scientific reports

OPEN

Dynamics of co-composting of pineapple harvest and processing residues with poultry litter and compost quality

Elvire Line Sossa[1✉], Codjo Emile Agbangba[2,3], Tatiana Windékpè Koura[4], Oladéji Jamali Ayifimi[1], Issiakou Alladé Houssoukpèvi[1], Nadège Donsaré Bana Bouko[1], Florent Yalinkpon[4] & Guillaume Lucien Amadji[1]

The production of pineapple generates significant quantities of harvest and processing residues, which are very little used. This study evaluates compost quality using pineapple residues and poultry litter. Five composting treatments were tested, varying following proportions of crown, pineapple processing wastes (PPW), pineapple harvest residue (PHR), and poultry litter (PL). Various parameters were analyzed, including pH, electrical conductivity, CO_2 evolution rate, water content, organic carbon, nitrogen compounds, phosphorus, potassium, calcium, magnesium, copper, and zinc. Additionally, the perceptions of producers and processors regarding compost quality were gathered. Results indicated that microbial decomposition increased temperature, pH, CO_2 release, and nitrogen content while reducing electrical conductivity and organic carbon. Composts demonstrated favorable characteristics for crop fertilization, with C4 (75% PHR + 25% PL) compost showing the best chemical properties. Producers and processors preferred the color, odor, and structure of C4 (75% PHR + 25% PL) and C5 (56.25% crown + 18.75% PPW + 25% PL) composts. Overall, composting pineapple residues with poultry litter yields composts suitable for plant fertilization, particularly C4 and C5 formulations, offering potential for sustainable waste valorization in agriculture.

Faced with population growth, production systems are under strong pressure to increase productivity and meet ever-increasing food needs[1,2]. To this end, intensive agricultural practices such as excessive use of chemical inputs on agricultural land, repeated tillage, short-cycle crop rotations and monoculture lead to environmental pollution, reduction in organic matter content, erosion and degradation of soil[3–5]. Growing public concerns for proper soil management, and human health, have encouraged farmers to seek safer and environmentally friendly alternatives[6]. Of these needs, the management of organic waste stands out, because it contributes to the transition from a linear production model to a circular production model through the reintegration of disposable materials into new production processes[7]. Indeed, agricultural activities generate a significant quantity of biomass residues from agricultural activities; animal breeding waste; food waste and agricultural by-products from processing[8,9]. This is often the case for pineapple production and processing systems[10] and poultry farming.

Pineapple (*Ananas comosus*) is a fresh fruit widely cultivated in tropical and subtropical regions of Africa due to its importance in the countries' economies[11]. In Benin, this fruit crop is mainly cultivated in South Benin by around 70% of producers[12]. Fresh pineapple harvest residues production (fresh pineapple biomass) are estimated at around 90–150 t ha^{-1} and contain on average 678 g kg^{-1} of organic matter, 10 g kg^{-1} of total nitrogen,

[1]Research Unit in Sustainable Management of Soil Fertility, Laboratory of Soil Sciences, Faculty of Agronomics Sciences, University of Abomey-Calavi, Calavi, 01, P.O. Box 526, Cotonou, Benin. [2]Laboratory of Research in Applied Biology, Department of Environment Engineering, University of Abomey-Calavi, Calavi, 01, P.O. Box 2009, Cotonou, Benin. [3]Laboratory of Biomathematics and Forest Estimations, University of Abomey-Calavi, Calavi, 03, P.O. Box 2819, Cotonou, Benin. [4]National Institute of Agricultural Research of Benin, 01, P.O. Box 884, Abomey-Calavi, Benin. ✉email: elvas2@yahoo.fr

1

approximately 1 g kg⁻¹ of phosphorus and 11 g kg⁻¹ of potassium[13]. Pineapple processing by factories generates around 5 tons of organic waste (crowns, pulp and peels) per day in Benin[14]. These residues constitute an important source of carbon[15] and contain on average 10 g kg⁻¹ of nitrogen; 2 g kg⁻¹ of potassium, 3 g kg⁻¹ of calcium, phosphorus and magnesium; 123 mg kg⁻¹ of zinc and 15 mg kg⁻¹ of Copper[16]. Despite their high availability, pineapple harvest and processing residues are poorly valorized in Benin. Pineapple harvest residues are the typical case of lignocellulosic biomass that have a very slow speed of decomposition when restituted to soil. To improve the speed of decomposition of plant material, work has suggested co-composting with ferments such as poultry litter[17]. Interestingly, over last 20 years, poultry farming has grown considerably in most countries, which has led to an increase of poultry waste production, and therefore an increase in the quantity of excrement[18]. Poultry waste, harvest and pineapple processing residues containing various nutrients as nitrogen, phosphorus, potassium, calcium, magnesium, zinc, copper; causes the contamination of soil and water, the spread of unpleasant odors and the emission of greenhouse gases, if they are not properly treated[19,20]. Improper management of pineapple wastes would result in the deterioration of environmental quality (soil degradation, water pollution, air pollution, biodiversity loss) which can be attributed mainly to sugar-rich components degradation[21–24]. Therefore, it is timely to implement effective strategies to recycle waste and minimize its negative impacts on the environment[18,25].

Co-composting is a widely accepted, simple and inexpensive solution to transform organic waste into a stable, non-toxic, nutrient-rich product[2,26]. Good quality composts production involves use of agricultural waste and its by-products which become available in intensive agriculture systems[6]. Compost application to cultivated land as a soil amendment improves physical structure and biological fertility of soil, as organic additive to strengthen the natural defense of the soil against soil-borne plant pathogens[4,6,27].

However, adoption level of composts is low, despite their proven usefulness in restoring and maintaining soil fertility. One of main reasons is that there is not enough information and certainty about their nutrient content and quality depending of types of raw materials used[4,28]. Producers often lack the time, space, information and skills necessary to produce compost[29–31]. Pineapple waste decomposition is slow because of their fibrous nature and acidity[30]. In this context, considerable efforts are needed to encourage organic fertilizers adoption through promotion of composting practices[28]. Recently, some studies have focused on the co-composting process of the pineapple harvest residues with different supplementary materials at an experimental scale[32–38]. In Benin, very little research has focused on testing composting of pineapple harvest and processing residues and on composts assessing criteria by producers. The main research question is: What is the combination of pineapple harvest and processing residues co-composted with poultry litter that gives superior quality compost appreciated by producers?

The general objective of this study is to evaluate in participatory way with actors (pineapple producers and processors), quality of compost based on harvest residues, pineapple processing and poultry litter in southern Benin. Specifically, it is a question of evaluating dynamics of pineapple harvest and processing residues decomposition and quality of composts (through determination of their macronutrients and main micronutrients content; and CO_2 release), depending on types and doses of composted materials. The producers and processors' perception of the final compost quality was evaluated after their participation in each composting stage.

Materials and methods
Study area and experiment material
The study was conducted in Allada municipality (6° 20′–6° 50′ N and 2° 00′ E, 3 to 175 m altitude) in Atlantic department, and in south of Benin. Allada's plateau, the main pineapple production area in Benin, is located in a tropical savannah climate with dry winter (Aw) according to Köppen–Geiger climate classification scheme[39]. This area thus has a climate with two rainy seasons (April–July and September–November) and two dry seasons (December–March and July–August). Average precipitation is 1100 mm year⁻¹. Average temperature varies from 25 to 29 °C. Poultry litter used for this experiment was collected from a private poultry farm in Allada municipality. The pineapple harvest residues (including leaves and stems) used were collected from a pineapple producer field and transported to the composting site; while the pineapple processing residues (including peel, core, pulp, and crown) were obtained from a pineapple processing company in Allada municipality These pineapple harvest residues and crown were shredded into 10–20 cm pieces using a shredder.

Composting process
In this study, the windrow composting method was used for compost manufacture[40]. Five types of composts were produced by combining different quantities of pineapple processing residues, pineapple fruit crowns, pineapple harvest residues and poultry litter (Compost 1 = 37.5% Crown + 18.75% Processing residues + 18.75% Harvest residues + 25% Poultry litter; Compost 2 = 75% Crown + 0% Processing residues + 0% Harvest residues + 25% Poultry litter; Compost 3 = 0% Crown + 75% Processing residues + 0% Harvest residues + 25% Poultry litter; Compost 4 = 0% Crown + 0% Processing residues + 75% Harvest residues + 25% Poultry litter; Compost 5 = 56.25% Crown + 18.75% Processing residues + 0% Harvest residues + 25% Poultry litter) (Table 1). The windrows were arranged following a Fisher block with 03 replications and 05 treatments corresponding to different types of compost produced. The windrows were installed on elementary plots (1.5 m × 1 m) disposed on slope of 10% in order to avoid water stagnation below. Polyethylene bags were used to cover the soil at the level of each elementary plot. For each compost type, the windrows installed had a weight of 1.5 tons and were arranged in 5 layers each consisting of 300 kg of raw materials. For each layer, the poultry litter were disposed on top of the different pineapple residues used according to the treatment. Poultry litter quantity was uniform in all windrows because it was used as a ferment for composting. A water add of 22 L (02 watering cans of 11 L) was made between two successive layers during windrows installation. Each window was covered with a polyethylene bag to protect

Composted materials	Compost 1	Compost 2	Compost 3	Compost 4	Compost 5
Crown	112.5 (37.5)*	225 (75)	0 (0)	0 (0)	168.75 (56.25)
Processing residues	56.25 (18.75)	0 (0)	225 (75)	0 (0)	56.25 (18.75)
Harvest residues	56.25 (18.75)	0 (0)	0 (0)	225 (75)	0 (0)
Poultry litter	75 (25)	75 (25)	75 (25)	75 (25)	75 (25)
Total	300 (100)	300 (100)	300 (100)	300 (100)	(100)

Table 1. Quantity (kg) and rate of materials (%) used per layer for each type of compost produced. *Values in parentheses represent incorporation rate of materials by compost type.

it against rainwater and favor the rise of temperature. The windrows were manually turned with a shovel four times at monthly intervals during composting for aeration. The total duration of composting is approximately four months. Any additives or accelerators have not been used to enhance decomposition during the composting process.

Physicochemical characteristics of raw materials

Each composting material (harvest residues, fruit crown, pineapple processing residues) was sampled before windrow establishment, in view to determine its dry matter content and its physicochemical characteristics in the laboratory. Three samples of each composting material were taken. The water content was determined by drying in an oven at 105 °C, until constant weight. The samples to be analyzed were dried in an oven at a temperature of 65 °C. They were then weighed and crushed using a mill, before analyses. pH, organic carbon (Corg), total nitrogen (Nt), total phosphorus (P), potassium (K), manganese (Mn), calcium (Ca), magnesium (Mg), Copper (Cu) and Zinc (Zn) were measured for this purpose.

Residues decomposition dynamics during composting

Direct measurements of pH, temperature, and humidity were carried out at two (02) day intervals on each windrow using a digital thermometer, pH meter and humidimeter. On each date, these measurements were repeated 9 times at different locations on each windrow.

At each turning at monthly intervals, a composite sample (mixture of five samples taken at different location) was taken by windrow for determination of water content, pH, electrical conductivity, Corg, nitrate-N (NO_3-N), ammonium-N (NH_4-N), total nitrogen (Nt) and CO_2 release at the laboratory.

Physicochemical analysis of composts

At the end of composting (03) composite samples were taken per compost for their water contents determination and chemical analysis such as pH, electrical conductivity, porosity, organic carbon, nitrate-N (NO_3-N), ammonium-N (NH_4-N), total nitrogen (Nt), CO_2 release, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), copper (Cu) and Zinc (Zn).

The compost's water content was determined by drying in an oven at 105 °C until constant weights[41]. Total nitrogen, nitrate-N, and ammonium-N, were measured by Kjeldahl method[42], total phosphorus by the method of Black[43]; bases (K, Mn, Ca, Mg, Cu and Zn) by the method of Helmke and Sparks[44], organic carbon by the method of Bell[45]; pH and electrical conductivity by the potentiometric method in a respective soil/distilled water ratio of 1/2.5[46], by reading using a pH meter and a conductivity meter. CO_2 evolution was evaluated Via the Alkaline Trap Method. So, a 25 g fresh compost sample, and a vial containing 20 mL of 0.11 M NaOH were placed in glass canning jars of 1 L, with airtight lids. The sealed jars were placed in an incubator at 37 °C. Carbon dioxide was trapped for periods of 0–24, 24–48 and 48–72 h. Each incubation included a blank, consisting of a sealed jar containing a NaOH trap, but no compost. The respiration rate from the compost sample was expressed as a fraction of the total C content of the compost. The respiration rate was calculated as R = A B [Vblank – Vsample] M^{-1} D^{-1}; where: R = respiration rate, mg CO_2-C g C^{-1} d^{-1}, A = millequivalent weight of CO_2-C, 6 mg meq^{-1}, B = molarity of HCl used to titrate NaOH, mmol mL^{-1}, Vblank = volume of HCl used to titrate the NaOH trap from the no-compost blank, mL, Vsample = volume of HCl to titrate the NaOH trap exposed to compost respiration, mL, M = mass of carbon in the sample (g), D = time (day)[47,48].

Sensory evaluation of compost quality

A group of 50 producers and processors were selected and filtered based on their sensory acuity on elemental odor and color. The examination consisted of asking them to identify the elemental odor and color, on coded samples of organic matter at different stage of mineralization (fresh, semi-decomposed and highly decomposed pineapple residues) on color and odor criteria[38]. After this step, the first 25 better producers and processors were retained and were invited to give their perception on quality of different composts produced, using physical indicators (color, odor, structure, pieces of residue presence)[49]. For this purpose, samples were taken 30–40 cm inside each compost pile at different locations and mixed to obtain a composite sample per compost type. The composts were coded and presented to producers for evaluation. For each criterion, a batch of 15 pebbles is distributed by each producer among the five composts, according to their perception. Under the evaluation, each producer expressed their overall preference.

Statistical analysis

An analysis of variance (ANOVA), followed by the post-hoc test of least significant difference (LSD), was performed after checking the normality of the data and the homogeneity of variances to evaluate and compare the composition of raw materials used in compost manufacturing.

To compare the mineralization dynamics of elements in different composts, a linear mixed-effects model for longitudinal data was used, considering replications as a random factor and compost types and dates as fixed factors. Marginal and conditional R^2 of the linear mixed-effects model were calculated using the function r.squared GLMM from the "MuMIn" package[50], which implements the method developed by Schielzeth and Nakagawa[51]. The marginal R^2 gives the variance explained by the fixed effects, while the conditional R^2 gives the variance explained by the entire model, including both fixed and random effects. Evolution curves of the different parameters over time for each compost were also created using the "ggplot2" package.

Moreover, the evolution of temperature, pH, and moisture of the composts every 2 days during composting was visualized using the "ggplot2" package. Linear mixed-effects models, followed by the post-hoc Tukey test, were conducted to compare the quality of the final composts based on the studied parameters, considering the compost type as a fixed factor and the replication as a random factor. Four linear mixed effect models were tested including the full model, random intercept model, random slope model, and random intercept and slope model. The best model was selected based on the Akaike Information Criterion (AIC), where a lower AIC indicates a more appropriate model. The contribution of the random factor (replication) to the total variability of the data for different parameters was evaluated by calculating the Intra-Class Correlation (ICC) and the variability due to replication. Barplots were also created with letters indicating significant differences at a 5% significance level between compost types for the different studied parameters.

A t-test was used to compare the mean value of the sensorial parameter for a given treatment to the overall mean for all treatments[52]. The most characteristic variables of a treatment are those whose associated t-value are greater in absolute value than 2. Moreover, if this value test is positive for a treatment, the sensorial variable has a high value for the treatment under consideration. In contrast, if the value is negative, the treatment has a low value for the parameter.

Various international standards (French NFU 44–051, Germany, Great-Britain, Switzerland, Canada and European) have been used to discussed values of compost parameters during and at the end of composting.

All analyses and visualizations were performed using R software version 4.3.0[53].

Declarations

Authors declare that the study which is carried out on pineapple has received the authorization of the institutions involved and the species concerned is not threatened or registered on the IUCN list. Authors also declare to have been permission from pineapple producers' associations and processors to collect pineapple residues for field experiments.

Results

Characteristics of initial raw materials

Table 2 shows the initial characteristics of raw materials used for the composting process. Except phosphorus, potassium and copper, all other chemicals characteristics (pH, carbon; nitrogen, C:N ration, calcium, magnesium and zinc) significantly varied ($p < 0.05$) within the composted raw materials (harvest residues; crown; pineapple processing waste; poultry litter). Poultry litter had a neutral pH (7.71 ± 0.77) while harvest residues, crown and pineapple processing wastes had acidic pHs (4.61 ± 0.33, 5.92 ± 0.48 and 4.82 ± 0.65 respectively). Furthermore, carbon (C) content of pineapple harvest residues (485.69 ± 50.64 g kg^{-1}) was not significantly different from those of pineapple crown (510 ± 11.75 g kg^{-1}) and processing wastes (543.37 ± 1.08 g kg^{-1}). However, poultry litter contained respectively 2, 2.5 and 2.5 times less C than harvest residues, crown and pineapple processing wastes. The C:N ratio was lower in poultry litter (16.65 ± 6.4) and was higher in harvest residues, crown and pineapple processing wastes. On the other hand, the total nitrogen content of poultry litter was significantly

Raw materials	Harvest residues	Crown	Pineapple processing waste	Poultry litter	P-value
pH	4.61 ± 0.33 c	5.92 ± 0.48 b	4.82 ± 0.65 bc	7.71 ± 0.77 a	0.000696***
Carbon (g kg^{-1})	485.69 ± 50.64 a	510 ± 11.75 a	543.37 ± 1.08 a	203.63 ± 49.72 b	$9.78e^{-06}$***
Total nitrogen (g kg^{-1})	7.98 ± 1.4 b	6.533 ± 10.32 b	9.987 ± 9.11 ab	12.227 ± 38.02 a	0.0397*
C:N ratio	60.86 ± 6.82 b	78.06 ± 11.46 b	54.41 ± 5.08 b	16.65 ± 6.4 c	$7.94e^{-05}$***
Phosphorus (mg kg^{-1})	19.91 ± 11.75 ab	27.88 ± 3.35 a	16.98 ± 7.66 ab	7.94 ± 1.62 b	0.056
Potassium (g kg^{-1})	17.11 ± 7.52 a	31.37 ± 2.66 a	24.22 ± 10.73 a	24.21 ± 8.51 a	0.26
Calcium (g kg^{-1})	21.46 ± 2.09 b	21.21 ± 0.29 b	21.09 ± 4.28 b	364.96 ± 181.71 a	0.00355**
Magnesium (g kg^{-1})	8.86 ± 3.88 b	9.63 ± 0.34 b	8.21 ± 2.82 b	26.52 ± 8.92 a	0.00587**
Cupper (mg kg^{-1})	10.41 ± 1.82 a	12.92 ± 1.02 a	15.42 ± 3.63 a	13.23 ± 4.06 a	0.291
Zinc (mg kg^{-1})	11.25 ± 0.29 b	11 ± 1.58 b	10.05 ± 1.45 b	87.35 ± 15.39 a	$3.77e^{-06}$***

Table 2. Chemical composition variation of raw materials used for composting. Parameters with the same letter are not significantly different at the 5% level; *statistically significant at $0.01 \le p < 0.05$; **statistically significant at $0.001 \le p < 0.01$; ***statistically significant at $p < 0.001$.

high (12.227 ± 38.02 g kg⁻¹) compared to that of harvest residues and pineapple crown. Among pineapple residues, nitrogen content of pineapple processing wastes was higher than those of harvest residues and crown. In addition, calcium (Ca), magnesium (Mg) and zinc (Zn) contents of poultry litter were relatively higher (364.96 ± 181.71 g kg⁻¹, 26.52 ± 8.92 g kg⁻¹ and 87.35 ± 15.39 mg kg⁻¹) compared to those of harvest residues, crown and pineapple processing wastes.

Decomposition dynamics evaluation during composting

Evolution of temperature, pH and humidity of composts

Temperature.   Figure 1 shows evolution of ambient temperature and the temperature of different types of compost. Ambient temperature varied between 21.85 and 37.80 °C throughout the composting period. Composts C5 (41.22 °C), C3 (43.33 °C) and C1 (44.48 °C) were in the mesophilic phase (< 45 °C) on the first day, while composts C2 (46.30 °C) and C4 (48.40 °C) were in the thermophilic phase (> 45 °C). Compost C1 reached the thermophilic phase (54.29 °C) on the second day, and maintained a temperature between 52.44 and 62.19 °C until the 17th day, then gradually joined a second mesophilic phase from 18th to 43rd day. Compost C2 remains in the thermophilic phase and maintains a temperature between 52.22 and 60.04 °C until the 17th day, then gradually reached a second mesophilic phase from the 18th to the 37th day. Compost C4 also remains in the thermophilic phase with a temperature between 50.22 and 62.26 °C until the 19th day, where it gradually reached a second mesophilic phase. The compost C5 joined the thermophilic stage on the 2nd day where temperatures were maintained between 51.26 and 59.07 °C from the 3rd to the 17th day before decreasing to less than 45 °C from the 18th to the 37th day, leading it thus in a second mesophilic stage. However, compost C3 entered the thermophilic stage with a temperature of 45.62 °C on day 2 and temperatures were maintained between 45.07 and 57.96 °C from 3rd to17th day before gradually decreasing below 45 °C where it entered in a second mesophilic stage from 18 to 37th day. At the end of composting, maximum compost temperatures were 31 °C after 100 days.

pH

The pH values had been varied between the different composts during composting process (Fig. 2). The composts C1, C4 and C5, pH values were between 6.0 and 7.0 (moderately—slightly acidic) during the first 25 days of composting, increased above 7.0 from 25 to 75th day and then stabilized at 7.88, 7.68 and 7.59 respectively at the end of composting. On the other hand, the pH of C3 compost was low (acidic) below 6.0 on first 25 days; they increased progressively taking values between 6.0 and 7.0 (moderately—slightly acidic) and above 7.0 (basic) respectively from 25 to 50th and 50th to 75th days. After that they stabilized at pH of 7.67 at the end of
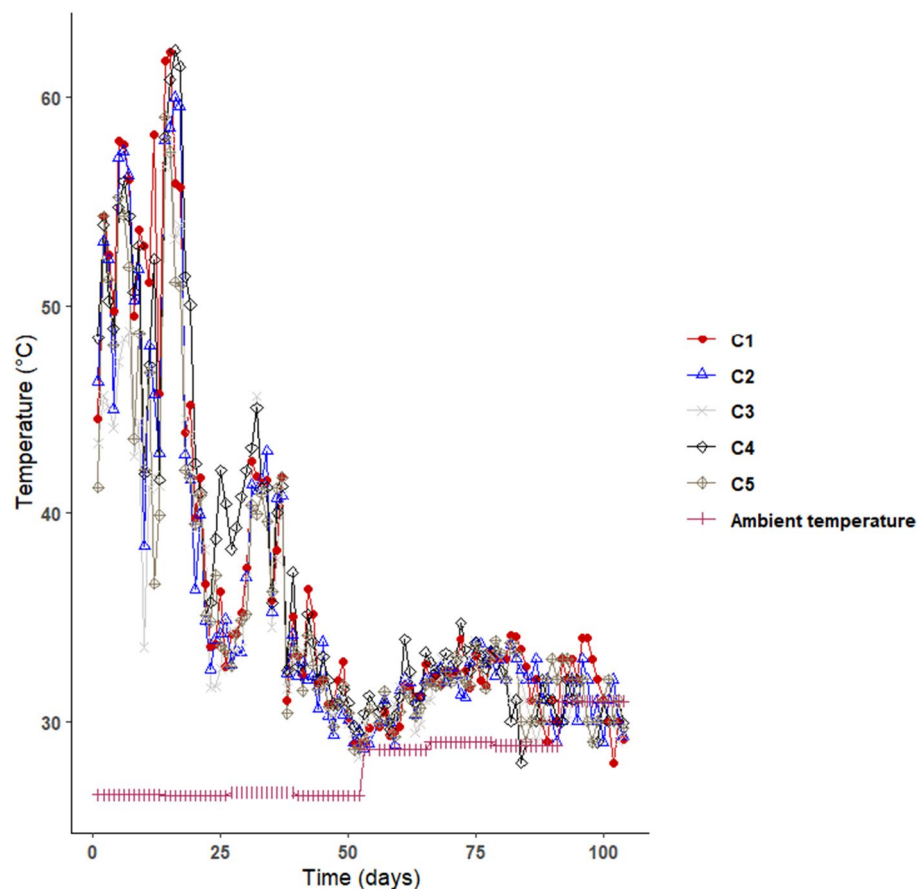

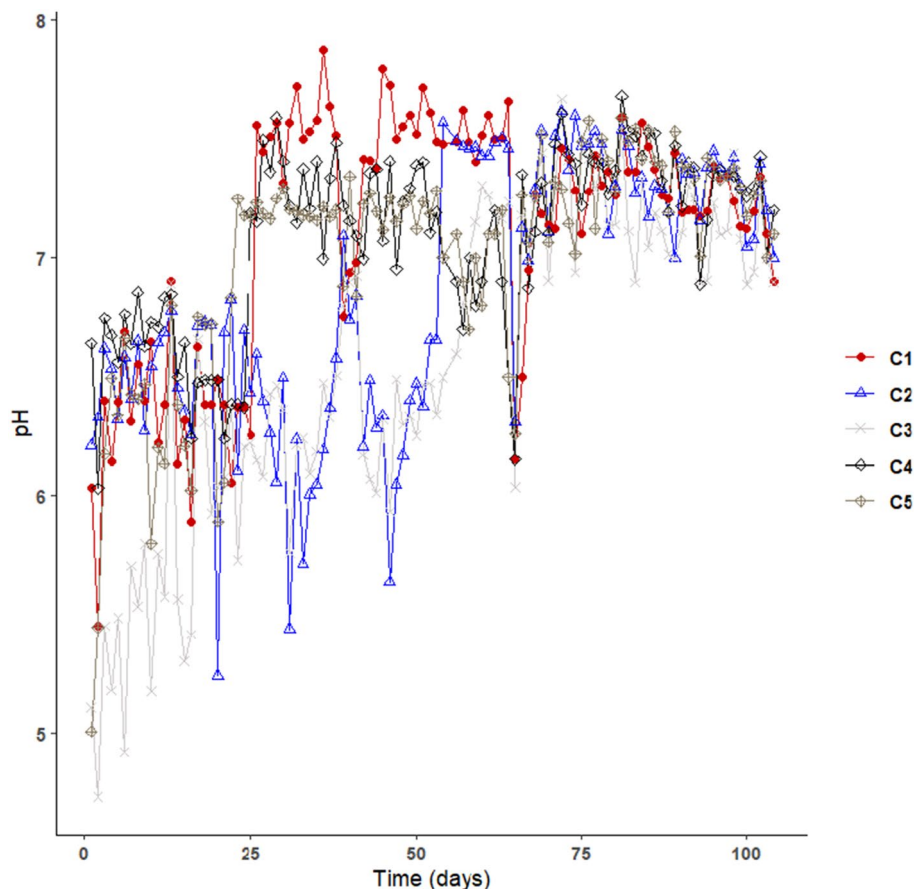**Figure 1.** Composts temperature variation over the time.

Figure 2. Composts pH variation over the time.

composting. As for C2 compost, its pH values was between 6.0 and 7.0 (moderately—slightly acidic) during first 50 days, before increasing above 7.0 (basic) between 50 and 75th days to stabilize at 7.62 at the end of composting. So, the pH of composts C3 and C2 increased progressively towards basic pH from 50th day of composting to stabilize at the end of composting.

Moisture
The compost moisture variation presented three stages (Fig. 3), an initial first 25 days where moisture content presented high fluctuation between 80 and 100% (0–25 days), followed by a second stage where moisture turned around 100% (25 to 75 days), and the third stage where moisture content decreased for all the composts (C1, C2, C3, C4 and C5), until the end of composting; for stabilize at values less than 40%.

Mineralization dynamics of composts over time
The Table 3 showed that interaction between the type of compost and turning date significantly influenced ($p < 0.05$) organic matter and carbon contents of composted materials. The turning date had a significant effect ($p < 0.05$) on the nitrogen content and electrical conductivity of composted materials. The NH_4-N content and electrical conductivity of the composts varied significantly depending on the compost type. Composts' NO_3-N content and their CO_2 release rate did not vary significantly during composting.

At the first turning, the highest organic matter contents were recorded in compost C5 ($68.53 \pm 8.84\%$), followed by composts C3 ($63.31 \pm 11.09\%$) and C4 ($52.57 \pm 5.81\%$). But from 2nd turning, these contents decreased in all composts except that of C4 compost which increased to 60.33% at the 3rd turning. At the last turning (the fourth month), the highest organic matter content was found in compost C4 ($44.58 \pm 2.09\%$), followed by composts C3, C1 and C2 (42.36 ± 1.34, 42.18 ± 7.43 and $42.18 \pm 7.43\%$); with the lowest value in C5 compost ($36.30 \pm 1.47\%$). The same trends are observed with compost organic carbon content (Fig. 4a,b).

The electrical conductivity (EC) of composts globally increased at 2nd turning; it first decreased at 3rd turning, before increasing again at 4th turning. The highest values were noticed with composts C3 and C2 until the third turning from which they decreased. At the last turning, the highest electrical conductivity values were recorded with C3 compost (3.80 ± 0.10) and lowest with C4 compost (2.36 ± 0.30) (Fig. 4c). N content increased with each turning for all composts and presented at the last turning the highest value under C5 compost (28.18 ± 5.71 g kg^{-1}) and lowest under C1 compost (23.00 ± 9.36 g kg^{-1}) (Fig. 4d).
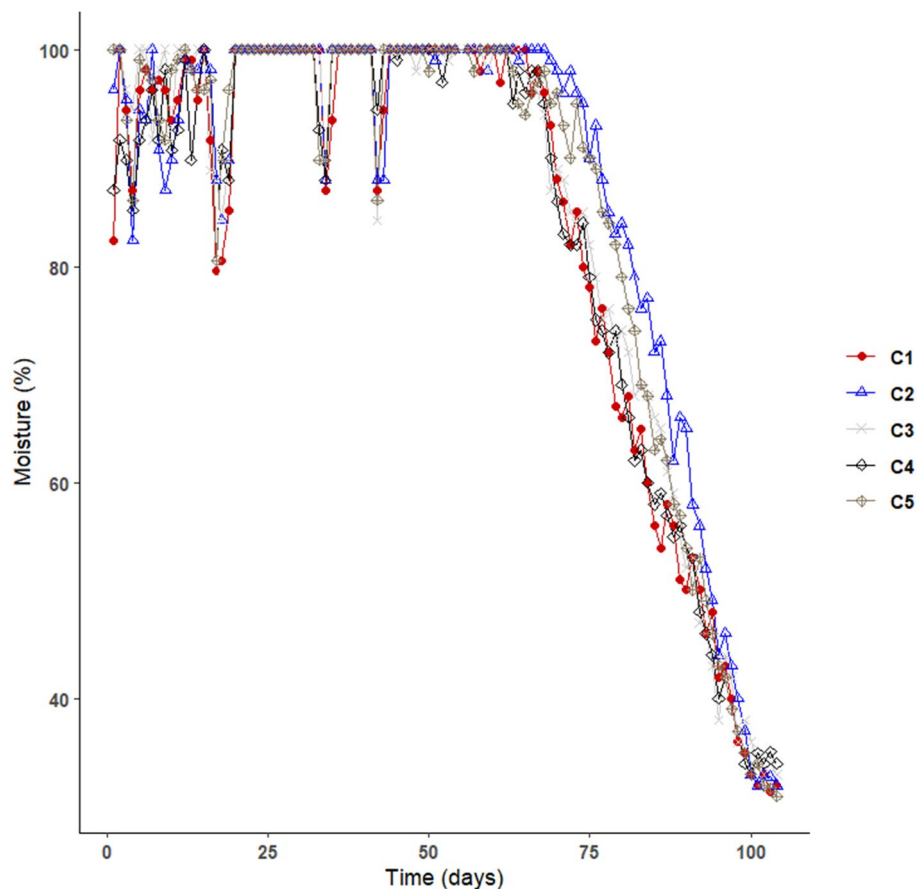
Figure 3. Composts moisture variation over the time.

Factors	Compost type	Compost turning date	Compost type × compost turning date	ICC replication
DF	4	3	12	
EC				
F	26.81	10.16	1.95	0.054
Prob	$1.295e^{-10}$	0.022	0.058	
% OM				
F	0.62	8.85	2.45	0.105
Prob	0.014	0.094	0.018	
% Corg				
F	0.09	8.84	2.45	NA
Prob	0.014	0.094	0.018	
NH_4-N (mg kg^{-1})				
F	2.85	8.28	1.77	0.06
Prob	0.0375	0.097	0.089	
NO_3-N (mg kg^{-1})				
F	1.41	0.55	1.64	0.047
Prob	0.2481	0.694	0.12	
N total (g kg^{-1})				
F	1.81	89.07	1.39	NA
Prob	0.146	7.83e−04	0.213	
C-CO_2 (mg CO_2-C g compost c^{-1} d^{-1})				
F	1.24	2.32	1.64	0.003
Prob	0.309	0.312	0.119	

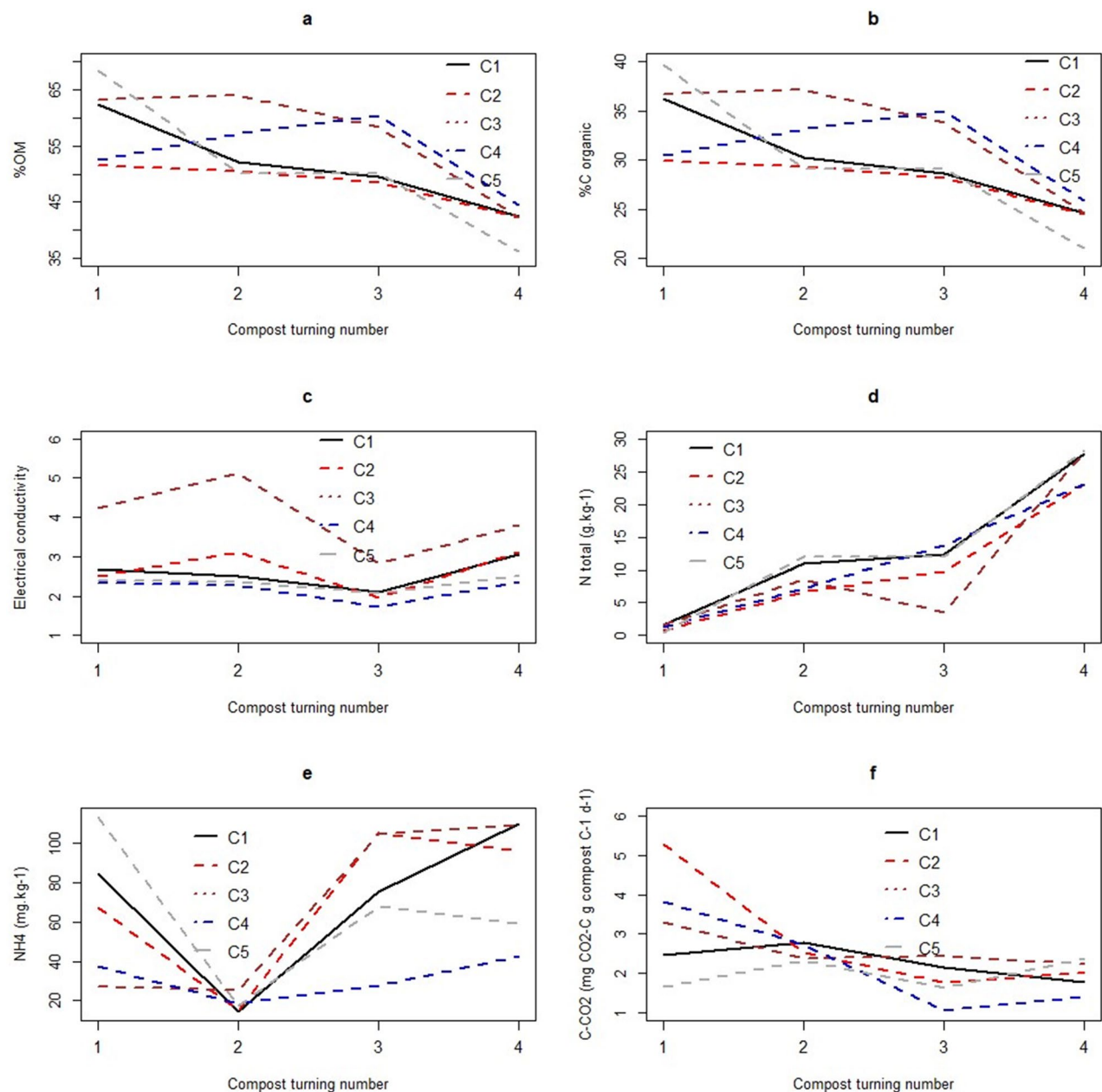**Table 3.** Composts parameters evolution over time at turning.

Figure 4. Composts parameters evolution over the time at turning. Organic matter (**a**), organic carbon (**b**), electrical conductivity (**c**). Total nitrogen (**d**), NH$_4$-N (**e**) and CO2 (**f**).

The NH$_4$-N contents of composted materials generally decreased at 2nd turning for all composts; they then increased from 3rd turning to all tending towards stabilization at 4th turnaround (Fig. 4e). Ammoniacal nitrogen contents of composts C3 and C2 had been higher values from third turning, while composts C1, C4 and C5′ ammoniacal nitrogen contents already presented high values from first turning. At the last turning, the highest NH$_4$-N contents were recorded in C3 compost (109.62 ± 31.37 mg kg^{-1}), and the lowest in C4 compost (42.46 ± 28.93 mg kg^{-1}). However, we note a general drop of CO2 release and increasing of nitrogen content for all composts between 1st and 4th turning (Fig. 4f).

Assessment composts quality

The composted material type had been a significant influence (p < 0.05) on physicochemical and biological characteristics (moisture, pH, Ec, density, Corg, Nt, NH$_4$-N, NO$_3$-N, P, C:N, Ca, Mg, Zn, Cu, CO$_2$) of obtained composts, at the end of composting process (Table 4). For this purpose, the highest water contents were recorded in composts C1 and C2 (45.53 and 44.24%) and the lowest in C3 compost (38.49%). Although pH of all composts was basic, the highest values were also obtained in composts C1 and C2 (8.54 ± 0.21 and 8.52 ± 0.37) and the lowest in compost C5 (7.94 ± 0.12) (Figs. 5a, 5b). The electrical conductivity was higher in C3 compost (3.83 ± 0.83)

Parameters	F-statistic for factor compost type
Moisture (%)	1,855,401***
pH	149,721,633***
EC	54,033,224***
Density	6,078,624***
% Corg	6,381,489***
N total (g kg^{-1})	9,366,047***
NH$_4$-N (mg kg^{-1})	3,782,802***
NO$_3$-N (mg kg^{-1})	205,862***
P (g kg^{-1})	68,859,727***
C:N	33,946,316***
Ca (g kg^{-1})	15,354,068***
Mg (g kg^{-1})	53,042,477***
K (g kg^{-1})	3.3837**
Zn (mg kg^{-1})	1,049,156***
Cu (mg kg^{-1})	1,081,955***
C-CO2 (mg CO2-C g compost c^{-1} d^{-1})	1.0661**

Table 4. Assessment of final composts quality. *Statistically significant at $0.01 \leq p < 0.05$. **Statistically significant at $0.001 \leq p < 0.01$. ***Statistically significant at $p < 0.001$.
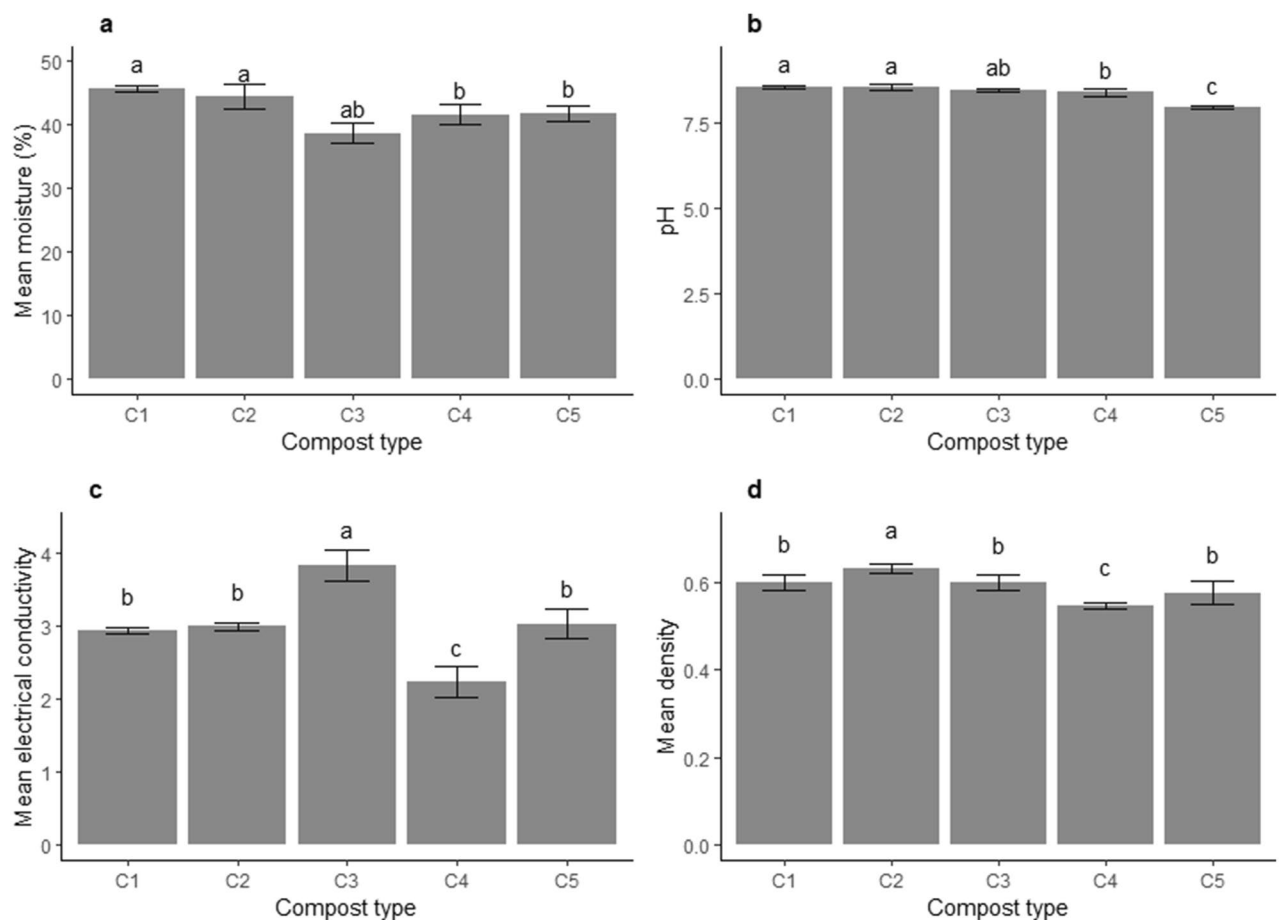

Figure 5. Composts final characteristics. Moisture (**a**), pH (**b**), Electric conductivity (**c**), Density (**d**). Parameters with the same letter are not significantly different at 5% level.

and lower in C4 compost (2.23 ± 0.81). However, its value was not significantly different in composts C1, C2 and C5. The density of C2 compost was the highest (0.63 ± 0.04) and lowest in compost C4 (0.54 ± 0.02) (Figs. 5c, 5d).

Corg, Ntot, NH_4-N, NO_3-N and CO_2 values were overall higher in C4 compost (136.07 ± 16.76 g kg^{-1}, 9.38 ± 0.37 g kg^{-1}, 2633.70 ± 3157.93 mg kg^{-1}, 3882.19 ± 4442.98 mg kg^{-1}, 2.64 ± 0.47 mg CO_2-C g compost C^{-1} d^{-1} respectively), and were respectively lower in composts C1 (113.84 ± 9.88), C3 (6.62 ± 1.89), C2-C5 (469.92 ± 308.57–440.208 ± 416.14), C2 (646.82 ± 542.93) and C3 (1.60 ± 0.74). On the other hand, the C:N ratio was lower in composts C4 (14.57 ± 2.4) and C5 (14.56 ± 1.83) and higher in compost C3 (18.77 ± 3.33) (Fig. 6).

The highest Mg, K, P contents were also recorded in the C4 compost (2800.58 ± 189.08 mg kg^{-1}; 1137.24 ± 833.29 mg kg^{-1}; 99.49 ± 5.70 mg kg^{-1}) while the lowest values were recorded respectively in composts C3 (1598.50 ± 267.25), C5 (174.07 ± 179.63) and C3 (41.42 ± 5.77). As for Ca, its content was higher in compost C2 ($11,164.53 \pm 917.33$ mg kg^{-1}) followed by C4 (9181.79 ± 3745.01 mg kg^{-1}) and lower in compost C5 (6466.95 ± 1212.16). Furthermore, the Zn and Cu contents were higher
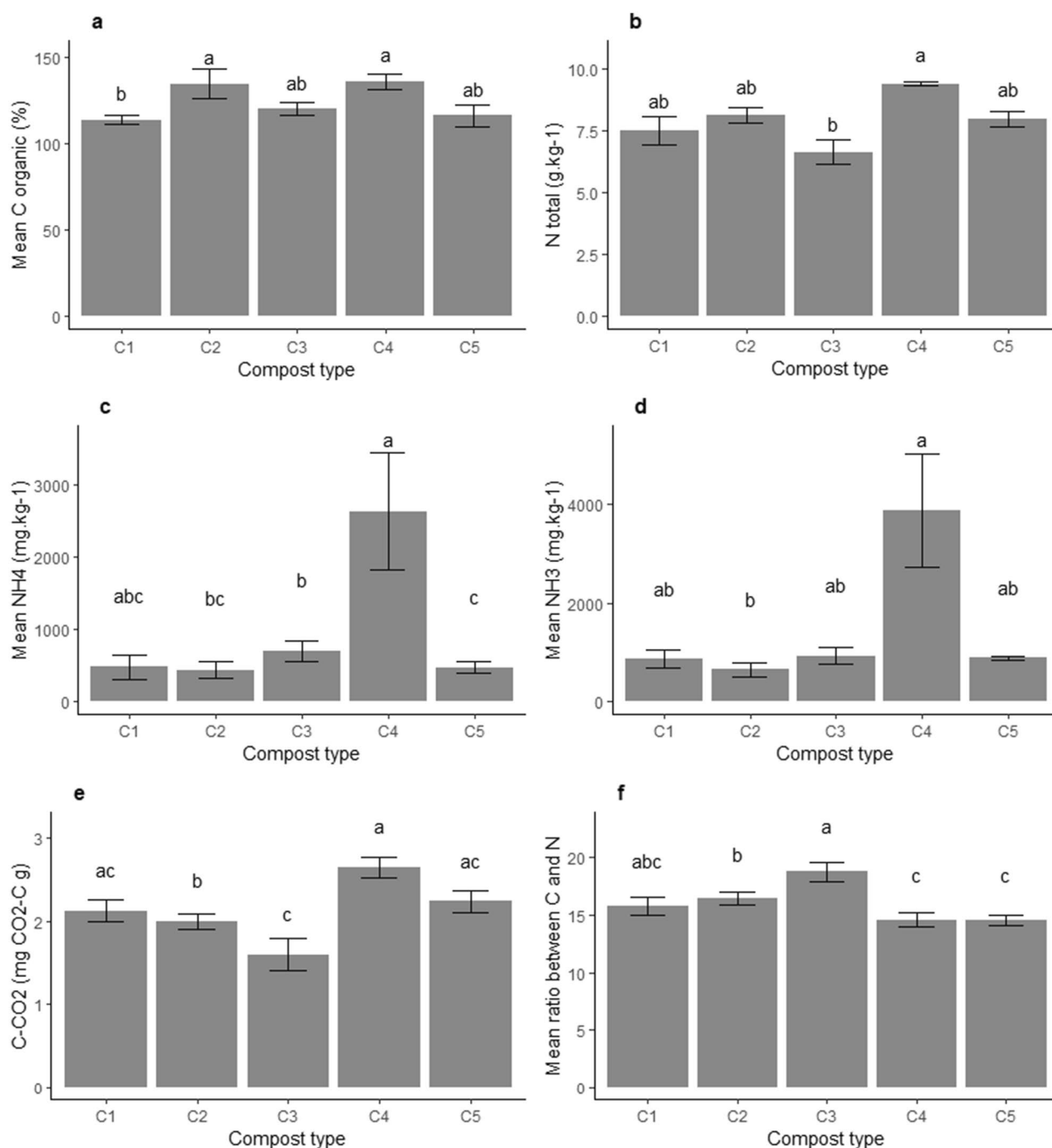

Figure 6. Composts final characteristics. Organic Carbon (**a**), Total nitrogen (**b**), NH_4 (**c**), NH_3 (**d**), CO_2 (**e**), C:N Ratio (**f**). Parameters with the same letter are not significantly different at 5% level.
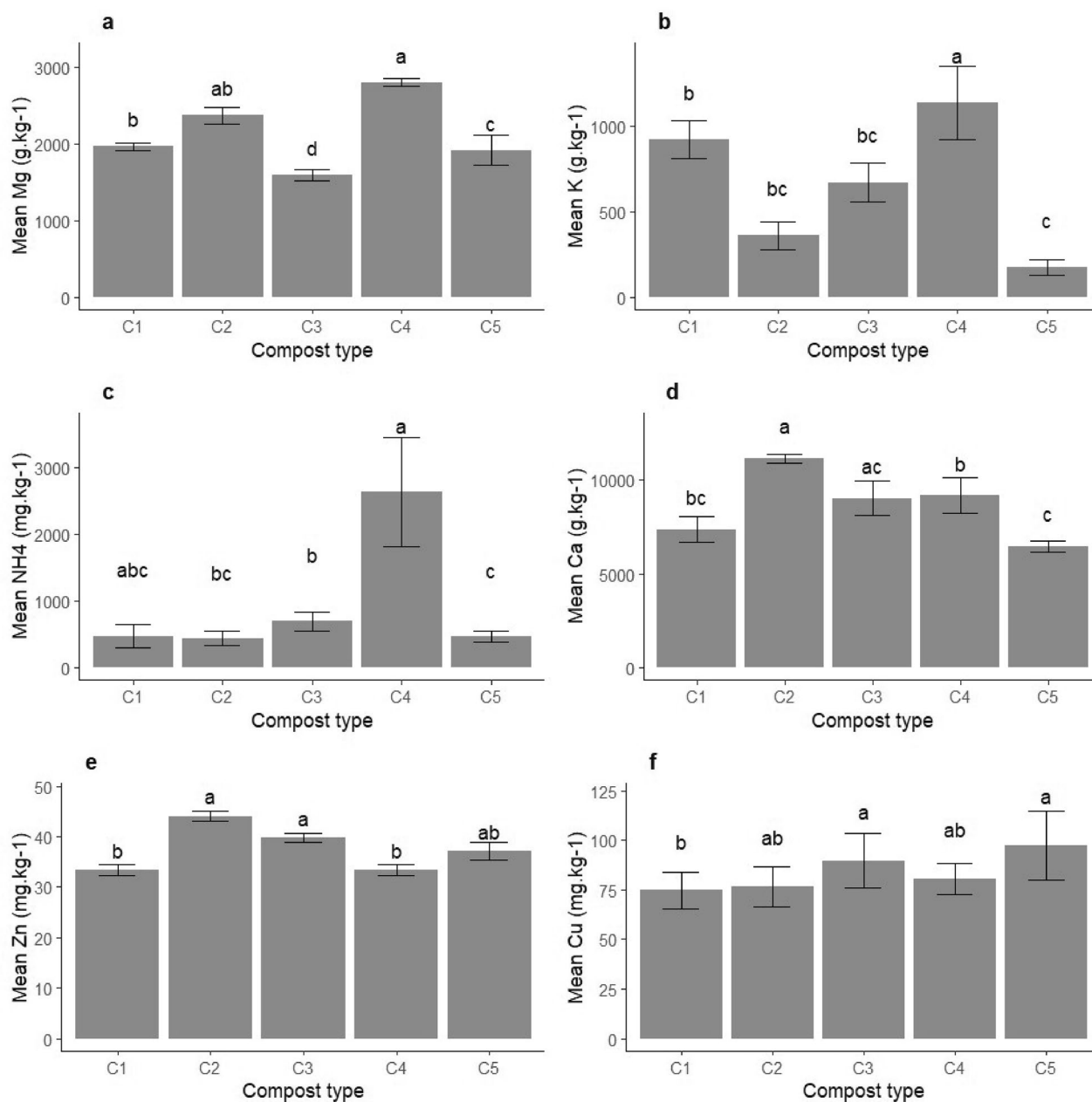
Figure 7. Composts final characteristics. Magnesium (**a**), Potassium (**b**), Phosphorus (**c**), Calcium (**d**), Zinc (**e**), Cupper (**f**). Parameters with the same letter are not significantly different at the 5% level.

respectively in C2 (44.05 ± 4.51 mg kg^{-1})–C3 (39.81 ± 3.25 mg kg^{-1}) and C3 (89.72 ± 53.42 mg kg^{-1})–C5 composts (97.36 ± 67.93 mg kg^{-1}) while they were lowest in composts C1 (33.30 ± 4.35)–C4 (33.36 ± 4.14) and C1 (74.76 ± 36.05) respectively (Fig. 7).
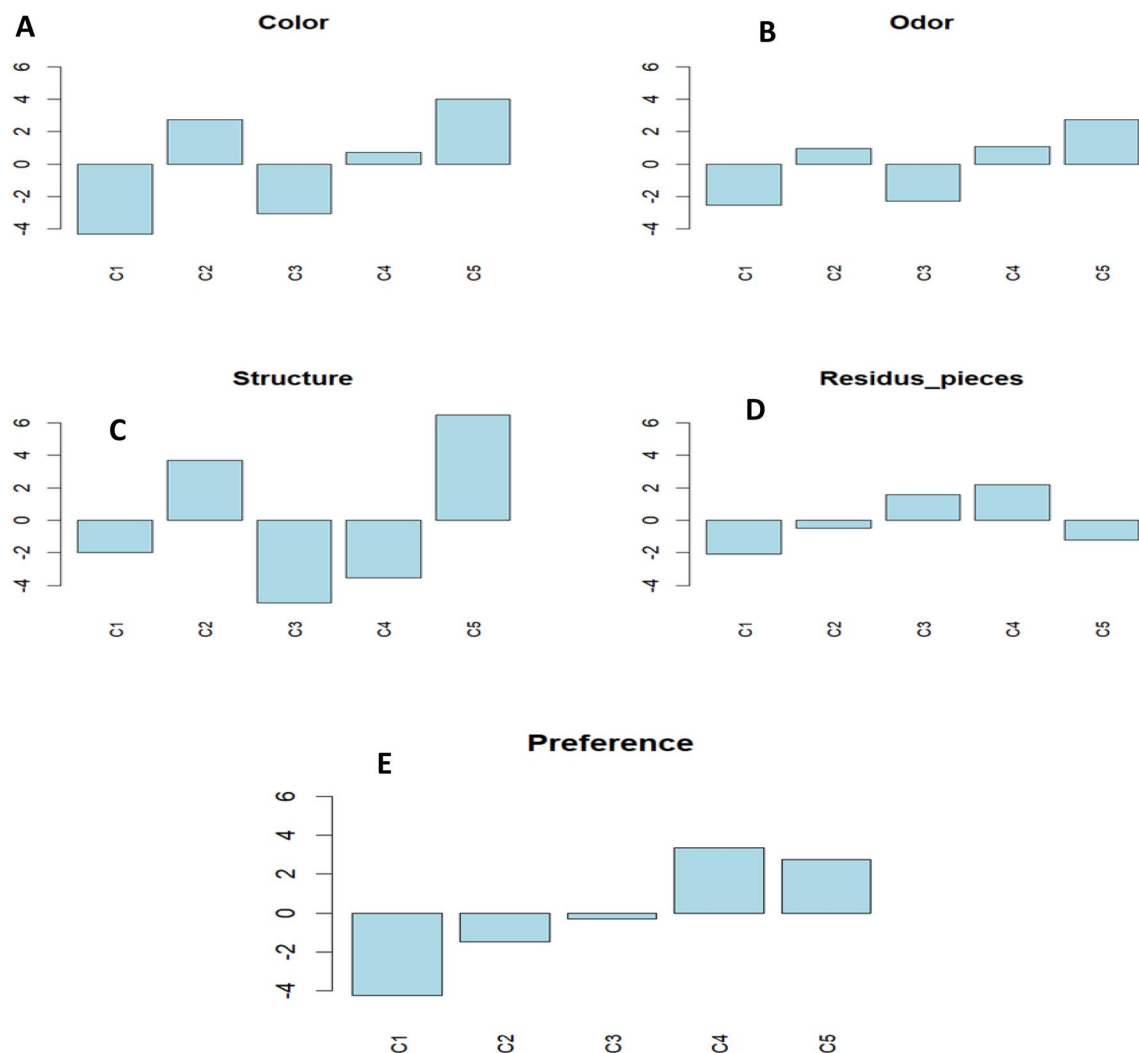
Figure 8. Quality criteria profile of composts: color (**A**), odor (**B**), structure (**C**), residues pieces (**D**) and preference (**E**).

Producers and processors' perception on composts quality

The color of composts C5 and C2 are most appreciated by producers (V. test ≥ 2, p < 5%), followed by that of C4 compost; while that of composts C1 and C3 are the least appreciated (V. test ≤ -2, p < 0.05). C5 compost odor was most appreciated, followed by that of composts C2 and C4, while the C1 and C3 composts odor were the least appreciated. Regarding structure (friability), composts C2 and C5 are most appreciated, while composts C1, C3 and C4 are less appreciated. The residues pieces are more fragile in C4 composts, while they are harder in C1 composts. Finally, producers globally preferred C4 and C5 composts. They less like C3 and C2 composts, but do not really like C1 compost (Fig. 8).

Discussion
Characterization of pineapple organic wastes types

To ensure successful composting, it is essential to control certain key factors such as C:N ratio and pH of raw materials[30]. The C:N ratio of initial composting materials therefore plays a crucial role in the composting process. A high C:N ratio (˃ 30) makes composting slow because there is too much carbon in relation to nitrogen, which reduces microbial activity. On the other hand, a low C:N ratio (< 20) means an excess of nitrogen, which can lead to nitrogen losses through ammonia volatilization or leaching[30,54,55]. The ideal pH of raw materials should be slightly acidic to neutral. Values above 8.4 can be harmful to plants, especially if associated with odor and NH_3 loss[56].

The results of analysis of raw materials used for composting showed that poultry litter used had a lower C:N ratio (15.66) with a higher concentration of total nitrogen (12.23 g kg⁻¹); and a higher pH (7.71) compared to pineapple residues (harvest residues, crown, pineapple processing waste). This was in line with the range values reported by Sangodoyin and Amori[57], Chng et al.[33], Zahan et al.[58]. These authors noted that poultry litter has a lower C:N ratio than harvest residues due to its naturally high nitrogen content. Moreover, this low C:N ratio

could be explained by the fact that the poultry litter resulted of food processing (metabolism) in the animal organism, compared with pineapple residues, which are crop and processing residues. Poultry litter contain uric acid, proteins (the main components of nitrogen) and other undigested nutrients[59]. This would justify the high levels of nitrogen in poultry litter. Compared to poultry litter, pineapple residues have an acidic pH, with a high C:N ratio with low concentrations of total N. However, among pineapple residues the crown had the highest C:N ratio and the harvest residues and pineapple processing waste had a very strongly acid pH, while the pineapple crown had moderately acid pH[60]. These values are consistent with those reported by Chng et al.[33] and Woods End[56]. In fact, pineapple residues contain a complex polymer of cellulose, hemicellulose and lignin, making them difficult to decompose 38–40, but favoring nitrogen immobilization and therefore reducing NH_3 emissions. These results reflect the high capacity for mineralization of poultry litter compared to pineapple residues and the low decomposition ability of crown compared to harvest residues and pineapple processing wastes[29,61]. In addition, poultry litter induces a high contribution of nitrogen and an increase in microbial activity[30,54,55] compared to pineapple residues; this explains its use as a ferment in the composting process. Finally, pineapple crown will better improve microbial activity than harvest residues and pineapple processing waste[30].

Raw materials decomposition dynamics during composting

Temperature is widely recognized as one of the most important parameters in the composting process[62,63]. During the mesophilic phase, mesophilic microorganisms metabolize easily degradable organic matters, such as sugar and proteins, producing heat[64]. The accumulation of this heat is responsible of compost temperature increasing[65]. The ideal temperature for this first stage is between 20 or 25 and 45 °C[31]. During the thermophilic stage (temperature ˃ 45 °C), thermophilic microorganisms degraded other proteins and carbohydrates, including relatively stable compounds such as lignin, cellulose and hemicellulose[66]. The compost will be free of pathogens if its temperature is maintained above 55 °C for more than 3 days during composting process[31,67]. The results of this study showed that the temperatures of composts C1, C3 and C5 were < 45 °C during the first 5 days of composting and increase to values ˃ 45 °C between 5 and 17th days; while the temperatures of composts C2 and C4 were ˃ 45 °C from 1st to 18th day of composting. From the 18th to the 37th day all the composts had temperatures below 45, which stabilized at values below 30 °C beyond the 37th day until the end of composting. These temperatures observed during the composting stages would indicate that composts C1, C3 and C5 went through the different phases of established composting guidelines (mesophilic, thermophilic, mesophilic and maturation) while composts C2 and C4 did not experience the initial mesophilic phase during the composting process (thermophilic, mesophilic and maturation). This can be explained by nature of raw materials contained in the different types of compost. Indeed, composts C1, C3 and C5 contain pineapple processing residues which are rich in sugars and which favored the activity of mesophilic microorganisms, while composts C2 and C4 consist of crown and harvest residues which are rich in lignin, cellulose and hemicellulose and rather facilitated the thermophilic microorganisms' activities[33,64]. Nguyen Thien et al.[38] reported the same observations in their study on the composting of pineapple processing residues and food waste. All composts types have crossed a thermophilic phase of at least 3 days, where temperatures were above 50 °C. This indicates pathogen destruction, as reported by Zhang and Sun[67]. Moreover, the temperature of all composts decreased during the maturation phase to reach ambient temperature at 120 days of composting, indicating a good stability degree of compost, induced by better stabilization of organic matter and slowly rate of microbial activity[67,68].

The composts moisture content determines the micro-organisms activity and therefore the rate at which the organic matter is broken down. The optimum moisture content depends on physical state and nature of substrate, and is conditioned by two phenomena that occur during the degradation process: the release of water during organic matter decomposition, and water evaporation under effect of heat released by fermentation. The optimum water content is between 40 and 60% of fresh matter[69]. Humidity less than 20% inhibits the decomposition of organic matter. On the other hand, values in excess 70% lead to a reduction in oxygen exchange and suitable conditions to anaerobiosis are created as the water fills the gaps. The high-water contents of composts observed up to 75 days can be explained by the high humidity level of pineapple residues used for composting[36,37]. The increase in the compost's temperature, despite their high-water contents, could be justified by the arrangement of each windrow on a slope of 10%, avoiding water stagnation, the regular turning of composts with aeration holes installed in the middle of each windrow and the permanent covering of compost windrows with polyethylene tarpaulins[70,71]. These results corroborate those of Mohd Sokri et al.[37], who found in a study on pineapple processing residues composting with horse manure that composts water content increase during the composting process.

pH levels monitoring is crucial when composting waste, as it indicates the progress of biological and biochemical decomposition[55]. The degradation process goes through two distinct phases: acidogenic and alkalinisation. Acidogenic phase occurs at composting beginning and is characterized by pH decreases to around 6 due to organic acids and carbon dioxide production by acidogenic bacteria. At this stage, bacteria decompose firstly degradable carbon sources, such as monosaccharides. The alkalinization phase begins after carbon and monosaccharides decomposition and is characterize by proteins degradation by microorganisms, resulting in the ammonium liberation and pH increase[72–74]. The results of this study showed that pH of composts C1, C4 and C5 increased rapidly towards basic pH from 25th day of composting while composts C3 and C2 increased progressively towards basic pH from 50th day of composting to stabilize. These results can be justified by high sugar and carbon contents of the components of composts C3 and C2 (Pineapple processing waste and crown) for which the alkanization phase would not have started quickly[74]. These results corroborate those of Zhang et al.[75] who noted an increase in pH values and their stabilization at alkaline values at the end of composting. The pH stabilization at the end of the process is attributed to ammonium oxidation by the bacteria and calcium carbonate precipitation. The composition of raw materials also influences changes in pH during composting, hence the slight difference between treatments.

The ammoniacal nitrogen (NH_4-N) contents during composting is an indicator of microorganisms mineralizing nitrogen activities. The decrease in NH_4-N content explain the transformation of NH_4-N into NO_3-N by ammonium oxidizing bacteria[75]. Its increase is associated with that of pH and reflects release of NH_4-N during organic nitrogen decomposition by microorganisms. The results showed that ammoniacal nitrogen decreased generally at the 2nd turning for all composts; They then experienced an increase at the 3rd reversal to all tend towards stabilization. Ammoniacal nitrogen contents of composts C3 and C2 had been higher values from third turning, while composts C1, C4 and C5′ ammoniacal nitrogen contents already presented high values from first turning. These results corroborate those of Sun et al.[76] and confirming the earlier starting of alkanization stage for composts C1, C4 and C5[74].

In accordance to established composting guidelines, the electrical conductivity (EC) increasing during the co-composting process can be attributed to release of mineral salts such as ammonium and phosphate during organic substances decomposition and mineralization[77]. Its decreasing is associated with increasing in pH values and reflects the release of NH3 during the mesophilic phase[78]. The results showed that composts EC generally increased at the 2nd and 4th turning (thermophilic phase), with an overall decrease at the 3rd turning (mesophilic phase). At the last turning, EC value was higher in C3 compost (3.80 ± 0.83 mS cm^{-1}) and lower in the C4 compost (2.36 ± 0.81 mS cm^{-1}). Unlike composts C1, C4 and C5, the highest EC values were noticed with composts C3 and C2 from first to third turning before their decreasing, explaining the high sugar and carbon content of their components. For all composts, the EC values were less than 4.0 mS cm^{-1}, indicating that composts do not exhibit phytotoxic/plant inhibitory effects[55,78–80]. Our results are in agreement with those of Jain et al.[81] who found a value of 3.5 mS cm^{-1} at the end of composting. Similarly, Wang et al.[79] had obtained final EC values of 1.07; 2.49; 3.09; 3.98 mS cm^{-1} respectively for composts based on sheep manure + corn straw (CK); CK + 0.01% compound microbial agents (M); CK + 0.01% M + 0.1% biochar and CK + 0.1% biochar; which was less than 4 mS cm^{-1}[79].

organic carbon content during composting is associated with carbon dioxide and nitrogen contents. The decrease in organic carbon content during composting is associated with increase in temperature and is attributed to organic matter decomposition[64] by microorganisms that consume carbon to generate energy. It is also linked to the loss of dry matter in the form of carbon dioxide during microbial activity[57,82]. The CO_2 emission rate during composting process is indicative of rapid decomposition of total organic matter and strong microbial activity with N content increasing[83]. The results showed a decreasing trend of organic matter, carbon contents and CO2 release but an increasing of nitrogen content for all composts between 1st and 4th turning. At the first turning, the highest organic matter contents were recorded in compost C5 (68.53 ± 8.84), followed by composts C3 (63.31 ± 11.09) and C4 (52.57 ± 5.81) while the higher values of CO2 release were recorded with composts C2 and C4. At the last turning (fourth month), the highest organic matter contents were found in compost C4 (44.58 ± 2.09%), followed by composts C3, C2 and C1 (42.36 ± 1.34, 42.20 ± 7.43 and 42.18 ± 7.43%), with the lowest values at the C5 compost level (36.30 ± 1.47%). At the last turning, organic matter content reducing rate (%) and CO2 release (mg CO2-C g compost C^{-1} d^{-1}) of composts C5, C3, C1, C2 and C4 was of respectively 47.01% and 2.34; 33.08% and 2.22 g kg^{-1}; 18.25% and 2.01 g kg^{-1}; 18.20% and 1.76 g kg^{-1}; 15.20% and 1.41 g kg^{-1}. Moreover, nitrogen content of composts C5, C3, C1, C2 and C4 at the last turning was of respectively 28.19, 27.91, 23.03 23.01 and 23.00 g kg^{-1}. This indicates that there was more raw material biodegradation within C5 compost followed respectively by C3, C1, C2 and C4. It can be explained by C:N ratio of raw materials used for each compost. Indeed, among pineapple residues the crown had the highest C:N ratio followed by harvest residues and pineapple processing waste. Composts C1, C3 and C5 contain pineapple processing residues, while composts C2 and C4 consist of crown and harvest residues which are rich in lignin, cellulose and hemicellulose whose decomposition is slower[33,64]. These results are in agreement with those of Al-Bataina et al.[84], Chng et al.[33], Tripetchkul et al.[85], who reported that compost nitrogen content increases while their carbon content decreases throughout co-composting, this due to degradation of organic carbon compounds and the contribution of nitrogen-fixing bacteria[26,75,86]. Many authors have noted that the highest CO_2 emissions occur at the start of composting process and gradually decrease over time[87,88]. This justifies drop in CO_2 release noted over time for all five composts. Indeed, Organic matter is oxidized to CO_2 and H_2O, including microbial biomass, during composting process[85]. Therefore, organic matter loss rate reflects overall composting rate[89].

Composts quality

Variations of physicochemical and biological characteristics of different composts
The water content of five composts varied in the following order: C1 (45.53%) > C2 (44.25) > C4 (41.42) > C5 (41.65) > C3 (38.49%). This variation in water content from one compost to another is thought to be due to the dry matter content of different types of pineapple residues. According to Amery et al.[90], Azim et al.[91] mature compost has water content between 40 and 60% or between 30 and 65%. On the other hand, the Swiss and German standards recommend a level of less than 45%. Amery et al.[90] and Sullivan et al.[92] reported that compost with low water content (less than 40%) is dusty, while compost with high water content (more than 60%) is generally lumpy and difficult to spread. It can therefore be deduced that composts C2, C3, C4 and C5 can be used in agriculture in any type of application. However, these values are lower than compost water contents obtained by Chng et al.[33], Miito et al.[36], Nguyen Thien et al.[38], which are higher than 50%. These variations depend of properties of raw materials used for composting, the composting process and conditions[30].

The pH of all the composts was basic and ranged in order C2 (8.52) > C1 (8.50) > C3 (8.46) > C4 (8.38) > C5 (7.94). Compared to NF U 44-051 and Belgiun recommended standards, all composts pH values were in the normal range between 6 and 9.5[75,90]. However, only compost C5 was in the acceptable range of 7.5–8.0 as recommended by USDA-NRCS[93]. The pH value of compost C5 was also in line with the values obtained by Chng et al.[33], Miito et al.[36], Nguyen Thien et al.[38]. However, according to Swiss standards, the values of pH for horticultural

use in the field would be < 7.8 or 7.5[94]. From these standards, we can deduce that the composts obtained are not applicable in horticulture.

Composts' electrical conductivity in this study varied in the following order C3 (3.83 mS cm⁻¹) > C5 (3.03) > C2 (3.00) > C1 (2.93) > C4 (2.23 mS cm⁻¹) and its value was not significantly different between composts C1, C2 and C5. EC of all composts was below the limits value of 6.1 mS cm⁻¹ according to Germany standard[95]; and limits value of 4.0 mS cm⁻¹ according to Zhang et al.[75].

The density of composts varied in the order C2 (0.63 ± 0.04) > C1 (0.60 ± 0.07) > C3 (0.59 ± 0.06) > C5 (0.57 ± 0.10) > C4 (0.55 ± 0.03). The results are near to findings of Brinton and York[96] who reported that during the composting process, microbial activity break down the loosely combined raw materials into smaller pieces after degradation resulting in decreased bulk density. The same remarks were reported by Anand et al.[97].

The organic carbon (Corg) content decreased during composting for all composts, indicating continuous decomposition of raw materials by microbial communities compared to the beginning[37,97]. The Corg values varied in the following order C4 (136.07 ± 16.76 g kg⁻¹) > C2 (134.82 ± 34.03) > C3 (120.21 ± 13.70) > C5 (116.32 ± 24.51) > C1 (113.84 ± 9.88). According to Germany and Switzerland standards for good compost maturity (Corg > 87.21 g kg⁻¹) and value limits for horticultural use (Corg < 290.7 g kg⁻¹), all five composts met these criteria[94]. However, the organic carbon contents recorded in the composts were lower than those obtained by Nguyen Thien et al.[38] (Corg = 187.35 g kg⁻¹), who composted pineapple residues and food waste. This would reflect the low capacity of pineapple residues decomposition with food waste compared to poultry litter. On the other hand, the works of Chng et al.[33], Miito et al.[36] recorded low organic carbon contents (62.2 and 83.2 g kg⁻¹) respectively with co-composting of pineapple harvest waste and earthworms and co-composting of pineapple leaves and chicken manure slurry comparatively to compost's organic carbon contents recorded in this study. This difference in organic carbon content may be attributable to the nature or type of co-substrate used, the size of pineapple waste particle, the mixture composted' proportion and the composting technique. However, our results are close to those of Bambang Irawan et al.[32], Mainoo et al.[35] who respectively composted pineapple wastes with earthworms and pineapple biomass with cow manure and *Trichoderma* sp. *inoculum*.

Compost's NH4-N values were varied in the following order C4 (2633.70 ± 315.93 mg kg-1) > C3 (697.41 ± 53.78) > C1 (479.21 ± 65.67) > C5 (469.93 ± 30.85) > C2 (440.21 ± 41.61) et NO3-N value were varied in order C4 (3882.19 ± 44.43 mg kg-1) > C3 (934.02 ± 61.94) > C5 (883.65 ± 15.08) > C1 (863.19 ± 706.35) > C2 (646.82 ± 54.29). Finstein and Miller[98] reported that composts is ready to use when NH4-N value is higher than that of NO3-N. These observations correlate with our results. The decrease of NH4-N content is an indication of good quality and completion of the maturation process[99]. The NO3-N levels' in the composts are in line with the Swiss standard[94] and the limit value (> 300 ppm NO3-N) of the Austrian Standards Institute[100].

The CO2 release is an indicator of compost maturity and stability[101]. The CO2 values of different obtained composts were in the following order 2.65 ± 0.47 (C4); 2.24 ± 0.52 (C5); 2.12 ± 0.51 (C1); 2.00 ± 0.36 (C2) and 1.60 ± 0.75 (C3) mg CO2-C g compost C⁻¹ d⁻¹ reflecting that compost C3 is very mature (stable decomposition) and composts C4, C5, C1 and C2 are mature (stable decomposition)[40,41].

In this study, the C:N ratio of obtained composts were in the following order C3 (18.77 ± 3.33) > C2 (16.42 ± 2.10) > C1 (15.77 ± 3.17) > C4 (14.57 ± 2.40) > C5 (14.56 ± 1.83). Compared to high C:N ratio of pineapple and processing residues, these low C:N ratios values obtained at the end of composting for all five composts can be attributed to carbon-rich organic matter degradation during the composting stage associated with enhancing of nitrogen content[24,33,34,36]. Indeed, the C:N ratio is widely used as an indicator of compost maturity[102,103], and there are no specific thresholds for this parameter[69]. Azim et al.[91] reported that a C:N ratio ranging from 7.8 to 20.5 with an average around 12 was indicative of maturity compost. Antil et al.[104] and FAO standards[105] indicated that a value between 15 and 20 was satisfactory. Furthermore, according to Asquer et al.[106] and the AFNOR standard[105], C:N values below 20 indicate sufficient nitrogen supply for plant growth. At the same time, according to Gómez-Brandón et al.[107], Singh et al.[108], Hoang et al.[34] a C:N ratio between 10 and 15 or 20 indicate stable and mature compost. It therefore appears that all five composts have a good C:N ratio of between 10 and 20 and are therefore mature.

The composts' total nitrogen contents were varied in the following order C4 (9.38 ± 0.37) > C2 (8.12 ± 1.15) > C5 (7.98 ± 1.21) > C1 (7.51 ± 2.21) > C3 (6.63 ± 1.89 g kg⁻¹). The higher concentration of total nitrogen recorded in C4 compost is linked to the nature of the pineapple waste used (pineapple harvest residues), compared with C2, C5 and C3 composts[109,110]. Indeed, pineapple harvest residues would be rich in nitrogen, which would have contributed to nutrient availability, especially nitrogen as they affect processes like mineralization of nitrogenous organic compounds and amount of nitrogen derived from these compounds. The nitrogen contained in the poultry litter would have also contributed to increasing of N content in C4 compost. These results are similar to those of Chng et al.[33], Miito et al.[36], who showed that pineapple harvest residues were rich in nitrogen. On the other hand, the high concentration of total nitrogen recorded in C4 compost compared with C1 compost is attributable to the proportion of pineapple harvest residues added to the mixture[36,109]. Thus, compost C4, with the highest proportion of harvest residues, proved to be the richest in nitrogen compared with compost C1, whose proportion of harvest residues was 4 times lower. However, if we refer to the standards values of AFNOR[105], French NFU 44-051[94] and Polish[69], all the composts meet the minimum nitrogen concentration require (5 g kg⁻¹). However, according to the Swiss standard, the total nitrogen content of the composts is below the minimum threshold required for use in horticulture (˃ 10 g kg⁻¹).

Composts' P and K contents were varied respectively in order C4 (99.48 ± 5.71) > C1 (71.66 ± 23.61) > C2 (61.75 ± 32.33) > C5 (56.15 ± 23.53) > C3 (41.42 ± 5.77 mg kg⁻¹) and C4 (1137.24 ± 83.32) > C1 (924.03 ± 42.57) > C3 (671.85 ± 44.29) > C2 (361.30 ± 31.90) > C5 (174.08 ± 17.96). The P and K contents of the five types of compost were found to be below to acceptable limits set by the French NF U 44–051 and Germany standards (< 1200–1400 and < 2000–4000 mg kg⁻¹ respectively). These values are also very low compared with those reported by Mainoo

et al.[35], Miito et al.[36] which were 4000–5000 mg kg^{-1} for total P and 9000–19,000 mg kg^{-1} for total K. This difference could be attributed to low K and P contents of wastes used for composting[24].

Composts' Mg and Ca contents varied respectively in order of C4 (2800.58 ± 189.08) > C2 (2373.32 ± 432.19) > C1 (1965.31 ± 190.94) > C5 (1918.24 ± 756.56) > C3 (1598.50 ± 267.25 mg kg^{-1}) and C2 (11,164.53 ± 917.33 mg kg^{-1}) > C4 (9181.79 ± 3475.01) > C3 (9028.69 ± 3607.92) > C1 (7369.61 ± 2688.39) > C5 (6466.95 ± 1212.16 mg kg^{-1}). These high contains are certainly due to their presence in pineapple harvest residues and crowns due to fertilizers applied during plantation. Moreover, the poultry litter used had higher Mg and Ca contents than pineapple harvesting and processing residues. The kind and rate of pineapple waste used, could have been a significant effect on composts micronutrient contents[110].

Copper concentrations in the various composts ranged in the following order: C5 97.36 ± 67.93 mg kg^{-1} > C3 (89.72 ± 53.42) > C4 (80.55 ± 30.38) > C2 (76.71 ± 38.51) > C1 (74.76 ± 36.05 mg kg^{-1}). These contents do not exceed the limit values of international standards (French NFU 44–051, Germany, Great-Britain, Switzerland, Canada and European standards) (< 100 or 200 mg kg^{-1})[94,105]. Likewise, the zinc concentrations of various composts ranged in the order C2 (44.05 ± 4.51 mg kg^{-1}) > C3 (39.81 ± 3.50) > C5 (37.10 ± 6.93) > C4 (33.36 ± 4.40) > C1 (33.30 ± 4.52 mg kg^{-1}). These contents are also below the limit values of French NFU 44–051, Canadian and European standards, German, Great-Britain and Switzerland standards (< 400 mg kg^{-1}). Compared with other studies, these copper and zinc contents in the obtained composts, are higher than those obtained by Chng et al.[33] (47.22 and 119.1 mg kg^{-1} respectively) after co-composting of pineapple leaves and chicken manure slurry in Malaysia. These results contradict also the conclusions of Amir et al.[111] and Pakou et al.[112], who reported that heavy metal levels tend to decrease through leaching following their release by decomposition of organic matter during composting. These observed differences could be explained by chemical composition of poultry litter used for composting, the composting technique and the analysis methods.

Producers and processors' perception on composts quality
The analysis of producers and processors perception on the physical quality of composts revealed that they prefer C4 and C5 composts. They less like C3 and C2 composts, but do not really like C1 compost. This is aligned with scientific criteria for compost quality. Indeed, the Compost C1 had more than 45% of water content and high pH (8.50), with low organic carbon (Corg) (2.12 mg kg^{-1}), low nitrogen (7.51 g kg^{-1}) and low Ca (7369.63 mg kg^{-1}) contents. C2 compost had the highest value of pH, a high-water content, and low contents of NO3- and K. Concerning C3 compost, its had the highest Ec and low contents of CO2, N, P and Mg. Producers and processors' perception can thus be explained by nutrient contents of composts, their color and odor, as well as the proportion and nature of residues pieces present in the composts at maturity. Thus, the producers appreciated color, odor and structure of C5, C2 and C4 composts. These results corroborate the observations of Trautmann and Krasny[41], Sullivan and Miller[113] who noted that color and odor are most criteria used for composts selection. These criteria will surely determine produced composts adoption by producers.

Conclusion
The Study of decomposition dynamics of pineapple harvest and processing residues during composting revealed that poultry litter used had a lower C:N ratio with a higher concentration of total nitrogen compared to pineapple residues; but among pineapple residues the crown had the highest C:N ratio and harvest residues and pineapple processing waste had a very strongly acid pH, while pineapple crown had moderately acid pH. The nature of raw materials containing in different types of compost influenced residues decomposition dynamics during composting and obtained composts quality. Composts containing pineapple processing residues which are rich in lignin (C1, C3, C5) favored the activity of mesophilic microorganisms, while composts containing crown and harvest residues which are rich in sugars (C2, C4), cellulose and hemicellulose facilitated the thermophilic microorganisms' activities, from the beginning of composting. Compared to compost C3 and C2 (high sugar and carbon contents), raw materials decomposition was more rapidly in composts C1, C4 and C5, with high reducing rate of organic carbon content, high CO2 release and high N content; which induces them quickly entering in alkanization stage (pH increasing), them high values' of ammoniacal nitrogen contents from the first turning and Electrical conductivity values' decreasing from the beginning of composting. Therefore, these composts (especially compost C4) presented good performance at the end of composting as high contents of Corg, N, Mg, K, P, NO3-, and low C:N ratio. These good chemical characteristics meet also producers and processors preferences who most prefered color, odor and structure of composts C4 (75% pineapple harvest residue and 25% poultry litter) and C5 (56.25% pineapple crown, 18.25% pineapple processing wastes and 25% poultry litter). These two types of composts can therefore be recommended as part of promotion of pineapple harvest residues or processing wastes for soil fertilization. So far, no literature has reported valorization of both pineapple harvest and processing residues through composting and study of stakeholder's perception on physical quality of organic fertilizers. Additional experiments should be conducted to determine the appropriate rates of these different composts to apply to pineapple and other crops (with or without addition of other organic and mineral fertilizers), in view of sustainable management of soil fertility, increasing yield and obtaining quality products. with regard to their characteristics (C:N ratio, N, P, K, pH), C4 and C5 composts would be respectively more suitable for long cycle and vegetable crops. For optimal and integrated valorization of pineapple harvest and processing residues in composting, it will be appropriate to dry them under cover and grind them before using them for composting.

Data availability
The data used for this study are available upon request by contacting the corresponding author.

References

1. Bai, Z. G., Dent, D. L., Olsson, L. & Schaepman, M. E. Proxy global assessment of land degradation. *Soil Use Manag.* **24**, 223–234 (2008).
2. Lopes, I. G., Braos, L. B., Cruz, M. C. P. & Vidotti, R. M. Valorization of animal waste from aquaculture through composting: Nutrient recovery and nitrogen mineralization. *Aquaculture* **531**, 735859 (2021).
3. Sleutel, S., De Neve, S., Singier, B. & Hofman, G. Organic C levels in intensively managed arable soils—Long-term regional trends and characterization of fractions. *Soil Use Manag.* **22**, 188–196 (2006).
4. Yee, L. L. *et al.* Selection of parameters for soil quality following compost application: A ranking method. *Chem. Eng. Trans.* **83**, 505–510 (2021).
5. Geethamani, R. *et al.* Production of cost affordable organic manure using institutional waste by rapid composting method. *Mater. Today Proc.* **45**, 764–768 (2021).
6. De Corato, U. Agricultural waste recycling in horticultural intensive farming systems by on-farm composting and compost-based tea application improves soil quality and plant health: A review under the perspective of a circular economy. *Sci. Total Environ.* **738**, 139840 (2020).
7. Singh, J. & Ordoñez, I. Resource recovery from post-consumer waste: important lessons for the upcoming circular economy. *J. Clean. Prod.* **134**, 342–353 (2016).
8. De Corato, U., De Bari, I., Viola, E. & Pugliese, M. Assessing the main opportunities of integrated biorefining from agro-bioenergy co/by-products and agroindustrial residues into high-value added products associated to some emerging markets: A review. *Renew. Sustain. Energy Rev.* **88**, 326–346 (2018).
9. Esparza, I., Jiménez-Moreno, N., Bimbela, F., Ancín-Azpilicueta, C. & Gandía, L. M. Fruit and vegetable waste management: Conventional and emerging approaches. *J. Environ. Manag.* **265**, 110510 (2020).
10. Aili Hamzah, A. F. *et al.* Recent updates on the conversion of pineapple waste (*Ananas comosus*) to value-added products, future perspectives and challenges. *Agronomy* **11**, 2221 (2021).
11. Mangara, A. *et al.* Phytoecological study of weeds in pineapple (*Ananas comosus* (L.) Merr.) orchards in Bonoua and N'douci localities in lower Côte d'Ivoire. *J. Appl. Biosci.* **36**, 2367–2382 (2010).
12. Helvetas-Bénin. *Appui à la Filière Ananas Biologique et Équitable: Document du Projet* (2008).
13. Liu, T. *et al.* Evaluation of cornstalk as bulking agent on greenhouse gases emission and bacterial community during further composting. *Bioresour. Technol.* **340**, 125713 (2021).
14. FICHE-ENTREPRISE-Fruits-Tillou-FR.pdf.
15. Zain, N. A. M., Aziman, S. N., Suhaimi, M. S. & Idris, A. Optimization of L(+) lactic acid production from solid pineapple waste (SPW) by *Rhizopus oryzae* NRRL 395. *J. Polym. Environ.* **29**, 230–249 (2021).
16. Olufunmi, O. *et al.* Elemental characterization of biochar of some horticultural crop wastes. *Growth* **18**, 22 (2018).
17. Liu, C. H., Liu, Y., Fan, C. & Kuang, S. Z. The effects of composted pineapple residue return on soil properties and the growth and yield of pineapple. *J. Soil Sci. Plant Nutr.* https://doi.org/10.4067/S0718-95162013005000034 (2013).
18. Toledo, M., Gutiérrez, M. C., Peña, A., Siles, J. A. & Martín, M. A. Co-composting of chicken manure, Alperujo, olive leaves/pruning and cereal straw at full-scale: Compost quality assessment and odour emission. *Process Saf. Environ. Prot.* **139**, 362–370 (2020).
19. Wood, D., Cowherd, S. & Van Heyst, B. A summary of ammonia emission factors and quality criteria for commercial poultry production in North America. *Atmos. Environ.* **115**, 236–245 (2015).
20. Li, F., Cheng, S., Yu, H. & Yang, D. Waste from livestock and poultry breeding and its potential assessment of biogas energy in rural China. *J. Clean. Prod.* **126**, 451–460 (2016).
21. Rabiu, Z., Maigari, F. U., Lawan, U. & Mukhtar, Z. G. Pineapple waste utilization as a sustainable means of waste management. In *Sustainable Technologies for the Management of Agricultural Wastes* (ed. Zakaria, Z. A.) 143–154 (Springer, 2018).
22. Ruslan, N. A. *et al.* A preliminary study on sustainable management of pineapple waste: Perspective of smallholders. *Int. J. Acad. Res. Bus. Soc. Sci.* **7**, 1–7 (2017).
23. Sarangi, P. K., Singh, A. K., Srivastava, R. K. & Gupta, V. K. Recent progress and future perspectives for zero agriculture waste technologies: Pineapple waste as a case study. *Sustainability* **15**, 3575 (2023).
24. Zziwa, A. *et al.* Nutrient recovery from pineapple waste through controlled batch and continuous vermicomposting systems. *J. Environ. Manag.* **279**, 111784 (2021).
25. Whitmore, A. P. Determination of the mineralization of nitrogen from composted chicken manure as affected by temperature. *Nutr. Cycl. Agroecosyst.* **77**, 225–232 (2007).
26. Huang, G. F., Wong, J. W. C., Wu, Q. T. & Nagar, B. B. Effect of C: N on composting of pig manure with sawdust. *Waste Manag.* **24**, 805–813 (2004).
27. Albiach, R., Canet, R., Pomares, F. & Ingelmo, F. Microbial biomass content and enzymatic activities after the application of organic amendments to a horticultural soil. *Bioresour. Technol.* **75**, 43–48 (2000).
28. Chia, W. Y. *et al.* Sustainable utilization of biowaste compost for renewable energy and soil amendments. *Environ. Pollut.* **267**, 115662 (2020).
29. Kaboré, T.W.-T. *et al.* Effect of the raw materials and mixing ratio of composted wastes on the dynamic of organic matter stabilization and nitrogen availability in composts of Sub-Saharan Africa. *Bioresour. Technol.* **101**, 1002–1013 (2010).
30. Reyes-Torres, M., Oviedo-Ocaña, E. R., Dominguez, I., Komilis, D. & Sánchez, A. A systematic review on the composting of green waste: Feedstock quality and optimization strategies. *Waste Manag.* **77**, 486–499 (2018).
31. Sayara, T., Basheer-Salimia, R., Hawamde, F. & Sánchez, A. Recycling of organic wastes through composting: Process performance and compost application in agriculture. *Agronomy* **10**, 1838 (2020).
32. Irawan, B., Jabbar, S. K. & Farisi, S. Application of Trichoderma sp in pineapple biomass composting. *Magna Sci. Adv. Biol. Pharm.* **9**, 048–053 (2023).
33. Chng, H. Y., Ahmed, O. H., Kassim, S. & Majid, N. M. A. Co-composting of pineapple leaves and chicken manure slurry. *Int. J. Recycl. Org. Waste Agric.* **2**, 23 (2013).
34. Hoang, H. A., Luu, Q. H., Le Phung, T. K. & Tran, V. T. Enhancement of pineapple residue composting by food waste addition. *Chem. Eng. Trans.* **72**, 217–222 (2019).
35. Mainoo, N. O. K., Barrington, S., Whalen, J. K. & Sampedro, L. Pilot-scale vermicomposting of pineapple wastes with earthworms native to Accra, Ghana. *Bioresour. Technol.* **100**, 5872–5875 (2009).
36. Miito, G., Komakech, A., Zziwa, A., Kiggundu, N. & Kambugu, R. *Assessment of the Suitability of Pineapple Waste as Feedstock for Vermicomposting* (2021).
37. Mohd Sokri, S. S. *et al.* Optimization on co-composting of horse manure with pineapple waste composition using response surface methodology (RSM). *IOP Conf. Ser. Earth Environ. Sci.* **1160**, 012026 (2023).
38. Nguyen Thien, M. *et al.* Composting of pineapple residues and food waste: A pilot-scale study. *Chem. Eng. Trans.* **83**, 301–306 (2021).

39. Rubel, F. & Kottek, M. Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen–Geiger climate classification. *Meteorol. Z.* **19**, 135–141 (2010).
40. Graves, R. & Hattemer, G. Chapter 2 Composting. Part 637 Environmental Engineering National Engineering Handbook. United States Department of Agriculture. *Nat. Resour. Conserv. Serv.* (2000).
41. Trautmann, N. M. & Krasny, M. E. *Composting in the Classroom: Scientific Inquiry for High School Students* (Kendall/Hunt Publishing Company, 1998).
42. Fleck, A. The determination of organic nitrogen. *Proc. Assoc. Clin. Biochem.* **4**, 212–215 (1967).
43. Black, C. Method of soil analysis part 2. *Chem. Microbiol. Prop.* **9**, 1387–1388 (1965).
44. Helmke, P. A. & Sparks, D. L. Lithium, sodium, potassium, rubidium, and cesium. *Methods Soil Anal. Chem. Methods* **5**, 551–574 (1996).
45. Bell, W., Roser, W. & Thomas, G. Diffraction analysis of dislocation pairs for detecting order in solid solutions. *Acta Metall.* **12**, 1247–1253 (1964).
46. Jackson, M. L. *Soil Chemical Analysis: Advanced Course* (UW-Madison Libraries Parallel Press, 2005).
47. Thompson, W., Leege, P., Millner, P. & Watson, M. Test Methods for the Examination of Composting and Compost. *U. S. Compost. Counc. Res. Educ. Found. U. S. Dep. Agric.* (2001).
48. Brewer, L. J. & Sullivan, D. M. Maturity and stability evaluation of composted yard trimmings. *Compost Sci. Util.* **11**, 96–112 (2003).
49. Van Der Wurff, A. W. G., Fuchs, J. G., Raviv, M. & Termorshuizen, A. *Handbook for Composting and Compost Use in Organic Horticulture.* https://research.wur.nl/en/publications/f56ea479-7183-4a42-8feb-f8d1736c0c06; https://doi.org/10.18174/375218 (2016).
50. Barton, K. *MuMIn: Multi-Model Inference. R Package Version 1.47.1* (2022).
51. Schielzeth, H. & Nakagawa, S. Nested by design: Model fitting and interpretation in a mixed model era. *Methods Ecol. Evol.* **4**, 14–24 (2013).
52. Husson, F., Lê, S. & Pagès, J. *Exploratory Multivariate Analysis by Example Using R* (CRC Press, 2017).
53. R Core Team, R. *R: A Language and Environment for Statistical Computing* (2023).
54. Epstein, E. Industrial composting. *Environ. Eng. Facil. Manag. N. Y.* **1**, 1 (2011).
55. Gao, M., Liang, F., Yu, A., Li, B. & Yang, L. Evaluation of stability and maturity during forced-aeration composting of chicken manure and sawdust at different C: N ratios. *Chemosphere* **78**, 614–619 (2010).
56. Woods End. Woods End Research Laboratory Interpreting Waste & Compost Tests. *Disponível Em Httpwww Woodsend Org Acessado Em* (2005).
57. Sangodoyin, A. & Amori, A. Aerobic composting of cassava peels using cow dung, sewage sludge and poultry manure as supplements. *Eur. Int. J. Sci. Technol.* **2**, 22–34 (2013).
58. Zahan, Z., Georgiou, S., Muster, T. H. & Othman, M. Z. Semi-continuous anaerobic co-digestion of chicken litter with agricultural and food wastes: A case study on the effect of carbon/nitrogen ratio, substrates mixing ratio and organic loading. *Bioresour. Technol.* **270**, 245–254 (2018).
59. Nahm, K. Evaluation of the nitrogen content in poultry manure. *Worlds Poult. Sci. J.* **59**, 77–88 (2003).
60. Hazelton, P. & Murphy, B. *Interpreting Soil Test Results: What Do All the Numbers Mean?* (CSIRO Publ, 2007).
61. Singh, S., Sharma, P. K., Singh, S. & Kumar, A. Addition of crop residues with different C: N ratios on the release pattern of available nitrogen and sulfur in different soils. *Commun. Soil Sci. Plant Anal.* **52**, 2912–2920 (2021).
62. Zhou, G., Xu, X., Qiu, X. & Zhang, J. Biochar influences the succession of microbial communities and the metabolic functions during rice straw composting with pig manure. *Bioresour. Technol.* **272**, 10–18 (2019).
63. Zhou, Y., Selvam, A. & Wong, J. W. C. Chinese medicinal herbal residues as a bulking agent for food waste composting. *Bioresour. Technol.* **249**, 182–188 (2018).
64. Bernal, M. P., Alburquerque, J. A. & Moral, R. Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresour. Technol.* **100**, 5444–5453 (2009).
65. Jat, L. K. *Studies on Temperature Fluctuation and Moisture Changes in Different Methods of Composting.* https://doi.org/10.13140/RG.2.1.3984.2803 (2016).
66. Upadhyay, A., Lama, J. P. & Tawata, S. Utilization of pineapple waste: A review. *J. Food Sci. Technol. Nepal* **6**, 10–18 (2010).
67. Zhang, L. & Sun, X. Improving green waste composting by addition of sugarcane bagasse and exhausted grape marc. *Bioresour. Technol.* **218**, 335–343 (2016).
68. Zhang, L. & Sun, X. Effects of rhamnolipid and initial compost particle size on the two-stage composting of green waste. *Bioresour. Technol.* **163**, 112–122 (2014).
69. Jakubus, M. A comparative study of composts prepared from various organic wastes based on biological and chemical parameters. *Agronomy* **10**, 869 (2020).
70. Richard, T. L., Hamelers, H., Veeken, A. & Silva, T. Moisture relationships in composting processes. *Compost Sci. Util.* **10**, 286–302 (2002).
71. Zhu-Barker, X., Bailey, S. K., Paw, U. K. T., Burger, M. & Horwath, W. R. Greenhouse gas emissions from green waste composting windrow. *Waste Manag.* **59**, 70–79 (2017).
72. Naher, U., Sarkar, M., Jahan, A. & Biswas, J. Co-composting urban waste, plant residues, and rock phosphate: Biochemical characterization and evaluation of compost maturity. *Commun. Soil Sci. Plant Anal.* **49**, 751–762 (2018).
73. Qian, X. *et al.* Co-composting of livestock manure with rice straw: Characterization and establishment of maturity evaluation system. *Waste Manag.* **34**, 530–535 (2014).
74. Tuomela, M. Biodegradation of lignin in a compost environment: A review. *Bioresour. Technol.* **72**, 169–183 (2000).
75. Zhang, Y. *et al.* Study on dynamic changes of microbial community and lignocellulose transformation mechanism during green waste composting. *Eng. Life Sci.* **22**, 376–390 (2022).
76. Sun, C. *et al.* Improve spent mushroom substrate decomposition, bacterial community and mature compost quality by adding cellulase during composting. *J. Clean. Prod.* **299**, 126928 (2021).
77. Wong, J. W. C. *et al.* Co-composting of soybean residues and leaves in Hong Kong. *Bioresour. Technol.* **76**, 99–106 (2001).
78. Zhang, P. *et al.* Effects of straw incorporation on the soil nutrient contents, enzyme activities, and crop yield in a semiarid region of China. *Soil Tillage Res.* **160**, 65–72 (2016).
79. Wang, Z. *et al.* Effects of biochar carried microbial agent on compost quality, greenhouse gas emission and bacterial community during sheep manure composting. *Biochar* **5**, 3 (2023).
80. Francou, C., Poitrenaud, M. & Houot, S. Stabilization of organic matter during composting: Influence of process and feedstocks. *Compos. Sci. Util.* **13**, 72–83 (2005).
81. Jain, M. S., Daga, M. & Kalamdhad, A. S. Variation in the key indicators during composting of municipal solid organic wastes. *Sustain. Environ. Res.* **29**, 9 (2019).
82. Tibu, C., Annang, T. Y., Solomon, N. & Yirenya-Tawiah, D. Effect of the composting process on physicochemical properties and concentration of heavy metals in market waste with additive materials in the Ga West Municipality, Ghana. *Int. J. Recycl. Org. Waste Agric.* **8**, 393–403 (2019).
83. Wu, C., Li, W., Wang, K. & Li, Y. Usage of pumice as bulking agent in sewage sludge composting. *Bioresour. Technol.* **190**, 516–521 (2015).

84. Al-Bataina, B. B., Young, T. M. & Ranieri, E. Effects of compost age on the release of nutrients. *Int. Soil Water Conserv. Res.* **4**, 230–236 (2016).
85. Tripetchkul, S., Pundee, K., Koonsrisuk, S. & Akeprathumchai, S. Co-composting of coir pith and cow manure: Initial C: N ratio vs physico-chemical changes. *Int. J. Recycl. Org. Waste Agric.* **1**, 15 (2012).
86. Said-Pullicino, D., Erriquens, F. G. & Gigliotti, G. Changes in the chemical characteristics of water-extractable organic matter during composting and their influence on compost stability and maturity. *Bioresour. Technol.* **98**, 1822–1831 (2007).
87. Lv, B., Zhang, D., Cui, Y. & Yin, F. Effects of C: N ratio and earthworms on greenhouse gas emissions during vermicomposting of sewage sludge. *Bioresour. Technol.* **268**, 408–414 (2018).
88. Yasmin, N., Jamuda, M., Panda, A. K., Samal, K. & Nayak, J. K. Emission of greenhouse gases (GHGs) during composting and vermicomposting: Measurement, mitigation, and perspectives. *Energy Nexus* **7**, 100092 (2022).
89. Diaz, L. & Savage, G. Factors that affect the process. *Compos. Sci. Technol.* **8**, 49 (2011).
90. Amery, F. *et al.* Compost quality indicators. *SoilCom Aarslev Den.* (2020).
91. Azim, K. *et al.* Composting parameters and compost quality: A literature review. *Org. Agric.* **8**, 141–158 (2018).
92. Sullivan, D. M., Bary, A. I., Miller, R. O. & Brewer, L. J. *Interpreting Compost Analyses* (Oregon State University Extension Service, 2018).
93. USDA-NRCS. Chapter—2 composting. In *Environmental Engineering National Engineering Handbook* 88 (2000).
94. Tremier, A. Home-made compost quality: Methods of assessment and results. *LIFE Project MINIWASTE* (2012).
95. De Bertoldi, M. *The Science of Composting* (Springer, 2013).
96. Brinton, W. & York, A. *Composting* (2003).
97. Anand, Prakasha, H. C. & Subbarayappa, C. T. Studies on variations in physico-chemical, biochemical and biological characteristics at different maturity stages of segregated and unsegregated urban solid waste of drum compost. *Int. J. Plant Soil Sci.* **35**, 1–15 (2023).
98. Finstein, M. S. & Miller, F. *Principles of Composting Leading to Maximization of Decomposition Rate, Odor Control, and Cost Effectiveness* (1985).
99. Tiquia, S., Tam, N. & Hodgkiss, I. Effects of turning frequency on composting of spent pig-manure sawdust litter. *Bioresour. Technol.* **62**, 37–42 (1997).
100. Forster, J. C., Zech, W. & Würdinger, E. Comparison of chemical and microbiological methods for the characterization of the maturity of composts from contrasting sources. *Biol. Fertil. Soils* **16**, 93–99 (1993).
101. Brinton, W. F. Compost quality standards and guidelines: An international view. *Woods End Res. Lab. Inc ME* **10**, 1 (2000).
102. Bernai, M. P., Paredes, C., Sanchez-Monedero, M. & Cegarra, J. Maturity and stability parameters of composts prepared with a wide range of organic wastes. *Bioresour. Technol.* **63**, 91–99 (1998).
103. Guo, R. *et al.* Effect of aeration rate, C: N ratio and moisture content on the stability and maturity of compost. *Bioresour. Technol.* **112**, 171–178 (2012).
104. Antil, R. S., Raj, D., Abdalla, N. & Inubushi, K. Physical, chemical and biological parameters for compost maturity assessment: A review. *Compos. Sustain. Agric.* **1**, 83–101 (2014).
105. Compaoré, E. & Nanéma, L. Compostage et qualité du compost de déchets urbains solides de la ville de Bobo-Dioulasso, Burkina Faso. *Tropicultura* **28**, 232–237 (2010).
106. Asquer, C. *et al.* Biomass ash reutilisation as an additive in the composting process of organic fraction of municipal solid waste. *Waste Manag.* **69**, 127–135 (2017).
107. Gómez-Brandón, M., Lazcano, C. & Domínguez, J. The evaluation of stability and maturity during the composting of cattle manure. *Chemosphere* **70**, 436–444 (2008).
108. Singh, Y. K., Kalamdhad, A. S., Ali, M. & Kazmi, A. Maturation of primary stabilized compost from rotary drum composter. *Resour. Conserv. Recycl.* **53**, 386–392 (2009).
109. Benito, M., Masaguer, A., Moliner, A., Hontoria, C. & Almorox, J. Dynamics of pruning waste and spent horse litter co-composting as determined by chemical parameters. *Bioresour. Technol.* **100**, 497–500 (2009).
110. Gnimassoun, E.-G.K., Ettien, J. B. D. & Masse, D. Caractérisation des propriétés physico-chimiques et chimiques d'un compost issu d'un mélange de rafles de palmier et de fientes de volaille au Sud-Ouest de la Côte d'Ivoire. *Int. J. Biol. Chem. Sci.* **14**, 289–305 (2020).
111. Amir, S., Hafidi, M., Merlina, G. & Revel, J.-C. Sequential extraction of heavy metals during composting of sewage sludge. *Chemosphere* **59**, 801–810 (2005).
112. Pakou, C., Kornaros, M., Stamatelatou, K. & Lyberatos, G. On the fate of LAS, NPEOs and DEHP in municipal sewage sludge during composting. *Bioresour. Technol.* **100**, 1634–1642 (2009).
113. Sullivan, D. M. & Miller, R. O. *Compost Quality Attributes, Measurements and Variability* (2001).

Acknowledgements

Author contributions

ELS and CEA conceived the research. ELS, CEA, and TK revised and made significant contributions. ELS, JOA and TK planned the work and set up the experiment. CEA, JOA and FY collected and analyzed the data. ELS drafted the manuscript. IH, NB and GLA contributed significantly to manuscript improvement. All authors contributed to the article and approved the submitted version.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to E.L.S.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.