are more dilute than saturated-paste extracts; the corresponding ECe values would be higher, so a salinity

risk for sensitive crops cannot be excluded at the highest ash doses and in T5–T6, and should be checked by ECE measurements, the EC1:5–ECe conversion factor increasing in coarse-textured soils [33,44]. pH and EC were closely correlated (r = 0.777, p < 0.001), indicating that alkalization and salinization progressed together with the ash dose [14].

3.4.3. Maximum Water Retention Capacity (MWRC)

Table 6. MWRC (%) Of Amended Ferrallitic Soil

	T0	T1	T2	T3	T4	T5	T6
MWRC(%)	12.0 ± 0.8 ^d	14.4 ± 1.4 ^{cd}	18.7 ± 1.0 ^{bc}	20.0 ± 2.9 ^{bc}	20.0 ± 4.2 ^{bc}	23.0 ± 2.9 ^{ab}	28.8 ± 2.6 ^a

Means ± SD (n = 4); means followed by the same letter are not significantly different (one-way ANOVA, Tukey HSD, α = 0.05); F(6,21) = 18.7, p < 0.001.

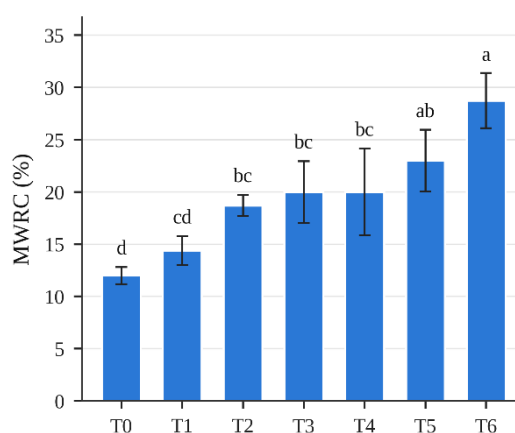


Figure 2. Effect of wood ash and compost on soil MWRC (means ± SD, n = 4; Tukey HSD, α = 0.05)

MWRC increased from 12.0% (T0) to 28.8% (T6) (F(6,21) = 18.7, p < 0.001; Table 6, Figure 2). Ash may contribute through its intrinsically high MWRC (95%) and the partial filling of macropores [45], and the effect of ash doses ≥ T2 was significant. Compost is likely to improve MWRC through its humified OM and the formation of organo-mineral microaggregates, as reviewed for compost-amended soils [46,47,48]. T6 showed the highest MWRC (+140% relative to T0), significantly higher than T1–T4 and well above the mean of its two components T1 and T5 (18.7%), which is relevant for irrigation management in sandy soils; aggregate stability was not measured.

3.4.4. Organic Matter

OM increased from 2.17% (T0) to 3.88–4.40% in amended soils (F(6,21) = 7.5, p < 0.001; Table 7, Figure 3); T1, T2, T5 and T6 differed significantly from T0, while T3–T4 were intermediate. For ash-only treatments, this apparent increase must be interpreted with caution: because OM was determined by LOI at 1,100 °C, the mass loss also includes CO₂ released by the carbonates of the ash (decomposed above ≈ 800 °C) and structural water of clay minerals, so that LOI overestimates OM in ash-amended soils [22]. Residual unburnt carbon in the ash, not quantified here, may also contribute. Likewise, the OM measured in T5 (4.19%) exceeds the value expected from the compost input alone (≈ 2.79%), with a high

variability ($SD = 0.92$). Compost is nevertheless expected to provide the more stable OM input, through humic compounds able to form organo-mineral complexes with Fe and Al oxides [49,50]; the lower values in T3-T4 than in T1-T2 were not significant and are not interpreted further.

Table 7. OM (% , Loss On Ignition At 1,100 °C) Of Amended Ferralitic Soil

	T0	T1	T2	T3	T4	T5	T6
OM(%)	2.17 ± 0.26 ^b	3.88 ± 0.47 ^a	3.61 ± 0.87 ^a	3.35 ± 0.11 ^{ab}	3.27 ± 0.24 ^{ab}	4.19 ± 0.92 ^a	4.40 ± 0.28 ^a

Means ± SD ($n = 4$); means followed by the same letter are not significantly different (one-way ANOVA, Tukey HSD, $\alpha = 0.05$); $F(6,21) = 7.5$, $p < 0.001$.

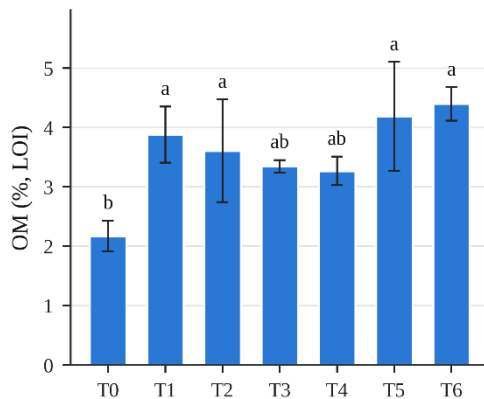


Figure 3. Effect of wood ash and compost on soil organic matter content (LOI; means ± SD, $n = 4$; Tukey HSD, $\alpha = 0.05$)

3.4.5. Cation Exchange Capacity (CEC)

Table 8. CEC (cmol(+)/kg) Of Amended Ferralitic Soil

	T0	T1	T2	T3	T4	T5	T6
CEC	6.37 ± 0.99 ^d	10.43 ± 1.18 ^{bc}	10.60 ± 0.85 ^{bc}	11.16 ± 0.82 ^{abc}	13.06 ± 0.70 ^a	9.96 ± 0.58 ^c	12.11 ± 0.54 ^{ab}

Means ± SD ($n = 4$); means followed by the same letter are not significantly different (one-way ANOVA, Tukey HSD, $\alpha = 0.05$); $F(6,21) = 25.7$, $p < 0.001$.

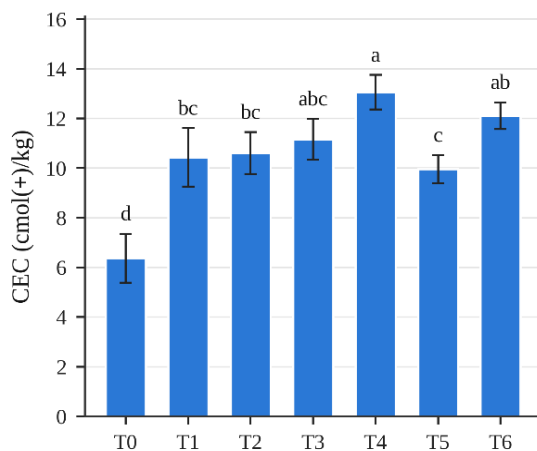


Figure 4. Effect of wood ash and compost on soil CEC (means ± SD, $n = 4$; Tukey HSD, $\alpha = 0.05$)

CEC increased significantly in all amended treatments ($F(6,21) = 25.7$, $p < 0.001$), from 6.37 cmol(+)/kg (T0) to

9.96–13.06 cmol(+)/kg (Table 8, Figure 4). The highest values were found in T4 (13.06) and T6 (12.11), which did not differ significantly. For ash treatments, the pH rise activates pH-dependent charges on kaolinite and OM ($Al-OH \rightarrow Al-O^- + H^+$) [42,51], and CEC was correlated with pH ($r = 0.727$) and Ca ($r = 0.618$). For compost, humified OM (CEC = 21.84 cmol(+)/kg) contributes carboxylate and phenolate exchange sites [27,52]; CEC was also correlated with OM ($r = 0.481$) and MWRC ($r = 0.591$). The CEC of T6 (12.11) exceeded the mean of its two components T1 and T5 (10.19 cmol(+)/kg), suggesting a positive interaction between ash and compost, although T6 did not differ significantly from T1.

3.4.6. Major Elements

Table 9. Total Kjeldahl N, Available P (Olsen), Exchangeable K, Pseudo-Total Ca and Mg, and HCl-Extractable Al and Fe (mg/kg) According To Treatments (T0-T6)

Elem.	T0	T1	T2	T3	T4	T5	T6
N	994 ± 13 ^e	1,023 ± 3 ^d	1,052 ± 2 ^c	1,054 ± 3 ^c	1,002 ± 3 ^{de}	1,159 ± 21 ^a	1,093 ± 7 ^b
P	105.3 ± 1.7 ^f	113.5 ± 1.3 ^e	126.3 ± 1.0 ^d	144.5 ± 1.3 ^b	174.0 ± 3.7 ^a	169.4 ± 1.4 ^a	136.8 ± 3.5 ^c
K	16.0 ± 1.4 ^e	49.5 ± 2.1 ^d	82.3 ± 2.6 ^c	145.5 ± 8.6 ^b	255.0 ± 1.6 ^a	75.4 ± 1.4 ^c	55.2 ± 2.6 ^d
Ca	15 ± 1 ^f	3,487 ± 118 ^d	6,378 ± 238 ^c	12,167 ± 67 ^b	23,857 ± 577 ^a	420 ± 4 ^f	2,317 ± 3 ^e
Mg	10 ± 1 ^f	1,054 ± 35 ^d	2,065 ± 31 ^c	4,378 ± 21 ^b	7,839 ± 45 ^a	66 ± 2 ^f	145 ± 10 ^e
Al	30.5 ± 3.1 ^{ab}	21.8 ± 1.7 ^c	20.0 ± 1.4 ^{cd}	17.3 ± 1.3 ^{cd}	15.0 ± 1.6 ^d	36.0 ± 5.1 ^a	29.0 ± 3.3 ^b
Fe	4,413 ± 175 ^a	4,000 ± 27 ^{bc}	3,900 ± 41 ^{cd}	3,800 ± 10 ^d	3,800 ± 12 ^d	4,500 ± 15 ^a	4,100 ± 14 ^b

Means ± SD ($n = 4$); within a row, means followed by the same letter are not significantly different (one-way ANOVA, Tukey HSD, $\alpha = 0.05$; $p < 0.001$ for all elements).

Ca, Mg, K and P increased with ash dose (Table 9; $p < 0.001$): Ca rose from 15 (T0) to 23,857 mg/kg (T4), Mg from 10 to 7,839 mg/kg, K from 16.0 to 255.0 mg/kg and P from 105.3 to 174.0 mg/kg. These increases agree with the mass balance of the ash inputs (e.g. expected Ca $\approx 3,802$ and 25,896 mg/kg in T1 and T4, measured 3,487 and 23,857 mg/kg; expected K in T4 ≈ 258 mg/kg, measured 255.0 mg/kg). Total N increased mainly in the compost treatments (T5: 1,159 mg/kg, +17%; T6: 1,093 mg/kg), in agreement with the expected values ($\approx 1,176$ mg/kg in T5, and 1,091 mg/kg in T6 as the mean of T1 and T5), compost being the only significant N source (Table 3). As expected for a 1:1 mixture of T1 and T5 soils, T6 values were close to the mean of T1 and T5 for N, P, K and TME. HCl-extractable Fe decreased from 4,413 (T0) to 3,800 mg/kg (T4, -14%), consistent with the dilution expected from mixing 1,000 g of ash with 5 kg of soil ($\approx -17\%$). HCl-extractable Al decreased from 30.5 to 15.0 mg/kg (-51%), which exceeds the dilution effect; since concentrated HCl also dissolves freshly precipitated hydroxides, this decrease may reflect a transformation of Al into less extractable forms at high pH, which requires speciation analysis. HCl-extractable Al is not a measure of exchangeable (potentially phytotoxic) Al; a reduction of Al toxicity at higher pH is therefore inferred from the

literature rather than demonstrated, although the decrease of exchangeable Al is the main agronomic benefit of liming acid soils [28,53,54,55]. Al was slightly higher in T5 (36.0 mg/kg) than in T0, but the difference was not significant.

3.4.7. Trace Metal Elements TME

Table 10. Pseudo-Total TME Concentrations (mg/kg, Aqua Regia Digestion) in Amended Soils

TME	T0	T1	T2	T3	T4	T5	T6
Cr	15.35 ± 0.28 ^a	15.06 ± 0.29 ^a	14.71 ± 0.40 ^{ab}	14.31 ± 0.38 ^b	13.36 ± 0.16 ^c	15.14 ± 0.34 ^a	15.22 ± 0.35 ^a
Cu	14.06 ± 0.26 ^b	13.49 ± 0.15 ^{bc}	13.73 ± 0.29 ^{bc}	13.08 ± 0.08 ^c	12.22 ± 0.17 ^d	14.95 ± 0.66 ^a	13.13 ± 0.12 ^c
Ni	4.90 ± 0.07 ^a	4.83 ± 0.08 ^a	4.77 ± 0.02 ^{ab}	4.62 ± 0.03 ^{bc}	4.42 ± 0.04 ^d	4.92 ± 0.10 ^a	4.57 ± 0.11 ^{cd}
Pb	14.13 ± 0.48 ^a	13.58 ± 0.24 ^{bc}	13.17 ± 0.03 ^c	12.39 ± 0.01 ^d	11.05 ± 0.06 ^e	14.07 ± 0.08 ^a	13.76 ± 0.09 ^{ab}
Se	6.98 ± 0.59 ^a	6.44 ± 0.36 ^{abc}	6.27 ± 0.04 ^{bc}	5.98 ± 0.10 ^{cd}	5.43 ± 0.06 ^d	6.63 ± 0.06 ^{ab}	6.57 ± 0.07 ^{abc}
Zn	22.64 ± 0.11 ^{bc}	22.26 ± 0.04 ^c	21.52 ± 0.06 ^d	19.94 ± 0.35 ^e	17.47 ± 0.44 ^f	24.46 ± 0.10 ^a	23.15 ± 0.38 ^b

Means ± SD (n = 4); within a row, means followed by the same letter are not significantly different (one-way ANOVA, Tukey HSD, $\alpha = 0.05$; $p < 0.001$ for all elements). All values are below the NF U 44-041 soil limit values: Cr 150; Cu 100; Ni 50; Pb 100; Se 10; Zn 300 mg/kg.

All treatments showed TME concentrations below the NF U 44-041 soil limit values (Table 10000). Ash significantly decreased TME contents at the highest doses (e.g. Pb: 14.13 → 11.05 mg/kg; Zn: 22.64 → 17.47 mg/kg in T4). Precipitation as hydroxides, carbonates or phosphates at alkaline pH reduces the mobile fraction of TME but cannot decrease their pseudo-total (aqua regia) content [56,57,58,59,60]; the decrease is mainly explained by dilution of the soil by an ash whose TME contents are 2–5 times lower than those of the soil (Table 2). Dilution fully accounts for the decrease in Cr (expected 13.27, measured 13.36 mg/kg in T4), whereas Pb, Zn and Se decreased slightly more than expected (e.g. Pb: expected 12.82, measured 11.05 mg/kg), possibly due to a lower aqua-regia extractability of TME in carbonate-rich, alkaline matrices. Compost alone slightly increased Cu and Zn (T5: 14.95 and 24.46 mg/kg), in line with its higher Zn content (109 mg/kg; Table 3), but all values remained far below limit values [58,61]. Neither amendment raised TME contents above soil limit values at the tested doses. This conclusion is, however, restricted to the ash characterized here: TME contents of biomass ashes vary widely with tree species and combustion conditions [62], and household ashes can increase the phytoavailability of Al and Zn [63], so that uncontrolled use of uncharacterized ashes should be avoided.

3.5. PCA and Structure of Relationships between Parameters

PCA was conducted on the 18 physico-chemical

variables measured in the 28 pots (7 treatments × 4 replicates), with standardized variables (correlation matrix; Section 2.5; Supplementary Tables S1–S3) [25].

Table 11. Eigenvalues And Explained Variance Of The PCA On 18 Variables (n = 28)

Axis	λ	Var.(%)	Cum.(%)	Interpretation
PC1	11.313	62.85	62.85	Ash gradient: Ca, Mg, K, pH, EC, CEC vs. Pb, Zn, Se, Cr, Fe, Al
PC2	3.469	19.27	82.12	Compost gradient: N, MWRC, OM, P
PC3	1.268	7.05	89.17	Residual (P, Fe, Cu)
PC4	0.651	3.62	92.78	Not retained ($\lambda < 1$)
PC5–18	< 0.407	< 2.26	100	Not retained ($\lambda < 1$)

PCA on the correlation matrix (standardized variables) of the 28 × 18 data matrix (7 treatments × 4 replicate pots). PC1 + PC2 = 82.12%; PC1–PC3 = 89.17% (Kaiser criterion).

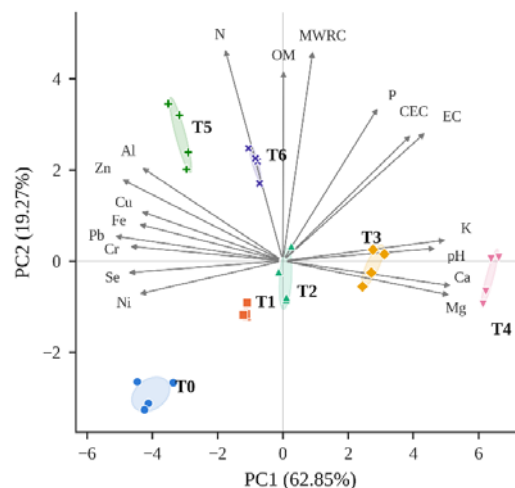


Figure 5. Biplot PCA projection of individuals (n = 28; 7 treatments × 4 replicate pots) and variables (vectors) onto the factorial plane PC1 × PC2, with 95% confidence ellipses around treatment centroids. PC1 + PC2 = 82.12% of the total variance

3.5.1. Variance Structure

The data were suitable for factor analysis (KMO = 0.83; Bartlett's test of sphericity: $\chi^2 = 934$, df = 153, $p < 0.001$), and PERMANOVA confirmed a strong overall treatment effect on the 18 variables (pseudo-F = 38.3, $R^2 = 0.92$, $p < 0.001$). Three components had eigenvalues > 1 and together explained 89.17% of the total variance (Table 11111); PC1 and PC2 accounted for 82.12% [24,25]. Communalities (h^2) on the three retained components ranged from 0.71 (OM) to 0.99 (Supplementary Table S2). Three limitations should be kept in mind. First, the observation-to-variable ratio ($28/18 \approx 1.6$) is low and the four replicates of a treatment are not independent individuals; the PCA is therefore used as a descriptive tool, treatment effects being tested by ANOVA and PERMANOVA. Second, standardization gives the same weight to variables with very small variation (Ni, CV = 4%; Cr, 5%) as to strongly varying ones (Ca, 116%; Mg, 124%), so that TME strongly structure PC1 although their absolute changes remain within 1–5 mg/kg, far below regulatory limits. Third, Ca, Mg and K are almost

collinear ($r = 0.995$ for Ca/Mg and 0.971 for K/Ca), which reinforces the weight of the basic-cation pole on PC1 [24].

3.5.2. PC1 (62.85%): Ash-Driven Mineral Gradient

PC1 (62.85%) is the dominant gradient. It is defined on the positive side by Ca (+0.973), Mg (+0.963), K (+0.942), pH (+0.885), EC (+0.820) and CEC (+0.738), and on the negative side by Pb (-0.972), Zn (-0.928), Se (-0.895), Cr (-0.886), Fe (-0.835) and Al (-0.813) (loadings; the sign of a component is arbitrary). The ash treatments move along PC1 in a dose-dependent manner from T1 to T4, with little change on PC2 (Figure 5). The grouping of pH, Ca, Mg, K and EC reflects the dissolution of the basic oxides, hydroxides and carbonates of the ash, i.e. its liming and potassic value, long described for wood ash [9] and confirmed on acid tropical soils, where wood ash raised pH and Ca, Mg and K in the soil solution [15]; recent reviews attribute to wood ash a simultaneous effect on acidity, nutrient availability and soil buffering capacity [64]. The negative correlations pH/Al ($r = -0.792$) and pH/Fe ($r = -0.856$) are consistent with the effect sought by liming acid soils, of which the decrease of exchangeable Al is the main agronomic benefit [55]; however, since Al and Fe were extracted with concentrated HCl, their decrease here mainly reflects dilution and a possible transformation into less extractable forms (Section 3.4.6). Likewise, the strong negative correlations between basic cations and TME (Ca/Pb, $r = -0.983$; Mg/Zn, $r = -0.963$) do not indicate chemical immobilization, which would affect only the mobile fractions [59,60], but the dilution of pseudo-total TME by an ash poorer in TME than the soil (Section 3.4.7).

3.5.3. PC2 (19.27%): Compost-Driven Organic Gradient

PC2 (19.27%) is dominated by N (+0.870), MWRC (+0.864), OM (+0.785) and P (+0.632). T5 and T6 project on its positive side and T0 on its negative side, which confirms the role of compost in rebuilding the organic pool and the water reserve of sandy soils. Compost incorporation increases porosity, aggregation and water retention [48], and compost-based amendments improve soil fertility under tropical conditions [65]; the correlations N/MWRC ($r = 0.619$), OM/MWRC ($r = 0.627$) and N/OM ($r = 0.556$) ($p < 0.01$) are consistent with this effect [47,48]. OM was independent of PC1 (loading = 0.004; r with pH = 0.12); ash, practically devoid of organic carbon, cannot restore the organic stock of a degraded ferralitic soil, a function fulfilled by compost. CEC occupies an intermediate position between both axes (PC1: +0.738; PC2: +0.519) and is more strongly correlated with pH ($r = 0.727$) and EC ($r = 0.841$) than with OM ($r = 0.481$). In kaolinitic, oxide-rich soils, a large part of the charge is pH-dependent: the rise in pH deprotonates Al-OH, Fe-OH and COOH groups and creates new exchange sites [42,51,55]. CEC therefore benefits both from ash-induced alkalization and from the organic charges supplied by compost. PC3 (7.05%) was mainly related to P, Fe and Cu and is not interpreted further.

3.5.4. Distribution of Individuals and Position of T6

T0 is positioned on the negative side of both axes (acid

pH, low OM and N, higher Fe, Al and TME), characteristic of ferralitic sandy soils [66]. T1-T4 progressively migrate toward the positive side of PC1, T4 reaching the extreme (maximal Ca, Mg and K), while T5 stands out on positive PC2 ($N = 1,159$ mg/kg); the 95% confidence ellipses of the treatment centroids are well separated (Figure 5). T6 lies above the centre of the factorial plane, combining acid correction (pH 7.86), Ca and Mg enrichment, organic enrichment (OM = 4.40%, $N = 1,093$ mg/kg), the highest MWRC (28.8%) and a high CEC (12.11 cmol(+)/kg), without the alkaline and saline excess of T3-T4. Similar benefits correction of acidity, increase in exchangeable bases and maintenance of microbial activity were obtained with wood-ash-amended composts on acid tropical soils of Cameroon [17,18], and wood ash is recognized as an additive improving the agronomic quality of composts [67]. By limiting the pH rise, the combination also avoids the extreme pH values that strongly alter soil bacterial abundance and community composition [68]. T6 therefore shows the most balanced measured physico-chemical profile among the tested treatments; whether this translates into better crop performance requires validation through crop-response trials, as done for integrated amendments by Abdul-Aziz et al. [69].

3.5.5. Pedological and Agronomic Implications of Correlations

Key correlations have potential practical implications: (i) EC/K ($r = 0.820$) and EC/P ($r = 0.796$): EC may serve as a simple screening indicator of mineral enrichment by ash, subject to local calibration; the close pH/EC correlation ($r = 0.777$) also indicates that the salinity risk increases with the ash dose [14]. (ii) Ca/Fe ($r = -0.734$), Ca/Pb ($r = -0.983$) and Ca/Zn ($r = -0.957$): mainly reflect the dilution of native Fe and TME by Ca-rich ash [23,54]. (iii) Cr/Zn ($r = 0.855$), Ni/Zn ($r = 0.715$) and Cr/Ni ($r = 0.590$): Cr, Ni and Zn co-vary, suggesting a common geochemical behaviour, with all values below NF U 44-041 limit values [58,70]. (iv) N/MWRC ($r = 0.619$) and OM/MWRC ($r = 0.627$): consistent with the role of compost OM in improving water retention [48]. In summary, ash structures PC1 (alkalinization, Ca/Mg/K inputs, dilution of Fe, Al and TME) and compost structures PC2 (N, OM and water retention). Among the treatments tested, T6 is the only one positioned favourably on both gradients.

4. Conclusion

This study evaluated, in an integrated and multivariate manner (ANOVA and PCA on 18 variables), the effects of household waste compost and wood ash on the physico-chemical properties of an acid ferralitic sandy soil from Brazzaville. Five major conclusions emerge.

First, the ferralitic soil studied combines several constraints (pH 5.52, 88.6% sand, OM 2.17%, CEC 6.37 cmol(+)/kg, very low Ca, Mg and K) that call for complementary organic and mineral inputs.

Second, wood ash (Ca = 15.5%, pH 11.0) induced a dose-dependent alkalization (pH 5.52 to 10.21–10.28 in

T3-T4), strong Ca, Mg and K enrichment and an EC increase up to 1,816 $\mu\text{S}/\text{cm}$, while HCl-extractable Fe and Al and pseudo-total TME decreased, mainly through dilution. Doses above 250 g per pot (T3-T4) led to over-alkalinization.

Third, household waste compost (OM = 31.56%, N_{tot} = 1.03%, C/N = 18.52) was the main source of nitrogen (T5: 1,159 mg/kg) and improved MWRC and CEC, without significantly modifying soil pH; effects on soil structure were not directly measured.

Fourth, combined treatment T6 (1:1 mixture of T1 and T5 soils, i.e. half doses of ash and compost) showed the most balanced measured profile: pH 7.86, highest MWRC (28.8%), OM 4.40%, N 1,093 mg/kg and CEC 12.11 cmol(+)/kg, without over-alkalinization; its EC (1,311 $\mu\text{S}/\text{cm}$, 1:5) remained lower than in T3-T4 but should be monitored. All TME remained below NF U 44-041 soil limit values.

Fifth, PCA revealed two main gradients: PC1 (62.85%), the alkalinizing and mineral effect of the ash; PC2 (19.27%), the organic and nitrogen effect of the compost. T6 lies between both gradients, consistent with the functional complementarity of the two amendments for improving the physico-chemical fertility of peri-urban ferralitic sandy soils of Brazzaville. These pre-cropping results now need to be validated by crop-response trials and longer-term monitoring.

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