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Optimising pH of layer and broiler litter of contrasting bedding materials through co-composting with wood ash and effect on co-compost quality

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Abstract

This study investigated whether co-composting chicken litter with wood ash could raise its pH to match agricultural lime's liming potential, since chicken litter's naturally low pH limits its capacity for correcting acidic tropical soils. Layer and broiler litter with coffee husks or wood shavings as bedding material, where 5 kg samples were combined with wood ash at the rates of 0.5, 1.0, 2.0, and 4.0 kg and co-composted for one-month to determine the minimum ash amount needed to raise the co-compost pH to the agricultural lime range (9–12), and assess the effect on co-compost quality. Layer litter with coffee husk bedding (LCH) needed the least wood ash, 0.85 kg per 5 kg of litter to optimise pH to 9.9 ± 0.1 whereas broiler litter with the same bedding (BCH) needed the largest, 1.83 kg wood ash, to attain optimum pH of 9.8 ± 0.1. Moreover, high Fe, Mn, and EC originally present in the litter and ash substrates were suppressed to acceptable levels in the co-composts. All co-composts had low C:N ratios, and coffee husk co-composts had excessive Mn, which can lead to nitrogen loss

through leaching and phytotoxicity, respectively. Coffee husks are better bedding choice for layers but wood shavings for broilers for production of co-composts of superior liming potential and fertiliser quality.

Key words: Broiler litter, co-composting, coffee husks, layer litter, pH optimisation, wood ash, wood shavings

Introduction

In Sub-Saharan Africa (SSA), soil acidity affects productivity of arable land by approximately 35%, leading to low crop yields (Agegnehu *et al*., 2021). Uganda is one of the countries in SSA with strongly acidic soils (pH 3.6 – 4.9) that traverse 20% of lowlands and 90% of the highlands (Mazur, 2017). Soil acidity severely constrains phosphorus availability to < 5 mg kg^{-}, even where total P reserves are high (300 – 400 mg^{-1}) as a result of Al^{3+}, Fe^{3+} and Mn^{2+} toxicity (Bulyaba *et al*., 2020). Soil liming reduces solubility and phyto-toxicity of these ions, resulting in reduced P fixation (Kyomuhendo *et al*., 2020); improved N availability, through enhanced N biological fixation by legumes and reduced N leaching (Warke and Wakgari, 2024); as well as increased availability of basic cations like K^{+}, Ca^{2+} and Mg^{2+} through reduced leaching (Agegnehu *et al*., 2021).

Chicken production is an important emerging enterprise in Uganda which is growing rapidly, with vast quantities of chicken litter generated (MAAIF, 2022). This litter has a high potential to ameliorate soil acidity due to its appreciable levels of organic matter content (8 – 11%), calcium carbonate (4.7%), and ammonium (0.5 – 0.8%), which can increase soil pH buffering capacity (Dai *et al*., 2021). Chicken litter also contains essential nutrients for plant growth (Pokhrel and Shober, 2024), unlike conventional agricultural lime. However, chicken litter substrates' pH (6 – 8) is lower than the 9 – 12 range for agricultural lime (Katuwal *et al*., 2023; Maruthamuthu *et al*., 2024). Low pH can also hinder microbial activity especially in the early stages of composting due to release of organic acids when the mesophilic microbes are active (Chen *et al*., 2020).

Over 90% of households in Uganda use wood fuel (firewood and charcoal wood fuel) (Bamwesigye *et al*., 2020), hence producing large amounts of wood ash for potentially increasing chicken litter pH. Co-composting with wood ash, whose pH is 13.0, can raise chicken litter-wood ash co-composts' pH to agricultural lime range, enhance nutrients supply (N, P, K Ca, Mg and Mo), and reduce toxicity of micronutrients (Fe, Cu, Zn and Mn) (Kuba *et al*., 2008; Bougnom *et al*., 2020). However, the minimum amounts of wood ash to co-compost with chicken litter that would raise the resultant pH to the desirable 9 – 12 range are not established; neither is their influence on the co-composts quality. Previous studies have focused on combined application of equal amounts of chicken litter and wood ash (Agbede and Adekiya, 2012; Dayo-Olagbende *et al*., 2018), overlooking the possibility that minimal wood ash rates may optimise chicken litter-wood ash composts pH. Also, there is a need to establish the inherent differences between broiler and layer droppings in different management settings.

Broilers fed more protein (20% CP) produce more NH_4^+, whereas layers fed more Ca (3.8 - 4.0%), may pass out droppings with higher pH (MAAIF, 2019). Besides, broiler litter is often treated with lime [$CaO_{(s)}$ or $Ca(OH)_{2(s)}$] to dehydrate the relatively wet droppings to suppress the proliferation of pathogens in the litter, which may positively influence initial substrate pH (Miles *et al*., 2011), and thus the amount of wood ash needed to optimise chicken litter+wood ash co-composts pH. Broiler litter is also frequently treated with acidifiers (e.g. sodium bisulfate), which can influence NH_4^+ retention and therefore, pH (Shah, 2021). The intrinsic differences between bedding materials further influence chicken litter pH. For example, coffee husks are richer in N (4.78%) than wood shavings (0.96%) and generate more NH_4^+ with a positive effect on pH (Zapata *et al*., 2015). Wood shavings are more acidic (pH 4.0 – 5.5) due to high cellulose, hemicellulose, and lignin contents (Geffert *et al*., 2019). Moreover, chicken layers' bedding lasts long in usage (up to 72 weeks), resulting in more NH_4^+ accumulation than broiler bedding, which is frequently replaced every 4 -7 weeks (MAAIF, 2019).

All these factors are likely to influence the minimum wood ash quantity needed to raise chicken litter pH to the agricultural lime pH range. Yet, no study has integrated their combined effects on co-compost pH, and how optimising co-composts pH might influence plant available P and quality of co-composts. Whereas high pH from wood ash may reduce P availability in the co-composts by forming insoluble Ca-P or Mg-P, presence of organic matter may increase extractable P by repelling phosphate ions from negatively charged OM sites, and reducing Fe, Ca, and Mg solubility by chelation (Johan *et al*., 2021).

Therefore, this study was conducted to: (i) Determine the effect of bird type (layers vs broilers), bedding materials (coffee husks vs wood shavings), and wood ash amounts needed to deliver high pH chicken litter+wood ash co-composts, and (ii) Evaluate the effect of optimising pH of chicken litter types on fertiliser quality of the co-composts. We hypothesized that: i) Layer litter would require a smaller quantity of wood ash than broiler litter to optimise its pH irrespective of bedding material; ii) chicken litter with coffee husks as bedding material would require smaller wood ash amount to optimise its pH than wood shavings as bedding material, irrespective of bird type;

and iii) optimising pH of chicken litter types through co-composting with wood ash would yield co-composts with superior quality.

Materials and methods

Collection and preparation of study materials

Chicken litter was collected from four chicken farms identified to be similarly intensively managed; each operating at 10,000 - 30,000 birds under deep litter system in Kampala City, Uganda. These were selected in a rapid assessment of large poultry farms in the City. Farms were paired by bird type (broiler or layer) and bedding material (coffee husks or wood shavings), yielding four chicken litter types: broiler-coffee husks (BCH), broiler-wood shavings (BWS), layer-coffee husks (LCH), and layer-wood shavings (LWS), i.e., each bedding material×bird type was represented by one farm. Broiler litters had been in use for 4 - 7 weeks with top-dressing and cleaned out per flock cycle; layer litters were in use for 72 weeks also with periodic top-dressing. Top-dressing in this context is the practice of adding a thin layer of new clean bedding material on top of used litter to increase litter volume which had reduced due to partial degradation so as to cut costs on bedding material. Representative chicken litter samples were separately collected from four randomly demarcated rectangular shapes (floor size; 36 m long × 7.5 m wide) per farm, by scooping the litter from four corners and center to obtain a composite sub-sample of 150 kg. The sub-samples for each chicken litter resource were then separately air-dried at room temperature and mixed on tarpaulins using spades to make composite samples at Makerere University Agricultural Research Institute, Kabanyolo (MUARIK) (spatial coordinates $0^{o}27'60''$N, $32^{o}36'24''$ E, altitudinal range 1250 m to 1320 m above mean sea level) located about 14 km north of Kampala City.

Wood ash was collected from surrounding institutions (schools and universities) that use firewood or charcoal for cooking. With the consent of school authorities and coordination with head cooks, wood ash was collected daily into 240 L metal drums provided by the researchers. Once full, the wood ash was transferred to 100/ kg polythene bags until 1,500 kg was realised. Wood ash was screened through a 5 mm sieve to remove cinders, homogenised, and air-dried also at MUARIK. The chemical properties of the chicken litter substrates and wood ash used in this study were characterized and are presented in Table 1.

Composting loading and set up

A semi-automated above-ground box system was constructed of wooden chambers (0.5 m × 0.2 m × 0.3 m) with open tops and bottoms and four perforations (6 cm diameter) along the sides. Each perforation was fitted with a bamboo pipe with ten random perforations each of diameter 1 cm to improve aeration. Each box was

Table 1. Chemical characteristics of broiler and layer chicken litters with coffee husks and wood shavings as bedding materials, and wood ash used in co-composting experiments

Parameter	Chicken litter substrate type				Wood ash
	Broiler (B)		Layer (L)		
	CH(BCH)	WS(BWS)	CH(LCH)	WS(LWS)	
pH (H_2O)	7.9	**8.2**	**8.4**	7.9	**12.3**
EC $mScm^{-1}$	5.3	**6.9**	4.0	5.2	**33**
OM%	61	67	60	62	Na
OC%	31.1	**34.1**	30.6	31.2	-
C:N	18:1	18:1	22:1	19:1	Na
TN%	1.7	1.9	**1.4**	1.7	Na
P%	0.9	0.9	1.1	0.9	**7.3**
K%	0.5	0.5	0.5	0.5	**2.4**
Ca%	4.4	4.0	4.6	5.0	**24.0**
Mg%	0.5	0.7	0.7	0.2	0.2
Fe mg kg^{-1}	3027	**4306**	**4306**	1331	3928
Cu mg kg^{-1}	34.6	48.4	51.8	41.5	**131**
Zn mg kg^{-1}	168.4	233.3	209.4	**59.7**	169
Mn mg kg^{-1}	**515**	369	**571**	491	**1120**

CH = coffee husks, WS = wood shavings, na = not applicable. All values in bold were superior to their respective counterparts except total N for LCH and Zn for LWS

loaded with 5 kg of each homogenised chicken litter type mixed with wood ash at 0, 0.5, 1, 2 and 4 kg, in three replicates, giving 60 experimental units (4 chicken litters × 5 wood ash levels × 3 replicates). Homogenised chicken litter-wood ash mixtures were moistened with tap water to the point when they were wet enough but no water coming out upon squeezing the mixtures in the hands. The experiment was set up in an open area. The empty boxes were partially embedded (0.5 cm) in the ground in a complete randomised design arrangement as per the treatments above. The embedding was to curtail entry of run-off water into the feedstock in case of heavy rains, and the bottoms were lined with 2 cm thick layer of dry grass straw. Part of the moistened mixture of chicken litter and wood ash was then gently spread in the custom box, reaching just below the line of perforations. Another 2 cm thick layer of grass straw was spread on top of the spread as a separator between layers. Perforated bamboo tubes (for aeration and air circulation) were carefully inserted end-to-end of the box chambers through the perforations. Another 2 cm separator grass straw layer was put over the bamboo and the remaining mixture of moistened chicken litter and wood ash spread on top. A 1 cm layer of the grass straw covered the arrangement. Each loaded box was then wrapped with a polythene sheet and secured with sisal strings to protect the feedstock from rainfall and direct sunshine during composting. The co-composting experiment was incubated *in situ* until stable temperatures within the boxes were reached.

The progression of the composting process was monitored by taking temperature measurements after every two days in the morning hours (between 8:00 am and 9:00 am) by inserting mercury-in-glass laboratory thermometer at the time of measurement, diagonally at three points (center and 5 cm away from the lower and upper box corners) to the depth of 15 cm in the pile to obtain the average reading per day up to when the readings were almost constant and similar to/below that of the surrounding area (Graves and Hattemer, 2000) which occurred by day 30 of the composting period. After the 30th day, composts were allowed one more week in the boxes to stabilize prior to harvesting (UN ESCAP, 2012) thus making a total of 37 days of composting.

Chemical analyses

The chemical composition of the chicken litters, wood ash, and co-composts including: pH, EC, total N, P, K, Ca, Mg, Fe, Cu, Zn and Mn were determined following standard methods in Okalebo *et al*. (2002). Co-compost and chicken litter samples were air dried, ground using a mortar and pestle and screened through a 2 mm sieve. Final composts were analysed at the Soil, Water and Plant Analytical Laboratory of Makerere University. Compost pH and EC were measured in a 1:10 (w/v) water extract using a PL-700AL multi-parameter meter. The OM was determined by loss on ignition at 650°C; OC was estimated as 54% of OM (Jiménez and García, 1992), and C:N ratio derived from total N. Total N, P, K, Ca, Mg, Fe, Cu, Zn, and Mn were determined by wet acid digestion (sulfuric acid–selenium–lithium sulphate). Total P was measured using the Olsen and Sommer (1982) method; K, Ca, Na via flame photometry; and Mg, Fe, Cu, Zn, Mn via atomic absorption spectroscopy. Moisture content was determined by oven drying at 105°C for 24 hours.

Data analyses

Data were analysed using Genstat 15th Edition SPI software. The data on the pH of the composts produced with the different quantities of wood ash was subjected to regression analyses. To select between linear and nonlinear regression for analysis, scatter plots of the dependent variable (compost pH) against the independent variable (wood ash amounts) data sets were conducted to check if their relationship was linear or curvilinear. Since the relationship was curvilinear, a quadratic equation of second order with one quantitative predictor was used: $Y = a + bX + cX^2$ and a standard curve regression (an exponential regression) model: $Y = a + \beta\, x\, p^X$ also with one quantitative predictor were tested. The standard curve regression model was selected for analysis since it best described the relationship between the two variables, by giving: (i) The highest R^2 value; indicating that highest percentage variation in dependent variable Y (compost pH) is explained by the independent variable X (amount of wood ash) and how well the model fits the data; (ii) The smaller s.e, indicating that the response Y values (pH values) fitted by the model are very close to the observed data. Differences in wood ash requirements among chicken litter types were tested using Kruskal–Wallis one-way ANOVA, and chi-square. For compost quality parameters (EC, OC, C:N, nutrients), data were either log or square root transformed to meet ANOVA assumptions, and a factorial ANOVA (wood ash levels, bird type and bedding materials) was performed. Means were separated at the 5% significance level using Tukey's HSD test.

Results

Chicken litter type and the amount of wood ash needed to optimise pH of chicken litter+wood ash co-composts

Chicken litter types significantly ($\chi^2 = 0.005$) differed in the wood ash amounts required to reach the target agricultural lime pH range (9.0 - 12.0). Expectedly, the pH of composts increased with increasing amounts of wood ash added until a saturation point was reached when additional amounts of ash had no effect on the pH of the compost (Fig. 1). Layer litter with coffee husks as bedding materials (LCH) required the smallest wood ash amount (0.85 kg per 5 kg chicken litter) to optimise co-compost pH (9.9 ± 1.0) whereas broiler litter with coffee husks (BCH) required the largest (1.83 kg per 5 kg chicken litter) to optimise (reach optimum) co-compost mean pH (9.8 ± 1.0) (Fig. 1), needing about 1.0 kg wood ash above that for LCH. For wood shavings, LWS required 1.13 kg wood ash per 5 kg chicken litter to optimise its co-compost mean pH (9.3 ± 1.0) whereas BWS required 1.36 kg per 5 kg chicken litter to optimise pH (9.6 ± 1.0). Within bird types, layers kept on coffee husks bedding materials required 0.28 kg smaller wood ash to optimise co-compost pH than layers raised on wood shavings bedding materials, moreover with a superior co-compost pH. In contrast, broilers raised on wood shavings required 0.47 kg smaller amount of wood ash than those raised on coffee husks as bedding materials.

Effect of optimising pH of different bird types and bedding materials co-composts with varying wood ash amounts on macronutrient contents

Effect on total nitrogen (N)

Bird type and bedding material significantly ($P < .001$) influenced %N in chicken litter+wood ash co-composts, but their interaction did not ($P = 0.513$). Broiler litters (BCH, BWS)+wood ash co-composts yielded higher %N than layer litters (LCH,

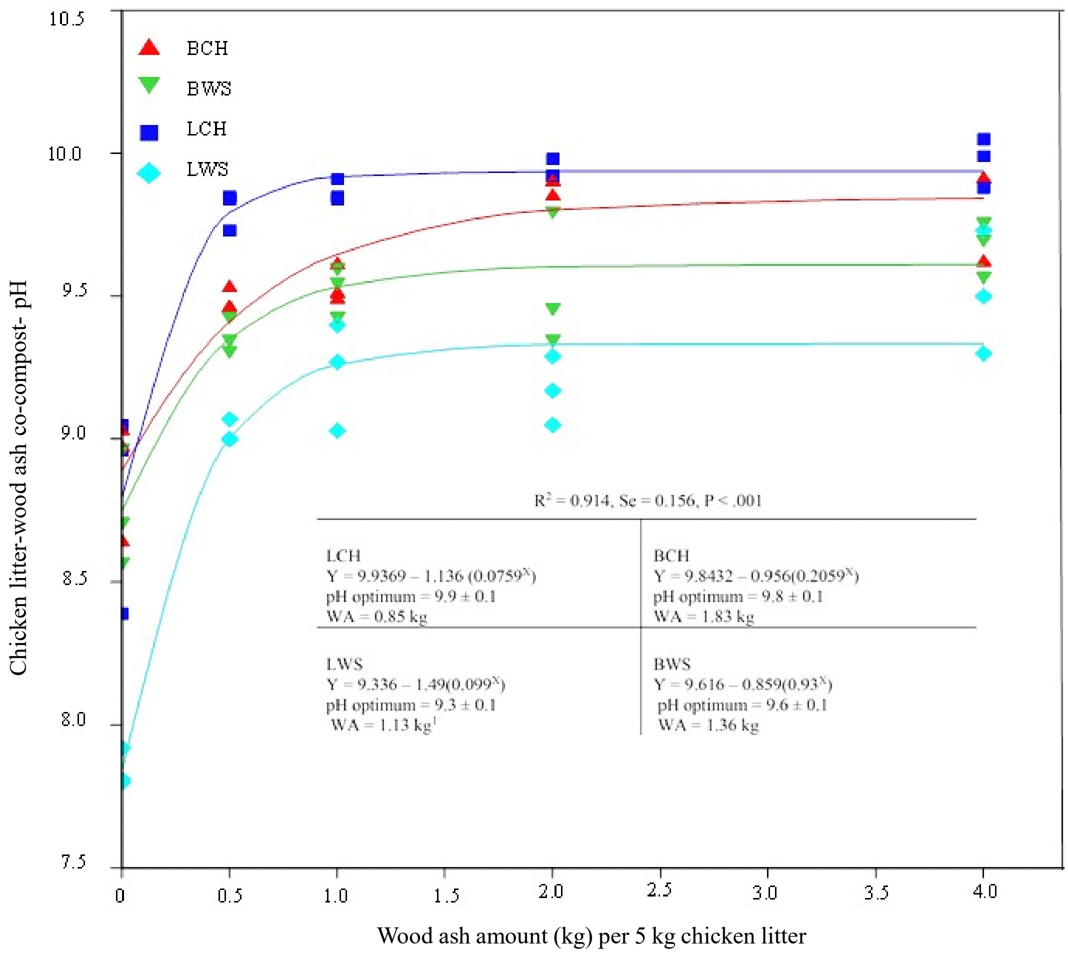

Figure 1. Standard curve regression analysis indicating relationship between pH of chicken litter+wood ash composts of different chicken types and bedding materials over different amounts of wood ash (WA).

LWS)+wood ash co-composts (Fig. 2a). The highest %N (10.6 ± 1.0%) was from BCH co-composted with 0.5 kg wood ash per 5 kg chicken litter. At this same wood ash rate, mean %N content for LCH+wood ash co-compost was 7.3 ± 0.2% N (Fig. 2a). The lowest N content (2.2 ± 0.5%) was of LWS co-composted with 2.0 kg wood ash per 5 kg chicken litter (Fig. 2a). Wood ash levels over 0.5 kg generally suppressed %N (Fig. 2a).

Effect on phosphorus (P)

The main effects of both bird type and bedding material as well as their two-way interaction were highly significantly ($P < .001$) on %P content of the chicken litter+wood ash co-composts, implying that the effect of bird type on P content depended on the type of the bedding material. The highest mean %P content (5.7 ± 0.3%) was from

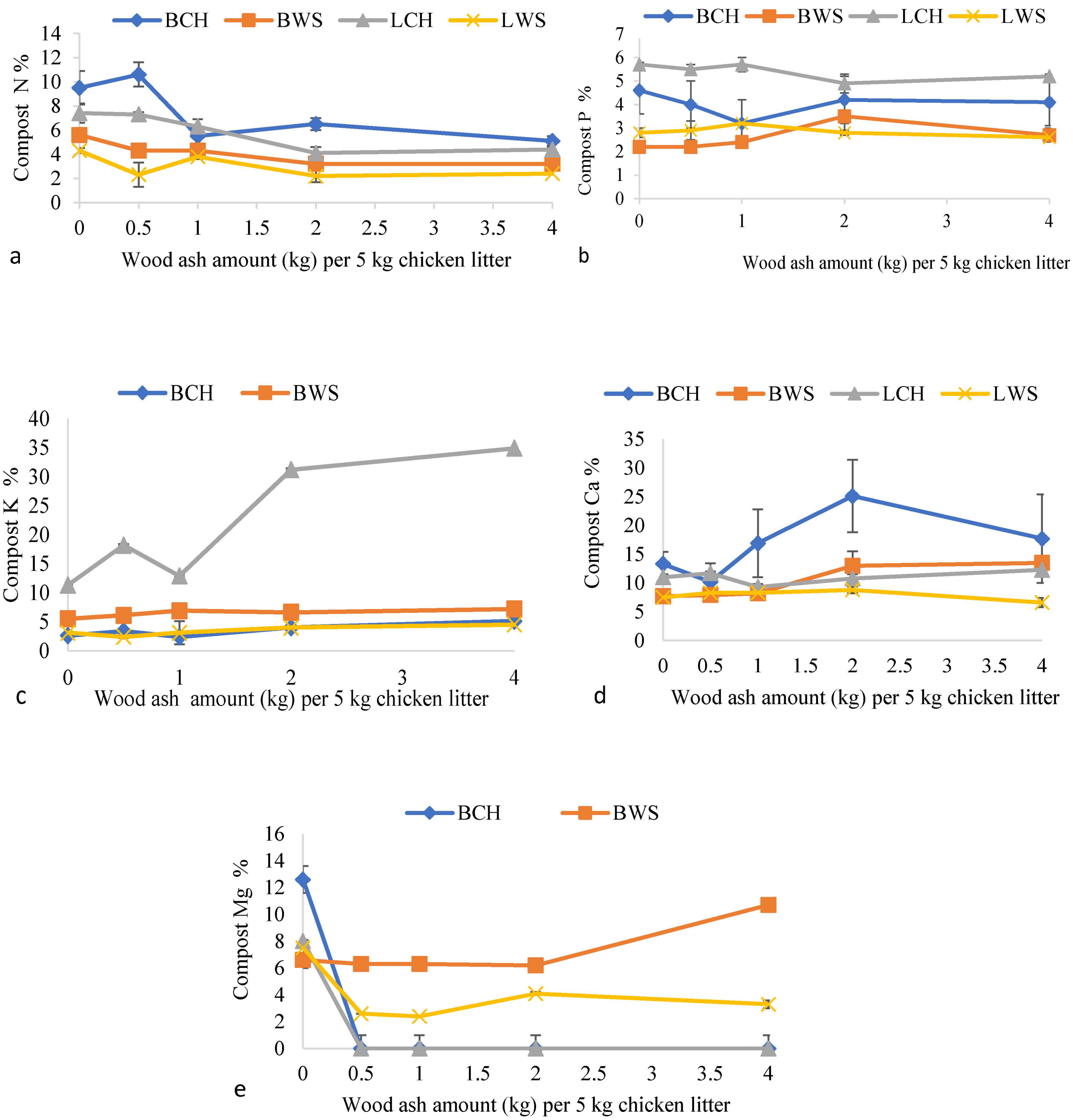

Figure 2a - e. Changes in macronutrients content of layer and broiler litter with coffee husks or wood shavings through co-composting with varying wood ash amounts.

LCH composted either without wood ash (0) or co-composted with 1.0 kg wood ash per 5 kg chicken litter. This wood ash ratio (1kg) also coincided with the highest mean %P content (3.2 ± 0.5%) for LWS-wood ash co-composts, which was the lowest %P content attained for BCH-wood ash composts (Fig.2b). The overall smallest mean %P (2.2 ± 0.2% P) was from BWS, either without adding wood ash or co-composted with 0.5 kg wood ash per 5 kg chicken litter (Fig. 2b). Generally, chicken litter-wood ash co-composts with coffee husks as bedding materials (LCH and BCH) had significantly higher %P contents than those with wood shaving (LWS and BWS), with %P contents of LCH+wood ash co-composts being significantly higher than for BCH+wood ash co-composts (Fig. 2b).

Effect on basic cations of potassium (K), calcium (Ca) and magnesium (Mg)
Both the main effect of bird type and bedding material, as well as their interaction were highly significant ($P < .001$) on %K content of the chicken litter+wood ash co-composts, similarly to the trend of %P. The highest %K (34.9 ± 0.1%) was from LCH co-composted with 4.0 kg wood ash per 5 kg chicken litter whereas the smallest (2.4 ± 0.2%) was from BCH and LWS co-composted with wood ash at 1.0 kg and 0.5 kg per 5 kg chicken litter, respectively (Fig. 2c).

The main effects of the bird type and bedding material on mean %Ca content of chicken litter+wood ash co-composts were highly significant ($P < 0.001$) but their interaction was not ($P = 0.233$), implying that the effect of bird type on %Ca content was consistent across the bedding materials. Overall, broiler litter+wood ash co-composts were superior to layer litter+wood ash co-composts in %Ca content, especially at wood ash ratios > 1.5 kg per 5 kg chicken litter. The highest %Ca (25.1 ± 6.3%) was from BCH co-composted with 2.0 kg wood ash per 5 kg chicken litter, a ratio close to the 1.83 kg wood ash per 5 kg chicken litter needed to optimise its pH whereas the smallest (6.6 ± 0.8%) was from LWS co-composted with 4.0 kg wood ash per 5 kg chicken litter (Fig. 2d). The %Ca content of all composts also generally increased with wood ash up to the 2.0 kg per 5 kg chicken litter, beyond which the Ca contents of BCH and LWS decreased whereas those of BWS and LCH continued increasing (Fig. 2d).

The main effect of bedding material on %Mg content of chicken litter+wood ash co-composts was highly significant ($P < .001$) whereas bird type was not ($P = 0.789$). The interaction of bird type and bedding material was significant ($P = 0.002$), implying that the effect of bedding material on %Mg content depended on bird type. The highest mean %Mg (12.6 ± 2.1%) was from BCH composted without adding any wood ash (0) whereas the smallest (0.0) was from both BCH and LCH at all ash levels above zero. At wood ash levels >0.5kg, %Mg content was higher in wood shavings (BWS, LWS) than in coffee husks (BCH, LCH) (Fig. 2e). Within the wood shavings beddings, %Mg contents were higher in BWS+wood ash co-composts than in LWS+wood shavings co-composts (Fig. 2e).

Effect of optimising pH of different bird types and bedding materials co-composts with varying wood ash amounts on micro-nutrient contents

Effect on total iron (Fe)

The main effect of bedding material, bird type, and their interaction on mean Fe content of chicken litter+wood ash co-composts were highly significant ($P< 0.01$). Chicken litter+wood ash co-composts with coffee husks as bedding material (BCH and LCH) had significantly higher mean Fe contents than those with wood shavings (BWS and LWS) (Fig. 3a). Within bedding materials, LCH+wood ash co-composts had significantly higher mean Fe content than LCH+wood ash co-composts whereas mean Fe contents of BWS and LWS+wood ash co-composts did not differ significantly (Fig. 3a). The LCH composted without adding wood ash had the highest mean Fe content (1946.8 ± 0.1 mg kg^{-1}) whereas BWS also composted with or without wood ash had the smallest (6.7 ± 0.02 mg kg^{-1}). Wood ash generally had a suppressive effect on mean Fe contents of coffee husks+wood ash co-composts.
Effect on total copper (Cu)

The main effect of bedding material and its interaction with bird type were highly significant ($P < .001$) on mean Cu content of the chicken litter+wood ash co-composts but the main effect of bird type was not ($P = 0.924$). Mean Cu contents were generally higher for LCH- and BWS+wood ash co-composts than for LWS- and BCH+wood ash co-composts. The highest mean Cu content (102 ± 4.5 mg kg^{-1}) was from LCH co-composted with 4.0 kg wood ash per 5.0 kg chicken litter whereas the smallest (43.3 ± 2.5 mg kg^{-1}) was from LWS co-composted with 1.0 kg wood ash per 5 kg chicken litter (Fig. 3b). The 0.85 kg wood ash per 5 kg chicken litter needed to optimise the pH of LCH-wood ash co-compost was within the 0.5 - 1.0 kg range of wood ash per 5 kg chicken litter which had a positive effect on the mean Cu content'. Mean Cu content for LCH-wood ash co-compost increased from 81.2 ± 9.1 mg kg^{-1} at wood ash rate of 0.5 kg per 5 kg chicken litter to 88.9 ± 4.2 mg kg^{-1} at wood ash rate of 1.0 kg per 5 kg chicken litter, indicating that co-composting chicken litter with wood ash to optimise pH generally has a positive effect on mean Cu of LCH-wood ash co-compost (Fig. 3b).

Effect on total zinc (Zn)

The main effects of both bedding material and bird type as well as their interaction highly significant ($P <.001$) on mean Zn content of the chicken litter-wood ash co-composts as it was also the case for mean Cu contents of the chicken litter-wood ash co-composts. Mean Zn content was generally higher for LCH- and BWS+wood

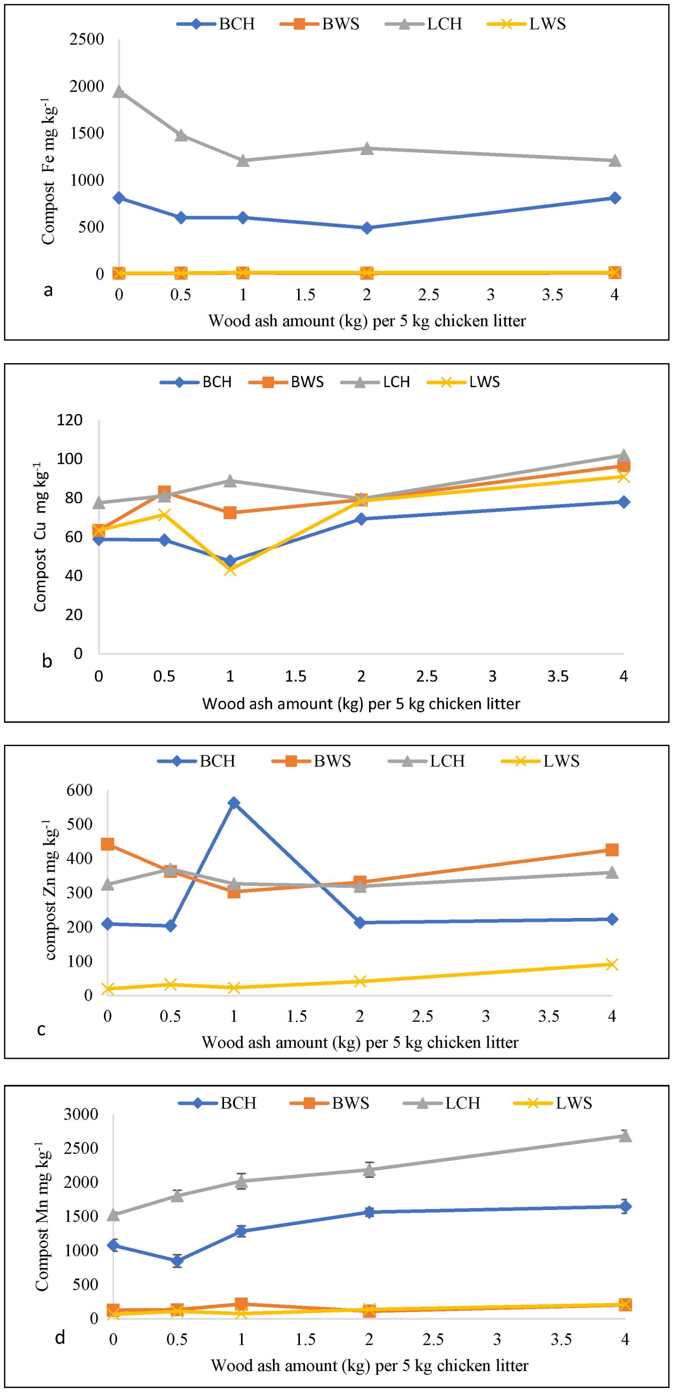

Figure 3a - d. Changes in macro- and micro-nutrients content of layer and broiler litter with coffee husks or wood shavings through co-composting with varying wood ash amount.

ash co-composts than it was for LWS- and LCH+wood ash co-composts. However, the highest overall mean Zn content (562.8 ± 46.6 mg kg^{-1}), was from BCH co-composted with 1.0 kg wood ash per 5 kg chicken litter whereas the smallest (19.7 ± 2.2 mg kg^{-1}) was from LWS composted without wood ash (Fig. 3c).The mean Zn content of BCH+wood ash co-compost at 1.0 kg wood ash per 5 kg chicken litter increased by 168% above that composted without any wood ash whereas mean Zn contents of LCH-, BWS- and LWS-wood ash co-composts were suppressed by 11.4%, 16.3% and 29%, respectively (Fig. 3c). Optimising pH of chicken litter through co-composting with wood ash tended to improve quality of co-composts with respect to Zn.

Effect on total manganese (Mn)

The main effects of both bedding material and bird type as well as their interaction were highly significant (P <.001) on mean Mn content of the chicken litter+wood ash co-composts as it was the case for mean Cu and Zn. Wood ash generally had a positive effect on mean Mn content of all chicken litter-wood ash co-composts. Mean Mn contents were higher for chicken litter+wood ash co-composts with coffee husks as bedding material (LCH and BCH) than for wood shavings (LWS and BWS) (Fig. 3d) as it was the case for mean extractable Fe (Fig.3a). The largest mean Mn content (2863.0 ± 81.3 mg kg^{-1}) was from LCH co-composted with 4.0 kg wood ash per 5 kg chicken litter whereas the smallest (77.6 ± 3.6 mg kg^{-1}) was from LWS co-composted with 1.0 kg wood ash per 5 kg chicken litter (Fig. 3d). Within bedding material, mean extractable Mn contents were significantly higher for LCH+wood ash co-composts than they were for BCH-wood ash co-composts at all the wood ash rates whereas mean Mn content of LSW- and BWS-wood ash co-composts did not differ significantly (Fig. 3d).

Effect of optimising pH of different bird types and bedding materials co-composts with varying wood ash amounts on indicators of co-composts quality

Effect on electrolytic conductivity (EC)

The main effects of bedding material and bird type and their interaction significantly (P < .001) influenced mean EC of chicken litter+wood ash co-composts. Mean EC generally increased with wood ash rate with one exception for LCH- and BCH-wood ash co-composts at 1.0 kg wood ash per 5 kg chicken litter (Fig. 4a). Mean EC was higher for LCH- and BCH-wood ash co-composts than it was for LWS- and BWS-wood ash co-composts (Fig. 4a). Within bird type, mean EC was higher for broiler litter+wood ash co-composts (BCH and BWS) than it was for LCH- and LWS-wood ash co-composts (Fig. 4a). The highest mean EC (4.9 ± 0.1 mS cm^{-1}) was from BCH co-composted with 4.0 kg wood ash per 5 kg chicken litter, which was close to 4.4 ± 0.1 mS cm^{-1} for LCH also co-composted with 4.0 kg wood ash

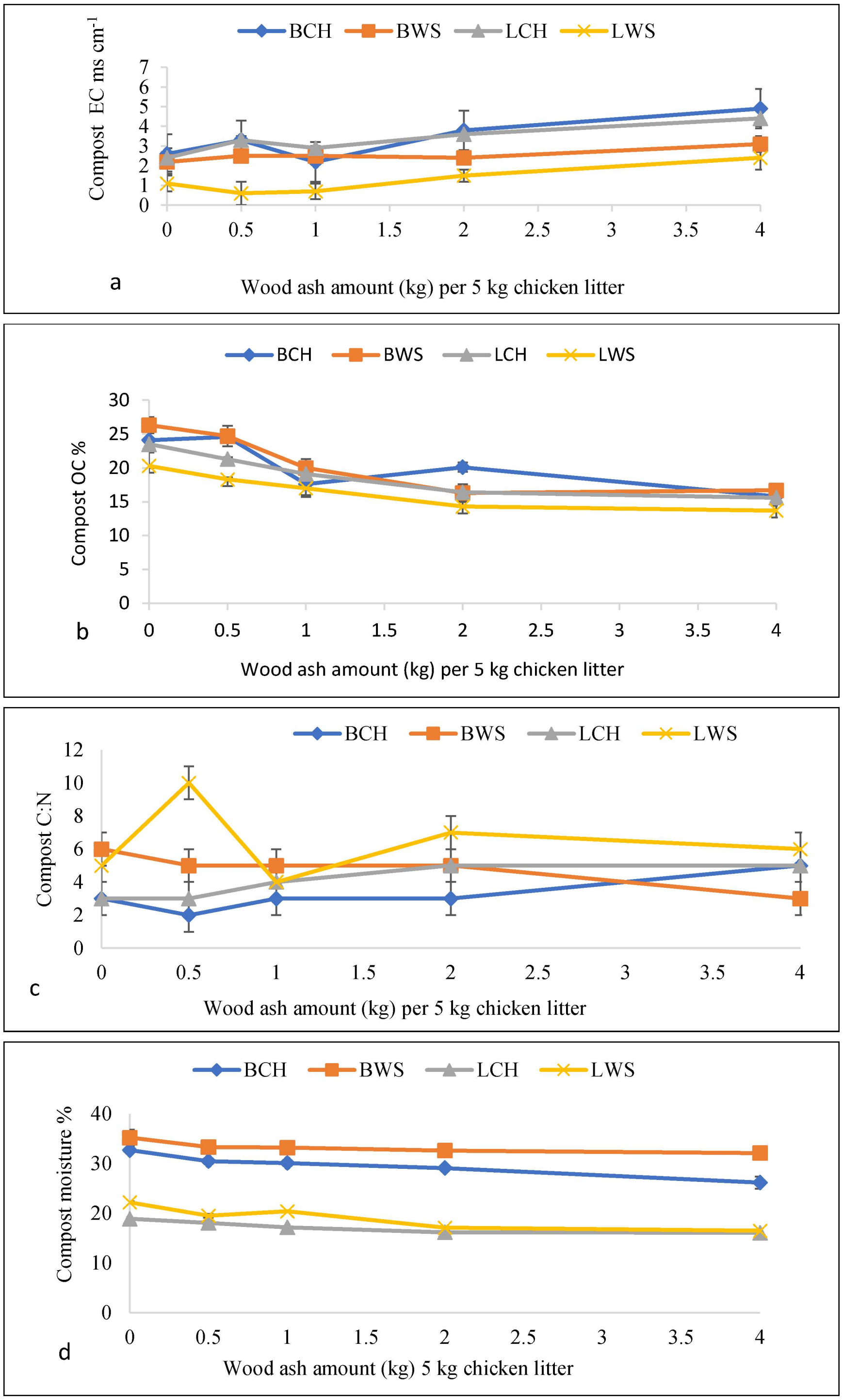

Figure 4a - d. Changes in EC, OC, C:N and moisture levels of layer and broiler litter with coffee husks and wood shavings through co-composting with varying wood ash amounts.

per 5 kg chicken litter; whereas the lowest EC (0.6 ± 0.6 mS cm^{-1}) was from LWS co-composted with 0.5 kg wood ash per 5 kg chicken litter (Fig. 4a). All EC values of the co-composts were smaller than those for their substrates (Table 1).

Effect on total organic carbon content (OC)

The main effect of bird type, bedding material, and the interaction of bird type and bedding material were highly significant ($P < 0.01$) on mean %OC content of chicken litter+wood ash co-composts. Mean OC content was generally higher for BWS- and BCH-wood ash co-composts than it was for LCH- and LWS-wood ash co-composts (Fig. 4b). The highest mean %OC (26.3 ± 3.5%) was from BWS composted without wood ash whereas the lowest (17.3 ± 0.7%) was from LWS composted with 4.0 t ha^{-1} wood ash (Fig. 4b). Generally, co-composting chicken litter suppressed mean %OC contents of all chicken litter+wood ash co-composts (Fig. 4b).

Effect on total carbon to nitrogen (C:N) ratio

There was highly significant effect of bedding material ($P < .001$), and the interaction of bird type and bedding material ($P = 0.003$) on mean C:N ratio of chicken litter+wood ash co-composts; implying that the effect of bird type on C:N ratio depended on bedding material. The main effect of bird type was not significant ($P = 0.321$). Mean C:N ratio was higher for chicken litter+wood ash co-composts with wood shavings as bedding materials (LWS and BWS) than it was for coffee husks (BCH and LCH) especially at smaller wood ash rates (Fig. 4c). Within bedding materials mean C:N ratio was higher for LWS+wood ash co-composts than for BWS+wood ash composts whereas mean C:N ratio of LCH+wood ash co-compost was higher than of BCH+wood ash co-composts at the same wood ash rates (Fig. 4c). The highest C:N ratio (10 ± 0.9) was from LWS co-composted with 0.5 kg wood ash per 5 kg chicken litter whereas the smallest (2 ± 0.6) was from BCH co-composted with the same wood ash ratio (Fig. 4c). Wood ash ratios 0.5 – 2.0 kg per 5 kg chicken litter generally had positive effects on mean C:N ratio of chicken litter+wood ash co-composts.

Effect on total moisture content (%MC)

The effects of bird type, bedding material, and their interaction were significant ($P < 0.05$) on %MC of chicken litter+wood ash co-composts, implying that the effect of bird type on mean %MC of chicken litter+wood ash co-compost also depended on the bedding material as it was also the case for mean EC, OC and C:N ratio. Mean %MC was significantly higher for BCH- and BWS-wood ash co-composts than it was for LCH- and LWS-wood ash co-composts (Fig. 4d), as it was also the case for mean %OC. Within bedding materials, mean %MC was higher for co-composts with wood shavings than it was with coffee husks as bedding material. The highest

%MC (35.2 ± 1.6%) was from BWS composted without wood ash whereas the smallest (16.1 ± 0.1%) was from LCH co-composted with 4.0 kg wood ash per 5 kg chicken litter (Fig. 4d). Mean %MC of chicken litter-wood ash co-composts generally decreased with increasing wood ash rates, implying co-composting chicken litter with wood ash to optimise pH of co-composts suppressed mean %MC of co-composts (Fig. 4d).

Discussion

Chicken litter type and the amount of wood ash needed to optimise pH of chicken litter+wood ash co-composts

The initial pH of LCH substrates (8.4) was higher than that of LWS and BCH (pH 7.9). This can be explained by the relatively higher Ca content of layer litter substrates (4.6 - 5.0%) compared to the 4.0 - 4.4% Ca of broiler litter substrates (Table 1). Layer feeds are supplemented with more Ca (3.8 -4.0%) than broilers (0.92%) to support eggshell formation. Excess $CaCO_3$ from excreta and feed spillage increases substrate pH and reduces the need for additional alkaline inputs (Pettit, 2017). In addition, unlike broiler litter which is cleaned out completely each time day-old chicks are restocked every 4-7 weeks, layer litter can be used for up to 55 weeks, resulting in higher accumulation of $CaCO_3$ and NH_4^+ ions with a positive effect on pH (MAAIF, 2019); thus less amounts of wood ash to optimise of the pH of LCH+wood ash co-compost. Coffee husks also release fewer organic acids during decomposition than wood shavings, thus possibly reducing suppressive effect on substrate pH, and hence the amount of wood ash needed to optimise (Ekinci *et al*., 2000). The higher wood ash requirement for broiler litter (BCH and BWS) was unexpected as substantial amounts of lime (CaO or $Ca(OH)_2$) are added to broiler litter to dehydrate the watery droppings to suppress pathogens (Plamondon, 2016).

Effect of optimising pH of different bird types and bedding materials co-composts with varying wood ash amounts on macronutrient contents

The higher mean %N of chicken litter-wood ash co-composts from coffee husks as bedding material than those from wood shavings can possibly be due to the inherent superior quality of coffee husks to wood shavings. However, the wood shavings-based litters (LWS and BWS) used in this study were relatively richer in N: 1.7% N (LWS) and 1.9% N (BWS) than LCH (1.4% N) and BCH (1.7%N). It is common practice in Uganda to harvest young, less lignified trees (Thurner *et al*. 2024) that are still actively growing with tissue richer in N. The suppressive effect of wood ash on total N content of the chicken litter+wood ash co-composts may be due to N loss through volatilisation as NH_3 with increasing alkaline conditions in the feedstock induced by wood ash (Schwenke, 2014). Fortunately, %N in the chicken litter+wood ash co-composts was superior to that in the chicken litter substrates. This is possibly attributed to the contribution of microbial biomass N during their death, and subsequent decomposition of the microbes during the composting process (L2 Espërance *et al*., 2024). The %N contents of all co-composts exceeded the 1% N threshold for standard high-quality composts (UNBS, 2017).

This higher P content of the co-composts is attributable to the high P contents of the wood ash added. It is also important to note that all chicken litter+wood ash co-composts had higher %P contents than those of the substrates from which they were derived as it was also the case for %N. Furthermore, even for BCH substrates which responded most positively to wood ash, there was no justification for adding wood ash > 2 kg per 5 kg chicken litter. The generally higher P contents in LCH- and BCH-wood ash co-composts compared with LWS- and BWS-wood ash co-composts can be explained by their higher N contents and associated increases in pH. Elevated pH enhances precipitation of Fe, Ca and Mg, which increases extractable P (Johan *et al*., 2021). The higher mean %P in layer litter+wood ash co-composts relative to broiler litter+wood ash co-composts up to 1.0 kg wood ash added can be explained by higher P accumulation from bird droppings during prolonged use of the litter compared to broiler litter that is cleaned out completely each time day old chicks are restocked every 4 –7 weeks (MAAIF, 2019). This effect was offset at wood ash rates of 2 kg and higher probably due to increased reaction of P and Ca under alkaline conditions. Reactions between P and Ca under alkaline conditions lead to formation of sparingly soluble Ca–P compounds (Johan *et al*., 2021), which may become available after application to acidic soils. Highest %P contents for LCH and LWS as well as for BCH where wood ash was added were observed at wood ash rates close to those for pH optimisation (0.85kg). All co-composts exceeded the 0.5% P threshold for high-quality composts (ARSO, 2018) by a wide margin, implying that the pH of chicken litters can be optimised through co-composting with wood ash without suppressing its mean fertiliser %P, as it was also the case for %N.

The consistently higher %K content of LCH+wood ash co-composts than other co-composts is attributed to their higher initial and final pH, which enhances potassium extractability (Agegnehu *et al*., 2021). Elevated concentrations of extractable Fe and Cu as observed in LCH increases competition with K for binding sites on organic matter, further improving K availability (Strobel, 2001). Generally, %K contents of all co-composts increased with increasing wood ash rates, attributable to the typically high %K content in wood ash. All mean %K contents in the chicken litter+wood ash co-composts exceeded the threshold for high-quality composts (Sullivan *et al*., 2018), highlighting the positive effect of optimising pH of the chicken litters through co-composting with wood ash on co-composts mean %K.

The generally positive effect of wood ash on %Ca of co-composts especially within wood ash rates for pH optimisation were attributed to its high Ca content (24%). The typically high %Ca contents of co-composts from broiler litters relative to those from layer litters could be attributed to the higher Ca content added to broiler beddings: 500 g CaO m^{-2} or 48.8 kg $Ca(OH)_2$ m^{-2} (Plamondon, 2016) to dehydrate the watery broiler litter and floor to forestall prevalence of parasitic insects such as mealworms (*Alphitobius diaperimis*), the beetles which can harbor bacterial pathogens such as *Salmonella* spp. and *Escherichia coli* (Kyakuwaire *et al*., 2019). Broiler litter is also widely treated with hydrated lime [$Ca(OH)_2$] to kill bacterial pathogens through elevation of litter pH to over 9.5 (Bennete *et al*., 2005). Though layers are fed higher Ca content (3.8 – 4.0%) than the broilers (0.92% Ca) (MAAIF, 2019), the Ca content used for treatment of broiler litter is considerably higher than that fed to layers. Mean %Ca content in all the chicken litter-wood ash co-composts exceeded the > 0.7% threshold for high-quality composts (SLSI, 2003).

The higher Mg contents of co-composts from chicken litter with wood shavings compared with coffee husks as bedding materials can be attributed to their lower %N contents and possibly the wider C:N ratios (100–500:1) for wood shavings versus 30–40:1 for coffee husks (Guthrie and Rogers, 2018). These conditions favour acidification through increased CO_2 and organic acid production, which inhibits Mg precipitation into sparingly soluble Mg-P, MgO, and Mg(OH), forms (Shemekite *et al*., 2014). This was evident in the lower optimum pH values of wood shavings-based co-composts compared with coffee husk-based co-composts. All detectable %Mg values in wood shaving-based co-composts also exceeded standard compost thresholds ($\geq$0.5 - 1.0%) (ARSO, 2018).

Effect of optimising pH of different bird types and bedding materials co-composts with varying wood ash amounts on micro-nutrient contents

The higher mean Fe content of chicken litter-wood ash co-composts with coffee husks as bedding material than those with wood shavings can be attributed to the generally higher extractable Fe content of the chicken litter substrates with coffee husks (3027 - 4306 mg kg^{-1}) than with wood shavings (1331 – 4306 mg kg^{-1}) as bedding materials. Coffee husks are richer in nutrients than wood shavings, including Fe (Dzung *et al*., 2013). Within bedding material, mean Fe content was higher (4306 mg kg^{-1}) in LCH substrates than in BCH substrates (3027 mg kg^{-1}). This explains the higher mean Fe content of the LCH+wood ash co-compost than of BCH+wood ash co-composts. Both layer and broiler feeds are supplemented with Fe in form of $FeSO_4$ to boost egg and meat colour (Lin *et al*., 2020). However, prolonged use of coffee husks as bedding material prior to disposal typical of layers, could have enhanced Fe accumulation in litter from layer droppings. Direct soil application of chicken litter substrates like BWS and LCH with such high mean Fe contents can induce phytotoxicity (Oyewumi and Schreiber, 2012). The Fe contents of the wood ash and chicken litter substrates generally exceeded the maximum permissible limit of 1000 - 2500 mg kg^{-1} in organic amendments for soil application (ARSO, 2018). The generally suppressive effect of wood ash on mean Fe contents of chicken litter+wood ash co-composts with coffee husks as bedding material (BCH and LCH) can be explained by the higher mean %N content of the co-composts and the subsequent higher optimum mean pH values in co-composts of LCH (9.9 ± 0.1) and BCH+wood ash co-composts (9.8 ± 0.1) than in LWS (9.3 ± 1.0) and BWS+wood ash co-composts (9.6 ± 1.0). High pH promotes precipitation of Fe^{2+} ions into $Fe(OH)_2$ thus, reducing the amount that is extractable (Zapata Marín *et al*., 2015). In contrast, the generally positive effect of co-composting LWS and BWS with wood ash on mean Fe content can be explained by the lower mean %N content of LWS- and BWS-wood ash co-composts and also the subsequent relatively lower pH of the co-composts. This is possibly attributed to production of organic acids from the N-poor and carbon-rich wood shavings during the composting process (Shemekite *et al*., 2014). Organic acids promote dissolution of FeO from wood ash, reducing the formation of sparingly soluble $Fe(OH)_2$ in the co-composts with wood shavings as bedding materials (Saleem *et al*., 2023).

Presence of micronutrients at potentially phytotoxic levels may degrade fertiliser quality of chicken litter composts (Wang *et al*., 2016). Mean Fe contents of all the chicken-wood ash co-composts were within the 1000 – 2500 mg kg^{-1} range considered standard for composts for soil application (ARSO, 2018). The suppression of the initially high Fe contents in the chicken litter substrates (3027 – 4306 mg kg^{-1}) and wood ash substrate (3928 mg kg^{-1}) in this study to within acceptable limits in the LWS co-composts, highlights the importance of co-composting chicken litter with wood ash prior to field application in preference to direct application of either substrates or mixtures of chicken litter with wood ash substrates as commonly practiced to minimise potential toxicities.

The generally higher mean Cu content for LCH- and BWS-wood ash co-composts than for LWS- and BCH-wood ash co-composts can be attributed to the higher mean Cu contents of LCH and BWS substrates than for BCH and LWS substrates. The overall suppression of mean Cu contents of all co-compost except LCH-wood ash co-compost at wood ash 0.5 - 1.0 kg wood ash range could be due to precipitation of Cu into $CuCO_3$ under alkaline conditions caused by presence of wood ash in the co-composts (Powell, 2020). In contrast, the smallest mean Cu content in LWS-wood ash co-compost, can be explained the fact that LWS substrates had the highest extractable Ca (5.0%), and probably, the associated carbonate as a result of supplementing layer feeds with lime ($CaCO_3$) to supply up to 3.8 – 4.0% Ca for proper egg shell development (MAAIF, 2019). High $CaCO_3$ content increases alkaline conditions in LWS-wood ash co-compost, which can result in precipitation of Cu as $CuCO_3$, thus reducing freely available Cu^{2+} ion concentrations in the co-compost. Also, mean Fe content was smallest (1331 mg kg^{-1}) in LWS substrate, a factor that can reduce competition between Fe^{2+} and Cu^{2+} ions for OM binding sites, thus resulting in increased binding of Cu in the chicken litter-wood ash co-composts to form stable organo-mineral complexes. Total Cu contents of all the chicken litter-wood ash co-composts were within the permissible limit of less than 300 mg kg^{-1} (UNBS, 2017).

The generally higher mean Zn content of LCH- and BWS-wood ash co-composts than of LWS- and BCH-wood ash co-composts can be explained by the higher extractable Zn in LCH substrate and BWS substrate than in BCH and LWS substrates; the higher mean Fe content in BWS and LCH substrates; higher mean Fe contents of the layer litter-wood ash co-composts with LCH; and the relatively higher OM content (67%) of BWS substrate determined in this study. Ferrous ions have highest affinity for binding onto OM sites in the order $Fe^{2+} > Cu^{2+} > Ca^{2+} > Zn^{2+} > Mn^{2+} > Mg^{2+}$, hence can increase Zn^{2+} extractability in co-composts (Buni, 2014). The highest mean Zn content from BCH co-composted with 1 kg wood ash can be explained by the higher total Zn content in BCH and BWS than in LCH and LWS substrates. Chicken farmers commonly supplement broiler diet with elevated Zn content in form of $ZnSO_4$; 100 mg Zn kg^{-1} and 80 mg Zn kg^{-1} for 1 - 21 and 22 - 42-day-old broilers, respectively, for improvement of body weight gain as compared to 29 – 44 mg Zn kg^{-1} for layer diet to enhance egg production, quality and hatchability (Abd El-Hack *et al*., 2021). This practice leads to excretion of excess Zn onto broiler litter (Kaur and Garg, 2021). The drastic reduction in Fe concentration in BCH-wood ash co-compost at 1.0 -2.0 kg wood ash added might have increased binding of Fe^{2+} ions in the co-compost to OM sites leaving Zn^{2+} and Cu^{2+} ions freely extractable (Buni, 2014). Similarly, the smallest mean Zn content in LWS-wood ash co-compost can be explained by the lowest Zn content in the chicken litter substrate. Good enough, mean Zn content in all the chicken litter-wood ash co-composts were within the maximum permissible limit of d" 2800 mg Zn kg^{-1} for high quality composts for soil application (U.S. EPA, 1993).

The higher mean Mn content of LCH- and BCH-wood ash co-composts than for LWS- and BWS-wood ash co-composts can be attributed to the higher mean Mn contents of their respective substrates. Coffee husks are inherently richer in nutrient contents than wood shavings (Dzung *et al*., 2013), hence the need to restrict wood ash to the rates for optimising pH of the co-composts to avoid either low or excess Mn or other micronutrients that can limit the use of such composts (Bulyaba *et al*., 2020). Mean Mn contents of all the co-composts with coffee husks as bedding material; BCH and LCH, exceeded the maximum permissible limit of 200 - 800 mg

kg^{-1} (ARSO, 2018), pointing to a limitation to sustained use of chicken litter+wood ash co-composts with coffee husks as bedding material as a soil amendment due to potential Mn-induced phytotoxicity. Fortunately, the Mn-induced phytotoxicity may not come up in soil under amendment with the chicken litter+wood ash co-composts with increased pH and increased liming potential. The chicken litter+wood ash co-composts with higher pH than the soil pH, upon increasing the soil pH leads to conversion of some of the soluble Mn into unavailable solids thus reducing the phytotoxicity (Bougnom *et al*., 2020).

Effect of optimising pH of different bird types and bedding materials co-composts with varying wood ash amounts on indicators of co-composts quality

Compost EC is a measure of the total amount of salt content in the compost, and an important indicator of the nutrient concentration and safety of the compost for soil application (Liu *et al*., 2018). The general increase in EC observed with incremental wood ash rates was expected. Wood ash is loaded with salts in form of nutrient oxides (K_2O, CaO, MgO, Na_2O, P_2O_5 and Fe_2O_3), which dissolve in the metabolic moisture generated during composting to release ions which increase the EC, possibly with a positive effect on fertiliser quality of the co-compost, provided the EC is within the recommended 2 – 4 mS cm^{-1} range (Mangan *et al*., 2013). The higher EC for the chicken litter+wood ash co-composts with coffee husks than with wood shavings as bedding materials can be attributed to the generally higher nutrient concentrations in the co-composts with coffee husks as bedding material. The N, P, Fe and Mn contents were significantly higher in BCH- and LCH-wood ash co-composts than they were in BWS- and LWS-wood ash co-composts. This was also the case for K and Cu of LCH-wood ash co-composts; and Zn for BCH-wood ash co-compost. Ions of these nutrients (NH_4^+, NO_3^-, PO_4^-, K^+, Fe^{2+}, Cu^{2+}, Zn^{2+} and Mn^{2+}) increase EC of the co-composts (Liu *et al*., 2018). Upon decomposition, BCH- and LCH substrates release more PO_4^- and Mn^{2+} ions that raise their EC. The higher EC for BCH-wood ash co-composts than LCH-wood ash co-composts could also be due to the practice of supplementing broiler diet with higher amount of table salt (0.4 - 0.6% NaCl) to meet the Na and Cl requirements for improved health and growth in broilers (Milles and Butcher, 2019), compared to 0.15% NaCl added in layer feeds for optimisation of egg production (NRC, 1994). Increased excretion of Na^+ and Cl^- ions in broiler urine elevates the EC of broiler litter substrate and subsequently wood ash co-composts (van der Hoeven-Hangoor, 2014). EC ranges 2 – 4 mS cm^{-1} are considered safe for soil application by the World Health Organisation standard (Sullivan *et al*. 2018) but over > 5 mS cm^{-1} as observed for chicken litter and wood ash substrates may induce osmotic stress and impair water and nutrient uptake in the rhizosphere with detrimental soil-plant salt effects (Liu *et al*., 2018).

At all the studied wood ash rates, mean EC values of the chicken litter-wood ash co-composts were within the limits of 2 - 4 mS cm^{-1} range in composts recommended for soil application, except of BCH-wood ash co-compost (4.9 mS cm^{-1}) and LCH-wood ash co-compost (4.4 mS cm^{-1}) at wood ash rate 4.0 application rate which exceeded the thresholds in composts safe for soil application (Sullivan *et al*., 2018). Fortunately, even composts with high EC values can still be applied at low applications rates or less frequently on soils that are neither saline nor sodic (Chen *et al*., 2022). Co-composting helps to immobilise salt cations including Na^+ and NH_4^+ ions, potentially suppressing their phyto-toxicity after soil application (Wang *et al*., 2016). The results further highlight the need to co-compost chicken litter and wood ash substrates prior to soil application to ameliorate potential salt toxicities from direct application of the substrates.

The purpose of composting is to reduce volume and bulkiness of wastes through loss of moisture and carbon so as to stabilise carbon prior to field application (Sullivan *et al*., 2018). However, application of wood ash in organic wastes prior to composting enhances OC degradation and CO_2 loss due to improved aeration, further reducing the OC content of the chicken litter+wood ash co-composts (Kuba *et al*., 2008). The higher mean %OC content for the broiler litter+wood ash co-composts than layer litter+wood ash co-composts can be explained by the higher OC content of the broiler litter substrates. Broiler litter is changed or cleaned out more frequently each time a new stock of birds is brought in before it has undergone substantial degradation compared to layer litter that can remain in use up to the age of 72 weeks (MAAIF, 2019).

The C:N ratio is an important indicator of compost quality, maturity and stability, dependent on the original materials (Sullivan *et al*., 2018). The generally higher mean C:N ratio for BWS- and LWS-wood ash co-composts than with BCH- and LCH-wood ash co-composts at wood ash rates 0 – 2.0 t ha^{-1} was expected. The generally low C:N ratios (2 ± 1.6 to 10 ± 0.9) of all the chicken litter-wood ash co-composts can partly be attributed to the low C:N ratios (18 – 19) of the chicken litter substrates used in this study. Narrow C:N ratios lead to rapid degradation of substrate and loss of C as CO_2 and N volatilisation as NH_3 as the compost pile temperatures increase and pH increases above 7.0, and to also lead to low C:N ratio in the compost (Ekinci *et al*., 2000). At all the wood ash rates, mean C:N ratios for all the chicken litter-wood ash co-composts were below the ideal thresholds for use as organic fertiliser (UNBS, 2017). Such low C:N ratios can exacerbate N loss in soil through leaching as NO_3^- ions, or ensure availability of N if applied at the right rate, time and place for crop uptake of the NO_3^- ions (Sullivan *et al*., 2018).

The higher mean %MC (moisture content) for the broiler litter+wood ash co-composts (BCH and BWS) than for the layer litter-wood ash co-composts (LCH and LWS) was expected. The initial %MC of BCH and BWS substrates was higher (13.2 - 15.4%) than it was for LCH and LWS substrates (10.6 – 12.4%). Broiler feed is normally supplemented with table salt (0.4 – 0.6% NaCl) which causes broiler birds to drink excess water and excrete watery droppings onto their litter compared to the layers (Milles and Butcher, 2019). The higher mean %OC content of BCH- and BWS-wood ash co-composts than for LCH- and LWS-wood ash co-composts can also elevate the water holding capacity of co-composts and increase %MC attributable to high charge density and large surface area of OC for binding and retention of water molecules (Hida *et al*., 2016) as observed especially for co-composts with wood shavings as bedding material. The general decrease in mean %MC of the co-composts with increasing wood ash rates, was contrary to the finding of Bougnom *et al*. (2020) who reported that %MC of manure+wood ash co-composts especially of cattle manure+wood ash co-composts increased proportionally with the amounts of wood ash added to the manure. This may be explained by: the lower moisture content of the wood ash used (9.6%) than of the chicken litter substrates (10.6 - 15.4%), which can enhance absorption of metabolic moisture generated during the decomposition process hence, lowering the moisture content of the co-composts by wood ash. Larger surface area of wood ash possibly also promoted absorption and retention of more moisture in the co-composts (Rafat, 2012). Small volumes of organic materials in the small composting boxes used did not aid accumulation and retention of metabolic water generated during the composting process (Sullivan and Miller, 2001). The %MC of BCH- and BWS-wood ash co-composts conformed to the 20% threshold recommended for compost to be neither dusty nor heavy and clumpy during soil application (Miller and Mann, 2021). However, none of the %MC of the co-composts met the 35% MC threshold for Uganda (UNBS, 2017) or 40 - 50% MC for the US Composting Council (http://compostingcouncil.org/test-methods-parameters/). The recommended ideal bin or chamber size to ensure that the compost pile is of sufficient volume to prevent rapid dissipation of heat and moisture yet small enough to allow good aeration is at least 1cubic yard (0.9 m × 0.9 m × 0.9 m, the equivalent to 1 m^3 (Trautmann, 1996).

Controlled and field trials are needed to validate the liming efficacy and crop yield impact of these co-composts, for translation from laboratory-scale findings into agronomic recommendations for widespread and responsible adoption.

Conclusion

This study demonstrated that co-composting chicken litter with wood ash was a viable and effective strategy for producing high-quality organic lime-fertiliser suitable for field application. It showed that the wood ash quantity needed to optimise co-compost pH was not a blanket amendment rate but depended on the interaction between bird type and bedding material, reflecting the underlying chemical conditions of each litter substrate. The pH of layer litter with coffee husks as bedding materials (LCH)+wood ash co-compost was optimised at 9.9 with the smallest amount of wood ash (0.85 kg wood ash per 5 kg chicken litter), making it the most efficient to optimise. In contrast, the pH of broiler litter with the same bedding material (BCH)+wood ash co-compost was optimised 9.8 with 1.83 kg wood ash per 5 kg chicken litter, making it the least efficient.

Besides pH optimisation, the superior macronutrient contents (%N, %P, %K and %Ca) of the resulting co-composts to the thresholds considered standard for high quality composts, confirmed their potential as high-quality organic fertilisers. The alkaline conditions achieved during the co-composting process did not compromise the extractable phosphorus content, which was significant given that P precipitation under high pH is a well-documented concern. The observed Mg precipitation in coffee husk-based co-composts, however, warranted further investigation to establish whether it became plant-available upon incorporation into acidic soils. Though the co-composting process effectively neutralised problematic levels of Fe and electrical conductivity within safe thresholds for field application, the elevated Mn concentrations recorded in coffee husk-based co-composts remained a concern that experts needed to plan for during application of the co-composts, such as controlling the co-composts application rate and timing the application to match crop nutrient demand. Overall, these findings confirmed that chicken litter-wood ash co-composting represents a practicable, low-cost approach to recycling agricultural waste into a nutrient-rich soil amendment with an increased liming potential, provided that litter-specific amendment (wood ash) rates are given due consideration.

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Conflict of interest

The authors declare no conflict of interest

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