

Evolution of Physicochemical Characteristics during the Composting of Maize Stalk Waste: Evaluation of Agronomic Potential of the Composts

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Abstract

In Togo, maize stalk waste is mainly disposed of by open-air burning, contributing to greenhouse gas emissions and soil degradation. This study aims to recover these residues through composting for use as an organic soil amendment. Four formulations were tested: C1 (100% maize stalk waste), C2 (80% maize stalk waste + 20% cow dung), C3 (95% maize stalk waste + 5% ash) and C4 (80% maize stalk waste + 15% cow dung + 5% ash). Monitoring of physico-chemical parameters (temperature, pH, electrical conductivity, organic matter, total Kjeldahl nitrogen and C/N ratio) was carried out over 180 days. The results show a typical composting progression with a thermophilic phase followed by maturation. Final pH values ranged from 6.89 to 8.88. The C/N ratio ranges from 12.95 to 23.09, indicating varying degrees of maturity depending on the formulation. The composts contain appreciable levels of fertilising elements (Ca, Mg, K, P), whilst concentrations of trace metals remain below the limits set by standard NFU 44-051. These composts show promising agronomic potential, although trials under real-world conditions are needed to confirm their effectiveness.

Keywords

Composting, Agricultural Waste, Maize Stalks, Soil Fertility, Recovery, Togo

1. Introduction

In sub-Saharan Africa, waste management remains a major challenge. Agricul-

ture, the main sector of economic activity, is the driving force behind development. In Togo, it accounts for around 54% of the working population in terms of the number of jobs it generates, and around 40% in terms of its significant contribution to the country's national wealth [1]. Furthermore, this activity generates substantial quantities of maize stalk waste, the predominant method of management for which is open-air burning. These practices pose major environmental problems, notably the production of greenhouse gases (GHGs) such as methane (CH₄) and nitrous oxide (N₂O), two gases whose global warming potential is 25 and 310 times greater than that of carbon dioxide (CO₂) [2] [3]. Furthermore, the open-field burning of crop residues not only harms the atmosphere but also poses a significant threat to soil fertility and productivity [4]. To optimise productivity, farmers favour the use of chemical inputs, which are costly and in short supply, and whose use generates potential environmental or health impacts [5]. In light of this situation, recovery through composting presents itself as a sustainable and suitable alternative in the context of developing countries. According to Lacour (2012) [6], agricultural waste consists of organic matter with high recovery potential and rapid decomposition kinetics. Several studies have demonstrated the benefits of compost on the physical and chemical properties of amended soils. The use of compost in agriculture has a positive impact on the soil-plant system, and the beneficial effect of compost application on plant nutrition is due to the fertilising elements it contains in varying quantities (N, P, K, Ca, Mg, S), as well as on crop growth and yield [7]. Furthermore, several composting studies carried out in Togo have demonstrated the benefits of compost made from household waste and natural phosphate [5] [8] [9], compost made from sewage sludge and household waste [10] and compost made from poultry manure and phosphate-rich waste [11] as a means of maintaining organic matter in the soil, as well as their effects on the yields of certain crops such as maize, tomatoes, carrots and cabbage. These studies have demonstrated the beneficial effects of compost on the physico-chemical properties of soils and agricultural productivity. However, the specific utilisation of maize stalk waste through composting remains poorly documented in Togo. This study therefore aims to analyse changes in physico-chemical parameters during the composting of maize stalks and to assess the agronomic quality of the resulting composts.

2. Materials and Methods

2.1. Study Site

The study was conducted on a farm located approximately 2 km from the village of Koudassi (**Figure 1**), a settlement in the Avé Prefecture, in Togo's Maritime Region, 82 km north-west of Lomé on the No. 5 national road. The geographical coordinates of the site are: 6°38'11.72"N and 0°52'04.50"E.

2.2. Materials

Figure 2 shows the raw materials used in compost production. These are:

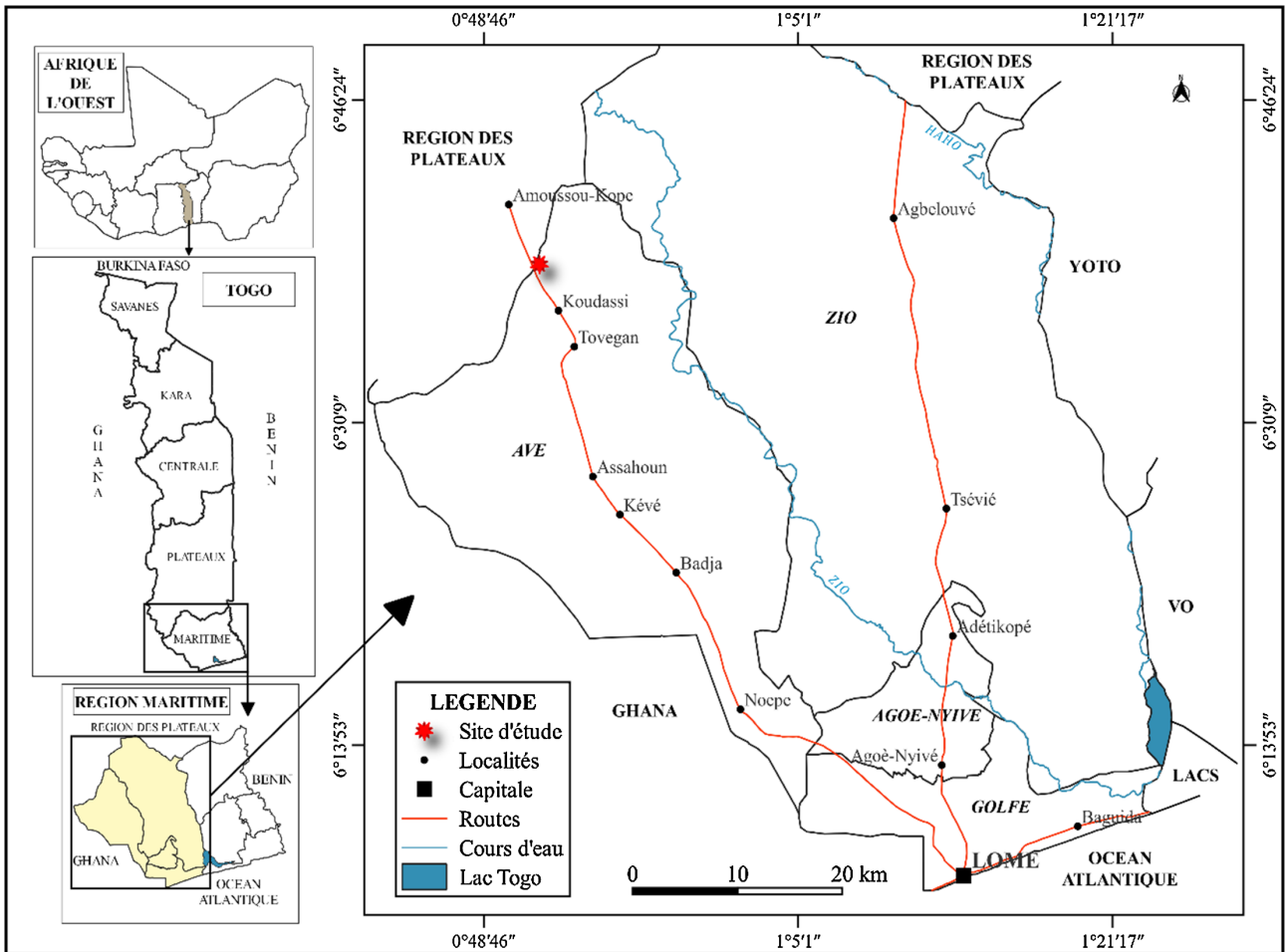


Figure 1. Map of the study area.

- ✓ Maize stalk waste collected from local farmers' fields;
- ✓ Ash from maize stalk waste obtained by incinerating the stalks;
- ✓ Cow dung collected from the cow pens at the composting site.



Figure 2. (a) Maize stalk waste, (b) cow dung and (c) ash from maize stalk waste.

Composting technique and process monitoring parameters

Figure 3(a) shows the composting platform designed for the experimental site. It is concrete-lined to prevent leachate from seeping into the soil and covered with

metal sheets to protect the compost from the sun and rain. In this study, we opted for windrow composting as shown in **Figure 3(b)**. The substrates are arranged in stacked layers. To ensure optimal decomposition of the substrates and prevent the compost from drying out or becoming waterlogged, the moisture content is maintained between 45 and 60%, in accordance with the literature. **Figure 3(c)** shows the appearance of the compost obtained after 6 months of composting. The piles are turned periodically at two days, four days, eight days, one month, two months, and three months, and are watered regularly depending on the moisture content of each pile. Several physicochemical parameters were also monitored after 30 days (T30), 90 days (T90), 150 days (T150), and 180 days (T180). These include pH, electrical conductivity (EC), organic matter (OM), and total Kjeldahl nitrogen (TKN).

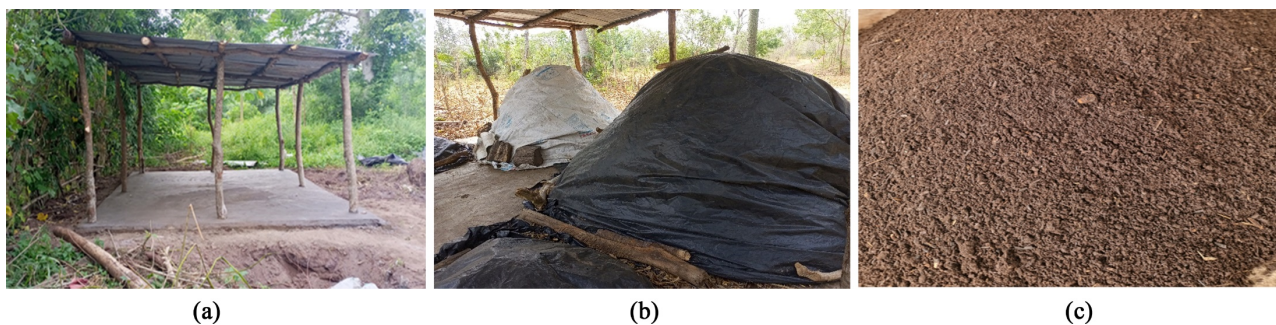


Figure 3. Compost production site: (a) composting platform, (b) photos of some windrows and (c) appearance of compost.

Table 1 shows the composition of the various windrows.

Table 1. Composition of the different windrows.

Windrows (kg)	Maize stalk waste	Cow dung	Ash from maize stalk waste	Total
C1	130	0	0	130
C2	104	26	0	130
C3	123.5	0	6.5	130
C4	104	19.5	6.5	130

C1: composts made from maize stalk waste; C2: composts made from maize stalk waste and cow dung; C3: composts made from maize stalk waste and ash from maize stalk waste; C4: composts made from maize stalk waste, cow dung and ash.

2.3. Methods for Analysing Physico-Chemical Parameters

Sampling

Samples for the characterization of physicochemical parameters were collected from the windrow. A composite sample consisting of four individual samples (1 kg each) was collected from each windrow at mid-depth and from different locations, and this composite sample was thoroughly homogenized.

Analysis of physicochemical parameters

The pH and electrical conductivity (EC) were measured using a “Toledo” glass-electrode pH meter and a “HANNA Instruments” conductivity meter, respectively, in accordance with the international standard NF ISO 10390 of November 1994. The organic matter content was determined by loss on ignition using an SNOL furnace in accordance with standard NFU 44-160 described in [12], while the total organic carbon (TOC) content was calculated from the organic matter content by dividing the latter by a factor of 1.724. The total Kjeldahl nitrogen (TKN) content was determined on dry compost samples in accordance with the AFNOR ISO 11261 method. This measurement involves several steps, including mineralization, distillation, and titration. The determination of nutrient element content (Ca, Mg, Na, and K) and trace metal content (Cu, Ni, Zn, Mn, Cd, and Pb) was performed in two steps following the NF ISO 11466 standard: mineralization of the compost sample and quantification by atomic absorption spectrophotometry (AAS). The total phosphorus content was determined using the method described by [13], which involves extracting 10 g of compost in an acidic medium to form a colored phosphorus-molybdate complex, which is then measured by colorimetry at 660 nm.

2.4. Methods for Analysing Physico-Chemical Units

The results were compiled in Microsoft Office Excel 2019 and statistically analyzed using IBM SPSS Statistics (version 2017). The mean value of the three (3) replicates for each treatment, as well as the standard deviation, were calculated. A comparison of the means of the different compost data sets was performed using the Tukey test following an analysis of variance (ANOVA). Principal component analysis (PCA) performed using XLSTAT software (version 2026) provided an overview of the parameters and highlighted correlations between the variables.

3. Results and Discussion

3.1. Physico-Chemical Characteristics of the Raw Materials

Table 2 presents the results of the physico-chemical and nutrient parameters of maize stalk waste, cow dung and ash from maize stalk waste. The pH of maize

Table 2. Physico-chemical parameters of the substrates.

Parameters	Maize stalk waste	Cow dung	Ash from maize stalk waste
pH	7.57 ± 0.27	9.6 ± 0.04	10.3 ± 0.04
EC (ms/cm)	1.519 ± 0.35	4.275 ± 0.06	4.47 ± 0.08
OM (%)	83.49 ± 0.65	49.22 ± 1.38	26.84 ± 0.14
TOC (%)	48.43 ± 0.39	28.55 ± 0.80	15.27 ± 0.34
NTK (%)	1.26 ± 0.11	1.97 ± 0.12	0.21 ± 0.01
C/N	38.44	14.49	72.71

stalk waste varies around neutrality, whilst that of cow manure and ash is basic. The pH value of maize stalk waste indicates that this substrate provides a favourable environment for the proliferation of bacteria and microorganisms responsible for the degradation of organic matter. Maize stalk waste has a high organic matter content, which, according to [12], would promote rapid development and decomposition of this substrate during composting. The results for nutrient elements indicate that these raw materials contain good levels of major (N, P and K) and minor (Ca and Mg) nutrients, thus justifying their agronomic qualities [14].

3.2. Temporal Monitoring of Physico-Chemical Parameters during Composting Identify the Headings

3.2.1. Temperature Trends in the Windrows

Monitoring the temperature of the windrows is essential for the composting process to proceed smoothly. **Figure 4(a)** and **Figure 4(b)** show the temperature trends for windrows C1, C2, C3, and C4 during composting. It should be noted that at the start of the process, the temperature fluctuated around 30.2°C for windrow C1, 31°C for C2, 30.5°C for C3, and 32.1°C for C4. On the 8th day of the process, the temperature of windrow C1 reached a maximum of 66.1°C and gradually dropped to 26.2°C. For windrows C2, C3, and C4, the temperature also rose to a maximum of 65°C, 63.2°C and 65.8°C on the 6th and 4th days, respectively, followed by a decrease and stabilization to 26.4°C, 27.8°C, and 27.6°C for C2, C3, and C4, respectively. However, observation of the temperature trends for the four windrows reveals two phases: oxidation due to a rise in temperature and mineralization characterized by cooling or a drop in temperature. The rise in temperature at the start of the process indicates intense microbial activity induced by the presence of readily biodegradable organic matter [5] [14] [15]. The drop in temperature can be explained by a slowdown in microbial activity leading to a

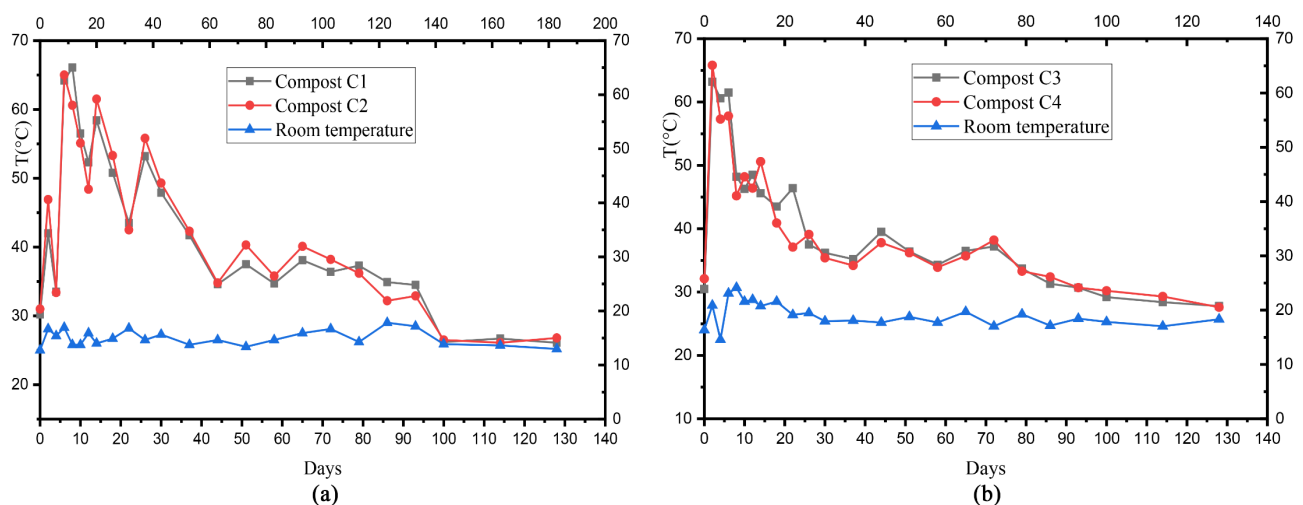


Figure 4. Temperature trends in windrows C1, C2, C3 and C4 over time. (a) Temperature of composts C1 and C2; (b) Temperature of composts C3 and C4.

decrease in readily biodegradable organic matter [9] [16]. A rise in temperature is observed after each turning, indicating that oxygen essential for the survival of decomposing microorganisms is being supplied. Our results corroborate those of [8] [17], which state that the temperature curves recorded at the center of compost piles can be divided into two phases : the heating phase, lasting from the 1st to the 23rd day, during which temperatures exceed 40 °C, and the cooling phase, which begins on the 23rd or 33rd day and lasts until the 74th day, during which temperatures stabilize around 30 °C.

3.2.2. Changes in Hydrogen Potential

The changes in pH during the composting of the four windrows are shown in **Figure 5(a)** and **Figure 5(b)**. The figures show a variation in pH from 7.57 to 7.29 for C1; 8.64 to 6.89 for C2; 8.50 to 8.78 for C3; and 8.67 to 8.88 for C4. Observation of the pH changes in the different composts reveals the absence of an acidification phase, but a slight decrease in pH towards neutrality is noted in compost C2 by the 30th day of the process, followed by a fluctuation down to a value of 6.89. For compost C1, an increase was observed up to the 90th day, followed by a decrease towards neutrality. As for composts C3 and C4, the trend remained alkaline: 8.50 to 8.78 and 8.67 to 8.88 respectively for C3 and C4. According to [8], the absence of an acidification phase indicates that there was therefore very little production of organic acids. The increase observed is attributed, according to [18], to the breakdown of easily degradable organic materials and to mineralisation. A basic pH at the end of the composting process is, according to [17], an indicator that the composting process has proceeded successfully. These results are similar to those of [19], which estimated that the pH of mature compost varies between 7 and 9.

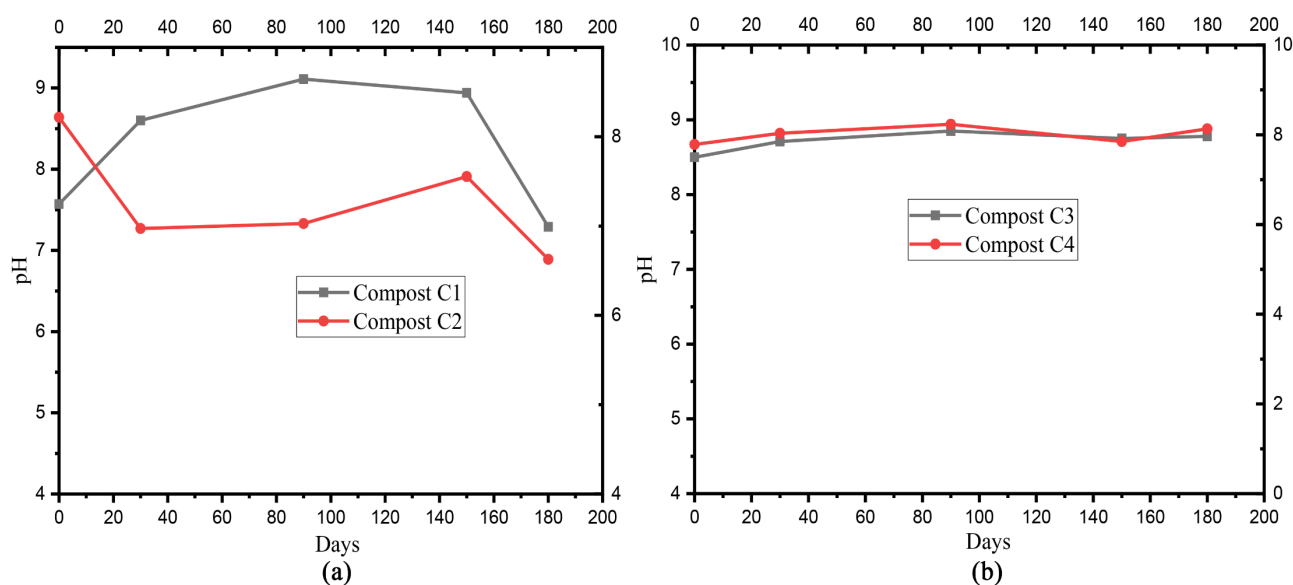


Figure 5. Changes in the pH of the different composts over time. (a) pH of composts C1 and C2; (b) pH of composts C3 and C4.

3.2.3. Changes in Electrical Conductivity

Electrical conductivity is a parameter that indicates the degree of salinity in the compost and suggests its potential phytotoxic effects on plant growth [20]. **Figure 6(a)** and **Figure 6(b)** show the evolution of the electrical conductivity (EC) of composts C1, C2, C3 and C4 during the composting process. Analysis of the curve showing the evolution of electrical conductivity for the different composts reveals an increase at the end of the composting process compared to the initial values. A variation is therefore observed from 1.12 to 3.08 ms/cm for compost C1, from 2.66 to 3.02 ms/cm for compost C2, from 2.19 to 2.21 ms/cm for C3 and from 1.86 to 2.57 ms/cm for compost C4. According to [21], the initial increase in electrical conductivity could be caused by the release of mineral salts such as phosphates and ammonium ions through the decomposition of organic matter. Our values do not exceed the set limit of 3 ms/cm and are comparable to those of [22], which state that compost with a conductivity between 2 and 3 ms/cm is acceptable for crops.

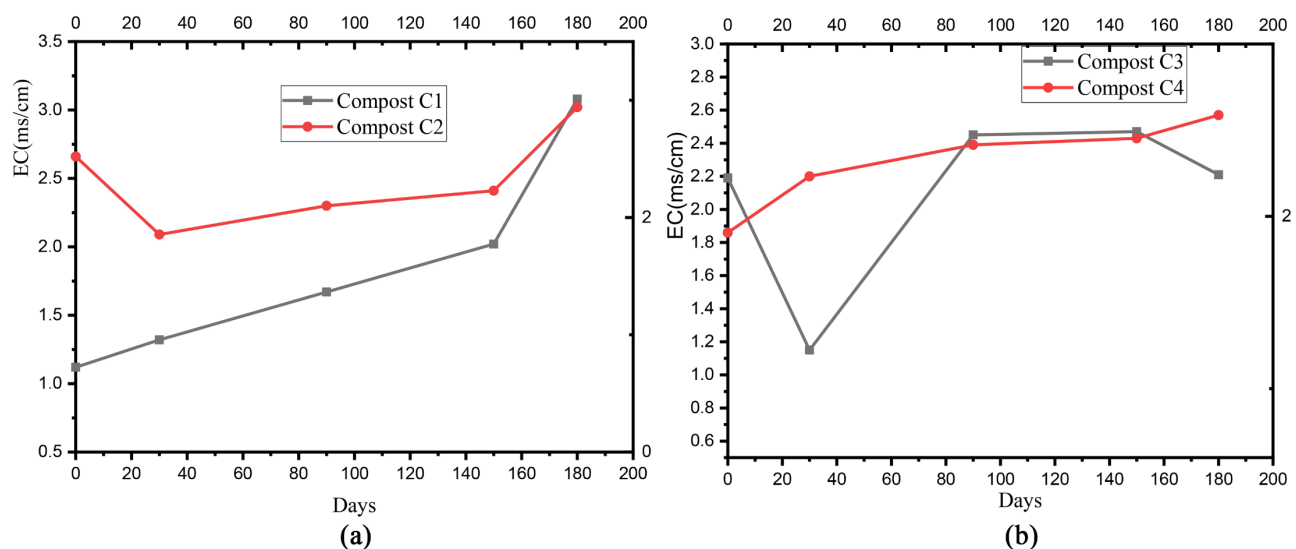


Figure 6. Changes in the electrical conductivity of the composts over time. (a) EC of composts C1 and C2; (b) EC of composts C3 and C4.

3.2.4. Changes in Organic Matter

The changes in organic matter content in the various composts during the composting process are shown in **Figure 7(a)** and **Figure 7(b)**. A decrease in organic matter content is observed after 180 days, ranging from 83.49% to 47.70%; 75.08% to 43.55%; 68.75% to 51.75%; and 61.73% to 43.69% respectively for composts C1, C2, C3 and C4. This decrease in the percentage of organic matter could be explained by its mineralization. According to [20] [23], 20 to 40% of the initial content was lost through decomposition by microorganisms to support cellular metabolism. These data are comparable to those reported by [23], which emphasise that mature compost should have an organic matter content of less than 50%.

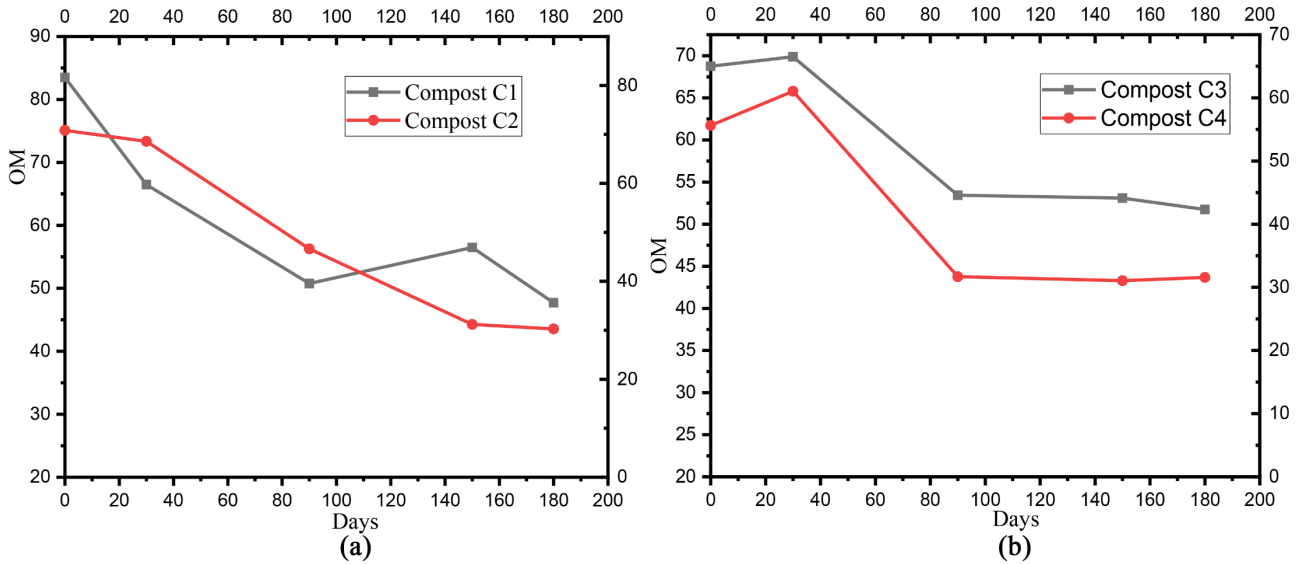


Figure 7. Changes in organic matter in composts C1, C2, C3 and C4. (a) OM of composts C1 and C2; (b) OM of composts C3 and C4.

3.2.5. Changes in Total Kjeldahl Nitrogen

Figure 8(a) and **Figure 8(b)** illustrate the results of the changes in total nitrogen in the different composts. Over the 180 days of composting, a variation of 1.26% to 1.35% was observed for compost C1 and 1.19% to 1.95% for compost C2. As for composts C3 and C4, a variation from 1.08% to 1.30% and from 1.22% to 1.91% was also observed for C3 and C4 respectively. Overall, the trend in total nitrogen in the composts over time showed an increase. According to [24], this increase in total nitrogen is likely due largely to the loss of dry matter.

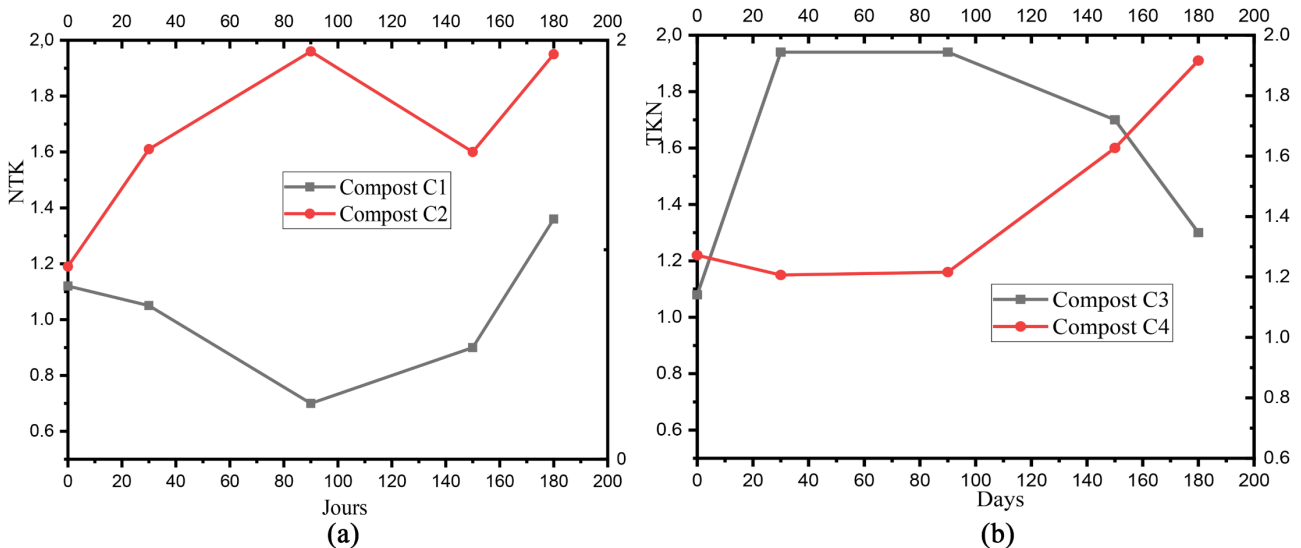


Figure 8. Changes in total nitrogen in the composts over time. (a) NTK of composts C1 and C2; (b) NTK of composts C3 and C4.

3.2.6. Changes in the C/N Ratio

The carbon-to-nitrogen ratio is one of the parameters used to assess the maturity of a compost. The results of monitoring the C/N ratio of the different composts

over time are shown in **Figure 9(a)** and **Figure 9(b)**. At the start of the process, the ratio was 38.44 for C1; 36.60 for C2; 36.93 for C3 and 29.35 for C4. These results are consistent with the initial C/N ratio (between 25 and 35) specified in the literature for a successful composting process. Observation of the curves showing the evolution of the C/N ratio over time indicates a decrease to values of 20.35; 12.95; 23.09 and 13.26 respectively for composts C1, C2, C3 and C4. According to [25], this decrease is due to the bio-oxidative phase, characterised by the decomposition of organic matter. For [20], this decrease can be explained by the fact that microorganisms consume more carbon (the main component of organic molecules) than nitrogen.

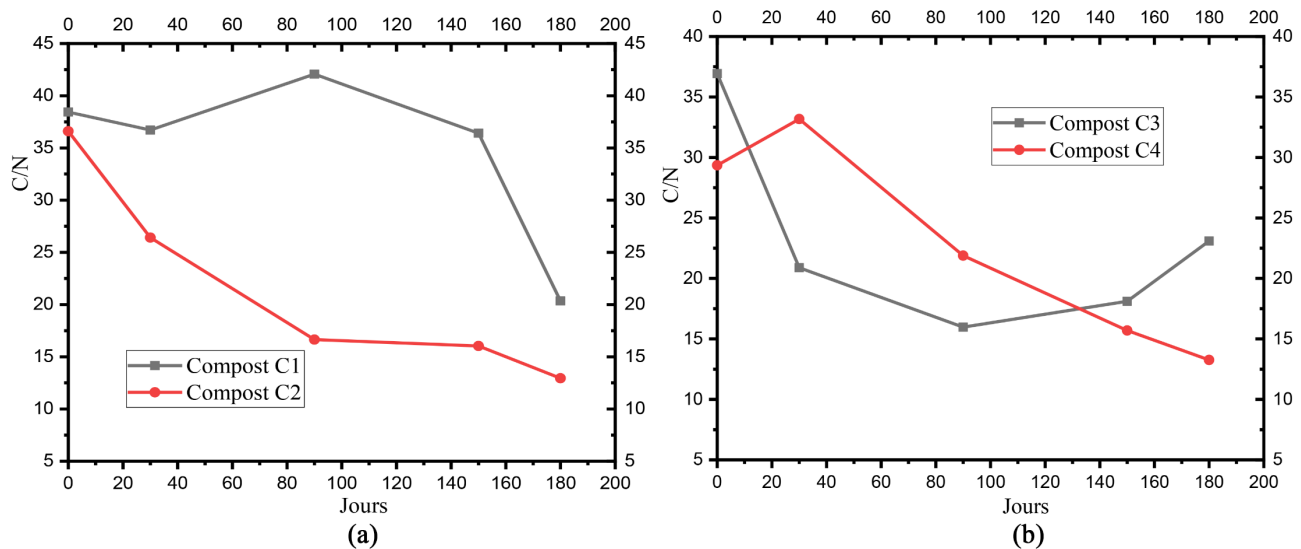


Figure 9. Changes in the C/N ratio of the different composts over time. (a) C/N ratio of composts C1 and C2; (b) C/N ratio of composts C3 and C4.

3.3. Physico-Chemical Characterisation of the Final Composts

3.3.1. Physico-Chemical Characteristics of the Different Composts Produced

The results of the physico-chemical parameters of the composts produced are shown in **Table 3**. The pH of composts C1 and C2 is around neutral, whilst composts C3 and C4 are slightly alkaline. A significant difference is observed between the pH of composts C1 and C2 and that of composts C3 and C4 at a 5% probability level. These values are consistent with those reported by [10] [19]. [19] noted that the pH of mature compost varies between 7 and 9. Composts C1 and C2 showed no significant difference at the 5% significance level with regard to electrical conductivity; however, a significant difference was observed between C2 and C3, and between C3 and C4. The electrical conductivity of the four composts is comparable to the values found by [5]. The results for the C/N ratio of the different composts showed no significant difference. The C/N ratios of composts C1 and C3 exceed the limit value set by standard NFU 44-051, as highlighted by [10], but composts C2 and C4 showed values that did not exceed this threshold. However, [26] noted that according to the AFNOR standard (2006), the C/N ratio limit must be between 15 and 20.

Table 3. Physicochemical parameters of the composts.

Parameters	C1	C2	C3	C4	[5]	NFU 44-051
pH (u pH)	7.29 ± 0.08 ^b	6.89 ± 0.05 ^b	8.78 ± 0.08 ^a	8.88 ± 0.07 ^a	8.42 ± 0.09	-
EC (ms/cm)	3.08 ± 0.07 ^a	3.02 ± 0.01 ^a	2.21 ± 0.02 ^c	2.57 ± 0.03 ^b	01.31 ± 0.05	-
TOC (%)	27.67 ± 0.34 ^b	25.26 ± 0.27 ^c	30.02 ± 0.26 ^a	25.34 ± 0.24 ^c	21.23 ± 0.92	-
NTK (%)	1.36 ± 0.04 ^a	1.95 ± 0.02 ^a	1.30 ± 0.25 ^a	1.91 ± 0.03 ^a	0.81 ± 0.10	<3%
C/N	20.35 ^a	12.95 ^a	23.09 ^a	13.26 ^a	26.4 ± 2.61	>8

Values on the same row and followed by the same letter are not significantly different at the 5% probability level.

3.3.2. Nutrient Content of the Composts

Table 4 presents the nutrient content of the different composts. Analysis of the results shows that there is no significant difference at the 5% significance level in the magnesium (Mg), potassium (K) and phosphorus (P) content of the different composts. A significant difference is observed between the different composts with regard to calcium (Ca) and sodium (Na) content. The calcium content of compost C1 is not significantly different from that of the other three composts, but compost C2 differs significantly from C3 and C4. A low proportion of fertilising elements was recorded in all the composts, which remained well below the limit values defined by standard NFU 44-051. Our results for calcium and potassium are slightly lower than those found by [5], but the proportions of phosphorus and magnesium remain similar.

Table 4. Nutrient content of the composts produced.

Parameters (%)	C1	C2	C3	C4	[5]	NFU 44-051
CaO	1.49 ± 0.09 ^{ab}	1.62 ± 0.02 ^a	1.44 ± 0.05 ^b	1.38 ± 0.02 ^b	1.59	2.5 - 5
MgO	0.47 ± 0.06 ^a	0.52 ± 0.05 ^a	0.48 ± 0.02 ^a	0.41 ± 0.01 ^a	0.28	-
Na ₂ O	0.09 ± 0.02 ^b	0.12 ± 0.02 ^{ab}	0.18 ± 0.02 ^{ab}	0.23 ± 0.03 ^a	-	-
K ₂ O	1.13 ± 0.02 ^a	1.20 ± 0.01 ^a	0.20 ± 0.03 ^a	0.16 ± 0.02 ^a	1.34	<3%
P ₂ O ₅	0.20 ± 0.02 ^a	0.19 ± 0.01 ^a	0.5 ± 0.05 ^a	0.47 ± 0.02 ^a	0.012	<3%

Values on the same row and followed by the same letter are not significantly different at the 5% probability level.

3.3.3. Trace Metal Content

The results for the various heavy metals determined in the composts produced are shown in **Table 5**. Statistical analysis of the results revealed a significant difference at the 5% level between the concentrations of Cu, Ni, Zn, Mn and Cd; however, none of the composts showed any significant difference in lead concentration. Overall, these values do not exceed the limit values set by standard NFU 44-051 for use as an organic soil amendment. For [12], the presence of trace metals in composts is a quality criterion provided it does not exceed the recommended standards; however, repeated applications of composts could, through the accumulation of pollutants, have a disruptive effect on the biological functioning of soils [5].

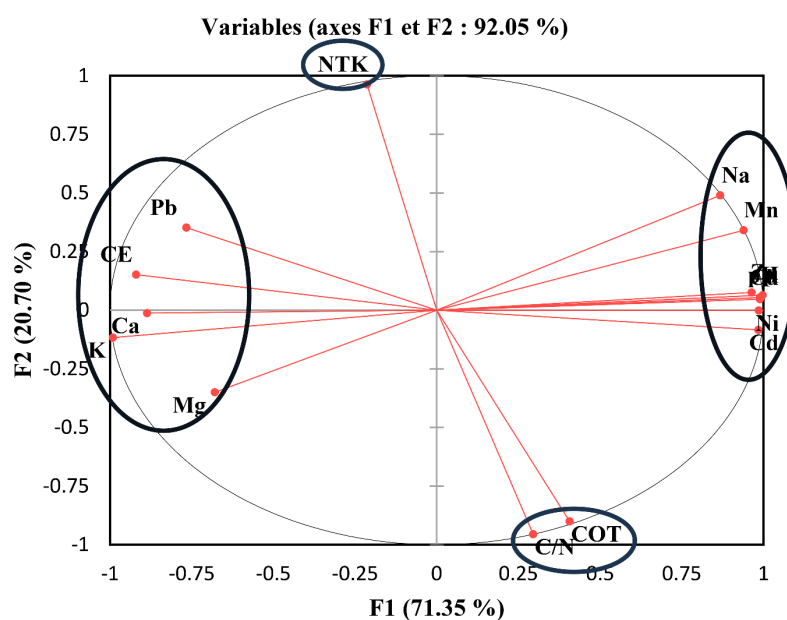
Table 5. Proportions of trace metals in composts.

Parameters (mg/kg)	C1	C2	C3	C4	NFU 44-051
Cu	9.69 ± 0.70 ^b	9.35 ± 0.41 ^b	21.31 ± 0.8 ^a	20.25 ± 0.45 ^a	300
Ni	4.16 ± 0.04 ^c	3.07 ± 0.29 ^c	36.4 ± 0.70 ^a	30.86 ± 0.61 ^b	60
Zn	1.8 ± 0.20 ^b	7.6 ± 0.40 ^b	53.32 ± 3.02 ^a	46.07 ± 0.87 ^a	600
Mn	6.06 ± 0.04 ^c	6.15 ± 0.55 ^c	267.76 ± 2.46 ^b	398.15 ± 3.05 ^a	-
Cd	0.15 ± 0.03 ^b	0.08 ± 0.02 ^b	0.78 ± 0.08 ^a	0.62 ± 0.08 ^a	3
Pb	17.49 ± 0.26 ^a	90.86 ± 0.66 ^a	9.18 ± 0.28 ^a	10.70 ± 0.93 ^a	180

Values on the same row and followed by the same letter are not significantly different at the 5% probability level.

3.4. Principal Component Analysis (PCA)

Figure 10 shows the correlation plot between the analysed variables. Two principal components (F1 and F2) are observed, accounting for 92.05% of the variation, of which 71.35% is explained by the first principal component (F1) and 20.70% by the second principal component (F2). pH, phosphorus (P), copper (Cu), nickel (Ni), cadmium (Cd), zinc (Zn), manganese (Mn), sodium (Na), electrical conductivity (EC) and calcium (Ca) are represented by component F1. Component F2 is represented by NTK, TOC and the C/N ratio. Component F1 is strongly and positively correlated with pH (99.7%), phosphorus (98.9%), copper (98.9%), nickel (98.5%), cadmium (98.4%), zinc (96.4%), manganese (93.9%) and sodium (86.7%), and negatively correlated with potassium (-99.1%), EC (-92%) and lead (-76.6%). Furthermore, the F2 component is characterised by a strong positive correlation with total nitrogen (96.3%) and negative correlations with TOC (-90%) and the C/N ratio (-95.5%).

**Figure 10.** Correlation plot of physico-chemical variables on the F1 × F2 axis system.

4. Conclusion

This research project was undertaken with a view to utilising maize stalk residues through composting in order to reduce open-air burning. Four composts C1, C2, C3 and C4 were produced for this purpose. The results of monitoring the physico-chemical parameters over time are consistent with values reported in the literature. The composts obtained contain significant levels of fertilising elements (Ca, Mg, K and Na), concentrations of trace metals (Cu, Ni, Zn, Cd and Pb) and physico-chemical characteristics (pH, EC, TOC, NTK and C/N) comparable to those reported in the literature. Based on the results, these composts could contribute to soil fertility and improved agricultural yields. Consequently, to confirm the agronomic potential of these organic soil amendments, field trials must be conducted to assess their impact on crop yields.

Acknowledgements

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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