detritus | Multidisciplinary Journal for Circular Economy and Sustainable Management of Residues

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CO-COMPOSTING OF SAWDUST WITH FOOD WASTE: EFFECTS OF PHYSICAL PROPERTIES ON COMPOSTING PROCESS AND PRODUCTS QUALITY

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Article Info:
Received:
21 August 2022
Revised:
21 April 2023
Accepted:
22 May 2023
Available online:
15 June 2023

Keywords:
Composting
Sawdust
Food waste
Physical properties
Bulk density

ABSTRACT

Sawdust and food waste have been part of solid organic waste causing great environmental pollution. Composting is a popular utilization method of converting waste like sawdust and food waste to sanitized and stabilized soil amendment. Unfortunately, many composting systems failed due to a dearth of information as a result of little or no scientific research focused on the effects of the physical properties of composting materials on the composting process. To fill this knowledge gap, three composting experiments of food wastes mixed with sawdust at ratio 20:80, 30:70, and 40:60 and compacted to different initial bulk densities of 15, 20, and 25 kg/m^3 respectively was carried out to explore the effect of physical properties on composting of sawdust with food wastes. Physicochemical parameters monitored include bulk density; porosity; particle density, temperature, moisture content; pH, and electrical conductivity (EC). The highest temperature (65.3°C) was recorded by trial 3 while trial 1 recorded the lowest temperature (49.3 0C). Among trials 1, 2, and 3, the maximum pH (9.2) and EC (5.1 mS/cm) were observed in compost trial 3. Additionally, the lowest pH (5.3) and EC (1.4 mS/cm) was observed in trial 1. Trial 3 had the highest percentage finest and lowest fibrosity content. A significant increase in bulk density, porosity, and particle density was observed in the three compost trials. The compost's bulk density of (25 kg/m^3) in trial 3 was observed to attain maturity and stability as compared with trials 1 and 2.

1. INTRODUCTION

A large amount of waste generated from agriculture and food waste is one of the global serious issues (Bello et al., 2021). The rate at which solid organic waste is being generated worldwide due to the rise in population and industrialization is alarming (Wu et al., 2014). Many of these wastes are disposed of untreated and it has caused environmental and health challenges (Lukashe et al., 2019; Sukholthaman et al., 2016, Awasthi et al., 2014;). Household wastes are mixed with other wastes and are disposed of at dumpsites without any efficient material or energy recovery (Oudal et al., 2016). Recently in Nigeria, there is an increase in demand for wood for furniture and other construction purposes, as a result, a considerable amount of sawdust from timber is generated from sawmills. South-west Nigeria alone with over 10,000 sawmills is currently processing over 500,000 logs of wood per year, with about 50-55% as waste informs of sawdust (Adegoke et al., 2014). As a result, a huge landfill of sawdust is being created at sawmill and it poses a threat to humans and the environment. Getting rid of sawdust requires maximum operational cost, as a result, many were dumped to form sawdust piles and many were burnt regularly. Abdul-Halim et al. (2019) reported that improper disposal and or indiscriminate burning of biomass are responsible for depleting the quality of air, contributing to an increase in greenhouse gas emissions, and significantly contributing to global warming, climate change, a source of contaminant to drinking water, soil pollution (Hwang et al., 2020) and threat to the environment and human health. Therefore, the need for more effective waste management and a reasonable plan should be adopted to overcome this environmental concern (Moh et al., 2017). Instead of burning sawdust as normal practices in some advanced Nations and due to its high carbon content (Bello et al., 2021), energy recovery through conversion of this ligno-cellulosic materials into compost could assist in soil carbon sequestration which has been widely adopted in agricultural practices.

Concerning food waste, it forms a major threat global-

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https://doi.org/10.31025/2611-4135/2023.17276

ly because it increases daily due to the increase in human population and improvement in the global economy. FAO statistics report of 2020 indicated that about one-third of food produced is wasted globally (FAO 2020) and Nigeria alone contributed about 32 million tonnes of wasted food (Adebayo et al., 2020). However, food waste is becoming an environmental challenge that threatens man and environmental resources (land and water resources) if it is discharged into the environment without prior treatment. It may cause pollution and harmful effects on human and animal health (Ghosh et al., 2019). It is however important to find effective management of these wastes to promote the effort concerning the development of a sustainable society.

Research has proved that organic waste products can be recycled using different technologies such as aerobic digestion, composting, fermentation, refuse-derived-fuels, and gasification (Nizami et al., 2017; Mashat, 2014; Kelleher, 2007). Composting has advantages over other methods and it is also considered a sustainable treatment for converting organic wastes into valuable products. Converting waste to valuable products through composting is eco-friendly, in addition to its cost-effectiveness, the valuable end product among others makes composting the most widely adopted method (Al-Rhumaihi et al., 2020). It is also considered the best option for recycling waste without causing environmental hazards (Calaby-Floody et al., 2019, Chen et al., 2018). Composting is gaining more attention as many developed nations have adopted composting as a method of recycling and processing waste. In Europe, over 4 million tonnes of organic waste were recycled by more than 124 compost facilities. Also, countries like; Holland, Spain, and France composted 24, 33, and 14% of the total waste generated in the year 2005 alone (Kelleher, 2007). Composting by-products has been extensively used as organic fertilizer to replenish lost soil nutrients (Wang et al., 2019) and as bioremediation to remove soil organic contaminants (Chen et al., 2015; Purnomo et al., 2011).

Composting converts organic waste into a hummus-like organic product through microbial decomposition under aerobic conditions to produce quality organic soil conditioner (Fernandez et al., 2014; Hemidat et al., 2018; Bao et al., 2016). The composting process starts with the mixing of an organic substrate which is the prerequisite for every composting management condition (Cao et al., 2020). However, setting up good management composting system requires a good knowledge of the physical properties of the substrates and the bulking agents. Knowing this could necessitate efficient maintenance and run of a composting plant. Inadequate information about the physical properties of compost material has made many composting systems fail. It is, therefore, necessary to have vital information about the physical properties of the materials involved and understand the composting system.

Composting needs oxygen and moisture for microbial activities (Assandri et al., 2021). The distribution of moisture, oxygen, and temperature within compost is an important factor in maintaining aerobic conditions during composting. The movement of moisture and air across the compost is greatly affected by the geometry and arrangement of the bulking agent where physical properties play a major role (Orthodoxou et al., 2015; Agnew et al., 2005). Moisture and air are required in moderate proportion during composting. Too much moisture and air could lead to excessive cooling and could prevent the compost from reaching the thermophilic condition that is necessary for optimum decomposition and sanitization of the matured compost. Also, inadequate moisture and air in the compost could result in to decrease in oxygen availability to microorganisms and heat evenly distributed across the compost matrix and this could lead to anaerobic conditions. Moisture and air transfer in the composting system are greatly controlled by the physical properties of the substrate.

Most of the physical properties of composting materials that attracted great attention are bulk density, porosity, and particle density. Bulk density of compost is the ratio of the mass of composting materials to the volume of the composting materials and it determines some mechanical properties of the compost such as strength, porosity, and ease of compaction (Mayur et al., 2018). The bulk density of compost determines how fast or slows the degradation of the compost. Due to this, knowing the bulk density of compost is an important requirement for designing an efficient compost system.

2. THEORETICAL RELATIONSHIP OF PHYSICAL PROPERTIES IN A POROUS ORGANIC MATRIX

When forming a compost pile, the physical properties of the composting mixture must be considered for optimal performance of the moisture content, and carbon-to-nitrogen ratio, and to provide a favourable condition for microorganisms (Mayur et al., 2018). Mayur et al. (2018) have identified some of the important physical parameters that affect the optimal performance of the composting process such as bulk density, moisture content and air-filled-porosity or free air space. As soon as the compost pile is formed, difficulties are often observed because the effects of some physical properties are always ignored or information about it is not available. For example, bulk density plays a crucial role in the strength and porosity of the compost pile. If the pore space gets filled with water in the presence of high moisture content, then there would be an increase in air space resistance, which results in oxygen deficit in the pile, and anaerobes started dominating aerobes. Bulk density is the ratio of the mass of compost to its volume. Its mathematical expression is kilogram per cubic meter (Kg/m^3) (Equation 1).

$$Bd_w = \frac{mass\ of\ the\ material}{volume\ of\ the\ bin} \quad (1)$$

$$BD_d = Bd_w\ x\ \frac{100\ -\ \%\ moisture}{100} \quad (2)$$

Another physical parameter that determines the distribution of air and moisture across the compost matrix is porosity. Porosity or air-filled porosity as popularly called in compost literature can be expressed in terms of bulk density and moisture content as described in Equation (3).

$$Porosity\ (\eta) = \left(1 - \frac{Y_{wet}}{P_d}\right) \quad (3)$$

where:

Y_{wet} is wet bulk density (Kg m^3)

P_d is the particle density

Many studies have been carried out on composting sawdust with food wastes or with other substrates (Jae-Han et al., 2020, Zaihua et al., 2020). These studies explained the efficiencies of unconventional bulking agents in composting food waste and end product (Jae-Han et al., 2020), about biological parameters such as oxygen uptake rate, carbon dioxide (CO_2) evolution rate, and Physico-chemical properties such as moisture content, volatile solids, C/N ratio and heavy metals (Singh and Kalamdhad 2013a; Nayak et al., 2014). However, little scientific data exist on the best physical properties of composting sawdust with food waste. This study was designed to investigate the effects of physical properties of composting materials on composting process during the composting of sawdust with food waste as well as to evaluate the best bulk density for composting sawdust with food waste.

3. MATERIALS AND METHODS

3.1 Experimental materials

3.1.1 The compost bin

60 liters of non-biodegradable plastic containers were used in this study (Figure 1). The inner diameter of the container was 290 mm while the height was 380 mm. Holes of 3 mm diameter separated by 10 cm were drilled on the side and bottom of the container corresponding to 10% surface porosity, for proper aeration and the drainage of the leachate during the composting.

3.1.2 Food waste and sawdust

The food wastes were collected from the University of Ilorin canteens and were made up of leftover cooked rice, bread, and waste vegetable. The bigger food particles were cut to smaller sizes < 1.5 cm. The sawdust was from a soft tree (Malaina tree) and was packed from a local sawmill. It was sieved by a 5 cm aperture size sieve to obtain the size of the same material. The two were then mixed at different proportions with a spade and were then loaded into bins. Three different composting mixtures at three different initial bulk densities were formulated as shown in Table 2.

3.1.3 Characterization of the raw materials

The composting materials have different properties as shown in Table 1. The moisture contents were found to be approximately 10.23% for sawdust and 64.23% for food waste. In composting experiment, the total organic carbon and nitrogen content of the materials is the nutritional characteristics of the composting materials, the ratio of the two (C:N ratio) is used to assess the nutritional balance for the microorganism. However, the C:N ratio of sawdust was 49.59, while that of food waste was 34.95. the C:N ratio of sawdust was slightly higher than that of the food waste. In addition, the two composting materials were slightly acidic with pH of 5.6 and 5.3 for sawdust and food waste respectively. The electrical conductivity of the composting materials was within the range of 7.55 dS/m for sawdust and 41.63 dS/m for food. The higher electrical conductivity recorded by food waste may be because of some salts present in the food materials. Fibrosity content was determined for sawdust only and was found to be 89.0%. Bulk densities for both materials were 15.12 and 10.23 Kg/m³ respectively.

TABLE 1: Basic characterization of raw materials used in the composting experiments.

parameters	Sawdust	Food waste
TN (%)	1.62 ± 0.16	1.54 ± 0.29
TOC (%)	80.34 ± 1.47	53.83 ± 0.20
C/N	49.59	34.95
pH	5.65 ± 0.11	5.36 ± 0.47
EC (dS/m)	7.55 ± 0.47	41.63 ± 0.65
Moisture content (%)	10.23 ± 0.23	64.23 ± 0.13
Fibrosity content (%)	89.0 ± 0.02	* Nd
Bulk density (Kg/m³)	15.12 ± 0.01	10.23 ± 0.14

Nd = not determined

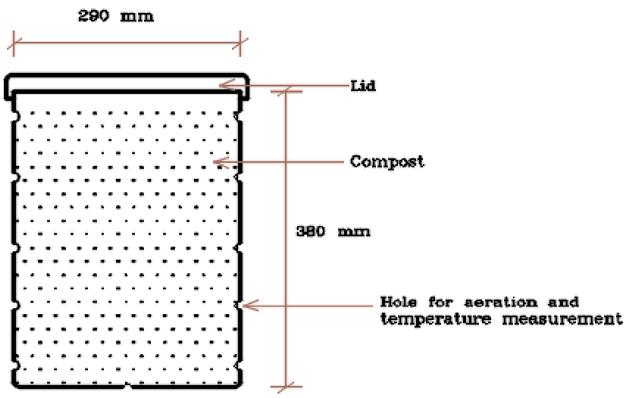

FIGURE 1: Schematic diagram of composting system.

TABLE 2: The initial experimental conditions of each of the composting mixture.

	Composting mixture			
Mixture	Sawdust (%w/w)	Waste food (%w/w)	Initial moisture Content (%)	Initial bulk density (kg/m³)
1	80	20	60	15
2	70	30	60	20
3	60	40	60	25

3.2 Experimental setup and monitoring process

3.2.1 Bulk density

Equation 1 was used to measure the bulk densities of the composting experiments. The bins were filled with a mixture of composting materials previously mixed at different proportions. Each bin was moderately compacted from predetermined heights of 100 mm, 150 mm and 200 mm respectively. After compaction, the procedure was repeated to fill the bin to the desired level and bulk densities. At the end of the process, each experimental mixture has the initial bulk densities of 15 kg/m^3, 20 kg/m^3, and 25 kg/m^3 respectively. The initial moisture contents of the experiments were set to 60%.

3.2.2 Physicochemical analysis during the composting period

The three composting bins were veered weekly. The maturity indexes were also measured weekly till the compost was matured. The temperature was recorded three times a day; at 8 a.m, 3 p.m, and 8 p.m, and a Reotem analog compost thermometer was used. Also, compost samples were oven dried at 105°C to constant weight to ascertain their moisture content.

0.050 Kg of compost were randomly picked from different parts of the bin and blended to earn 0.15 Kg weekly which was divided into three. For pH and Electrical conductivities (EC) determinations, 0.050 Kg of the blended compost was used. The pH and EC were measured by mixing the known sample with 10 cm^3 of distilled water and then shaking. A pH meter (pH-3C, Shanghai, China) was inserted to measure pH, and Electrical Conductivity (EC) was also determined using a conductivity meter (LeiCi, Shanghai, China). The method described by Wang et al. (2021a) was used to measure the total organic carbon (TOC). Total nitrogen (TN) was measured using the Kjeldahl method (Cao et al. 2018) and the ratio of TOC to TN gives the C: N ratio. The remaining 0.05 kg compost sample was used to measure the bulk density and moisture content of the sample throughout the composting period.

The free air space or porosity of the compost was measured from the bulk density and particle density of the compost mix using Equation (3). Bulk density was measured using a plastic container whose volume is approximately 50 cm^3. The plastic container was filled to one-third height and gently tapped on the plain surface to eliminate voids; then, filled up to two-thirds and after that up to the top brim of the container. Bulk density was calculated by dividing the mass of the compost by the volume of the plastic container. A pycnometer was improvised using a plastic bottle having a screw cap to measure the particle density of the compost material. A hole of 2 mm diameter was drilled on the cap. Small-plastic tubing was attached to the hole with about 30 mm length of tube projecting into the bottle when covered with a cap. The rest of the tube was bent on top of the cap and conducted excess liquid out when the bottle was filled with liquid. The lower density of compost makes distilled water unsuitable to use as displaced fluid to measure the density of the compost material; therefore, kerosene was used as a reference fluid because of its lower density following the Mayur's et al. (2018) method.

3.3 Analysis of the final products

The physical, biological, and chemical properties of the final compost obtained were analyzed. The chemical properties of the final compost assessed include; EC, pH, Cation exchange capacity (CEC), C: N ratio, Phosphorus, and Nitrogen contents, while the physical assessment was based on the loose bulk density, and percentage finest of the product. The biological assessment of the product was based on phytotoxicity evaluation using the Germination index (Tibu et al., 2019). Compost extracts were prepared from the final compost by mixing 20 g of air-dried compost in 10 cm3 of distilled water. The mixture was then shaken for 30 min after which was filtered using Whatman No 4 filter paper to produce compost extract which was then used in germination index tests. Tomatoes seed (Solanum lycopersicum) (Viability as tested = 90%) was used for the germination index test. Whatman No 4 filter paper already moistened with an extract from compost was laid in a Petri dish and Ten (10) viable seeds of tomatoes were placed on it. A control experiment was also set up using deionized water only. The experiments were replicated thrice and were set up in the laboratory where the temperature was maintained at room temperature. After 7 days of incubation, germinated seeds were counted (Tibu et al., 2019) and the germination index (GI) was evaluated according to Equation 4.

$$GI\ (\%) = \frac{\%\ seed\ Germination \times Root\ Lenght\ of\ Treatment}{\%\ seed\ Germination \times Root\ Lenght\ of\ Control} \times 100 \quad (4)$$

where:
GI is the germination index

3.4 Physical properties analysis of the final compost

3.4.1 Percentage finest determination

The percentage finest determination of the matured compost was done using a mechanical shaking method. From each of the compost, a known representative sample of dried compost was placed on a stack of 5 standard test sieves arranged on the shaker and shaken for 10 minutes. The mass (g) of compost retained on each sieve was measured and recorded. The procedure was repeated three times for the products. The retained compost samples on each sieve were classified into four different fraction sizes: oversize, coarse, pin, and fine. Particle size < 24 mesh (>850 µm) were oversize, 24-60 mesh (500 - 850 µm) were coarse, 60-70 mesh (400-500 µm) were pin size and 70 - 80 mesh (177-400 µm) were classified as fine particle size.

3.4.2 Fibrosity content determination

The fibrosity content of the matured compost was measured by the method described by Boylan et al. (2009). A compost sample with Known volume and water content was saturated overnight in a concentration of 40g/L solution of sodium hexametaphosphate to disperse the fibers. The sample was then washed in a 150µm sieve with distilled water. The retained material on the sieve was then gently rubbed by hand and the remaining fibers with a diameter greater than 0.5 mm were removed using tweezers. This was then oven-dried at 80°C to a constant mass. Percentage fiber was then calculated using Equation (5).

$$Fibrosity\ content\ (\%) = \frac{M_{fibre\text{-}dry}}{M_{original\text{-}dry}}\ x\ 100 \quad (5)$$

where:
$M_{fibre\text{-}dry}$ is a dry mass of fibers
$M_{original\text{-}dry}$ is the original dry specimen mass

3.5 Statistical analysis

All the experiments were repeated three times and for each sampling; the mean and standard deviation were reported in this study. All the calculations and graphical analysis were done using Microsoft excel 2010.

4. RESULTS AND DISCUSSION

4.1 Composting temperature evolution

Composting temperature is one of the key parameters of the stability index that indicate the stability and maturity of the compost (Mayur et al., 2018). The breaking down of complex organic compounds into simpler units is enhanced by temperature (Waqsa et al., 2018). Figure 2 shows the temperature profile of mixtures 1, 2, and mixture 3 for different bulk densities respectively. As shown in the figures, temperature ranges and duration at each stage differ in each of the experimental mixtures and this could attribute to the different experimental conditions of each of the composting mixtures. Microbes' activities are responsible for an increase in temperature during an active composting period (Prashant et al., 2019). For it to perform at optimum, it should be provided with adequate nutrients, moisture, and oxygen. In this study, it was observed that the temperature of the three composting mixtures increased rapidly from day 1 of the experiment, peaked on different days, and started cooling until they were stable and reached ambient temperature. This shows that biodegradation of organic materials through the activities of microbial has started. Jakubus (2020) recorded the same in the study of comparative compost prepared from various organic wastes based on biological and chemical parameters. In this study, each of the composting mixtures recorded the three temperature phases i.e mesophilic < 45 oC, (heating period), thermophilic > 45°C (high temperature period) and cooling phase < 45°C (Mayur et al., 2018). The optimum temperature range to kill pathogen is 40-65°C (Wang et al. 2021, Bao et al. 2016) and it must last for three to four days to sanitize the compost. In this study, the observed temperature ranged between 42.3°C and 65.3°C throughout the experimental period and this is enough to kill pathogens in the compost.

Mixture 3 recorded the highest temperature (65.3°C) and it lasted for more than three days. In mixture 3, the initial bulk density was 25 Kg/m^3; therefore, the physical structure of this mixture allows even distribution of oxygen and moisture for microorganisms. The increase in the activities of microorganisms in this mixture leads to a rapid increase in temperature. Compost mixture 1 recorded the lowest temperature during the high-temperature period (49.3°C). The lowest temperatures recorded in this mixture indicate lower activities of microorganisms. In mixture 1, the compost materials are closely packed together as a result of compaction, a high rate of biodegradation occurred and this led to high-temperature evolution within the compost. This shows that a bulk density of 25 K/gm^3 is favourable for temperature rise as free air space is reduced therefore more oxygen and moisture is available for microorganisms. Therefore, it may be assumed that the high bulk density corresponds to less free air space. Microorganism decomposes organic matter and heat is released; the temperature of the composting mixture increases at the beginning of the process. With the decrease in organic matter content of the materials and through heat loss by ventilation and evaporation (Arias et al., 2021), the temperatures of the mixture gradually decreased and reach ambient temperature. However, the best bulk density from the perspective of temperature in this study was that of experiment mixture 3.

4.2 Moisture content

Estimation of moisture is important for optimum productivity of composting process and one of the major fac-

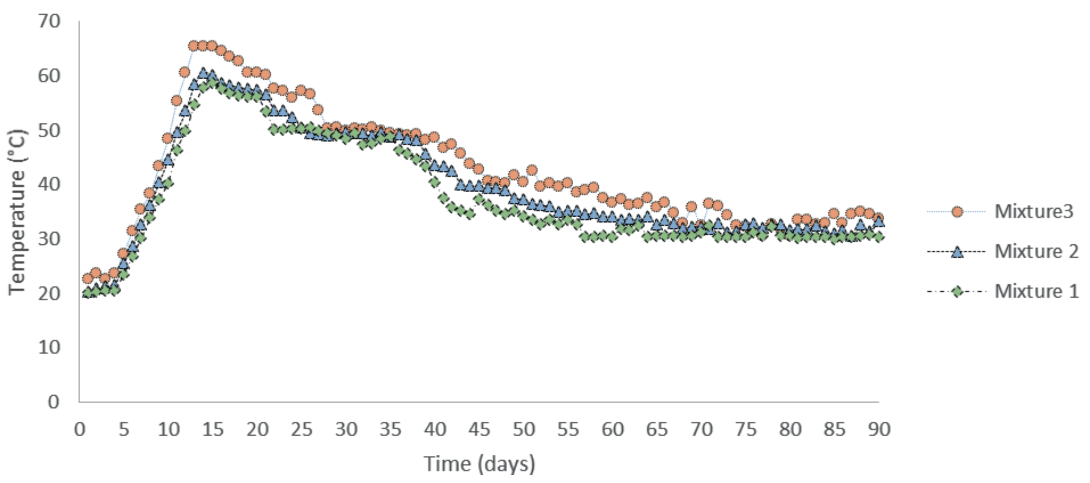

FIGURE 2: Variation of the temperature of the three mixtures during composting.

tors that need to be considered in the composting system design (Hemidat et al., 2018). Moisture must flow for an adequate supply of oxygen for proper microbial activities. Literature reported different moisture content, for example, Liang et al. (2003) recommended moisture within the range of 70% while Wang et al. (2021) recommended moisture within the range of 50-60%. Moisture content greater than 60% is not recommended as it prevents oxygen from the tiny pore of the compost pile and lowers its aerobic activities (Nahm, 2005). This is supported by Looper (2002) who found that moisture content above 60% produces odour and stops temperature to rise to thermophilic during composting. Bulk density directly influenced the moisture needed for effective composting. The theoretical volume of water needed is related to the initial bulk density and air-filled porosity of the compost (Equations 1 and 2). Concerning mixture 1, 2, and 3, the initial moisture contents were adjusted to the required range of 60% (Wang et al., 2021). Consistent with other reported data, this moisture range was the best to support microbial activities. Generally, the moisture content of the three compost mixtures decreased gradually during the composting process in the first four weeks of the composting period. This can be attributed to active microbial activities and the turning frequency of the compost (Cao et al., 2020). The change in moisture content was more pronounced in mixture 3, followed by mixture 2, and least in mixture 1. This result is in line with the findings of Pezzola et al. (2021) in the study of the use of new parameters to optimize the composting process of different organic waste.

The moisture content of mixtures 2 and 3 was significantly decreased and the highest temperatures were also recorded in these mixtures. The decrease in moisture content in mixtures 2 and 3 may be due to the activities of microorganisms that consume moisture (Jae-Han et al., 2020). In mixture 3 which had the highest bulk density, a maximum moisture content reduction of more than 50% was observed. This could be a result of the highest bulk density of the compost (Mayur et al., 2018). During active composting, bulk density increases and eliminates or reduces the air-filled-porosity which is believed to be inaccessible to microorganisms (Mayur et al., 2018) and this leads to a decrease in porosity; as a result, less moisture would be available for microorganisms and this would reduce their activities (Makan et al., 2013). As the compost approached stability, the moisture content in all the mixtures gradually decreased to around 23.33%, 21.54%, and 18.43% in mixtures 1, 2, and 3 respectively. There was no significant relation between mixing ratio and moisture content, but mixture 3 with the highest bulk density recorded the lowest reduction of moisture content.

4.3 Evaluation of pH and electrical conductivity (EC)

4.3.1 pH

Figure 4 shows the evaluation of the pH of the composts. The pH range during the composting period is used to assess the progress of composting as it influences the microorganism growth and gaseous loss of ammonia (Hemidat et al., 2018). Changes in pH were observed in the three mixtures throughout the composting period in this study. Many researchers have reported that the initial pH value of the mixture should range from about 6.0 to 7.0 (Chang et al., 2019; Varelas, 2019). However, the initial pH value of the mixtures after mixing in this study was slightly alkaline (6.3-6.9) which was optimum for microbial activities. This was in agreement with the finding of Abdul-Halim et al. (2019) who recorded the same range of initial pH values. As the composting was progressing, the pH value varies across the experiment. However, after the third week, i.e during the thermophilic stage, pH values in the mixtures significantly increased. The significant increase in pH value was more pronounced in mixture 3. The pH increase in all the mixtures may be a result of volatilization of organic acid under high temperatures (Manu et al., 2019), consumption of organic acids by microorganisms, the production and accumulation of NH4+ and humic substances (Elkinci et al., 2019, Manu et al., 2019), and mineralization of acidic compounds such as carboxylic and phenolic group (Madejon et al., 2021) and due to the breaks down of complex amino acids and peptides with the release of NH^{+4} (Sundberg et al., 2013). The pH changes in mixtures 1 and 2 followed a similar pattern. After then, pH values in all the mixtures were then decreased. According to Wang et al. (2021), the production of NH3 gas from the decomposition of nitrogen tends to increase the pH value in the early weeks of composting but decreases later due to the decomposition of organic acid to organic matter. At the end of the experiment, the pH of the three mixtures of this study decreased and was observed to be lower than the initial values and almost alkaline. Mixture 1 with an initial bulk density of 15 Kg/m^3 showed the lowest final pH range (7.4), while mixture 2 and 3 was a little bit higher than mixture 1 (Figure 3).

4.3.2 Electrical conductivity of the composting mixtures

Electrical conductivity (EC) determination is crucial during composting as it indicates the salinity and the usability of final compost products. An increase in EC would lead to phytoinhibitory effects (Zhou et al., 2019). The electrical conductivity greater than 4 mS/cm is considered injurious to plants (Manu et al., 2018) because the soluble salts can negatively affect seed germination. The electrical conductivity of each of the mixtures displays an irregular pattern throughout the composting period. It first increased then decreased and later increased at the end of the experiment. When the experiment was started, compost mixture 3 recorded the highest EC (Figure 5). This observation might be a result of the highest proportion of food waste in mixture 3 which leads to the buildup of soluble salt which is assumed to be a result of food salinity or the presence of mineral salts like phosphates and NH_4^+ through the breakdown of compost materials (He et al., 2020). The initial EC of mixture 3 is significantly higher than compost mixtures 1 (1.8 mS/cm) and 2 (1.8 mS/cm). This may be due to the highest proportion of food waste in compost mixture 1. Mixture 1 had the smallest proportion of food waste so it had the smallest initial EC value. Early in the third week, compost mixtures 1 and 2 showed a similar value of EC, except for mixture 3 which still maintained a higher EC value

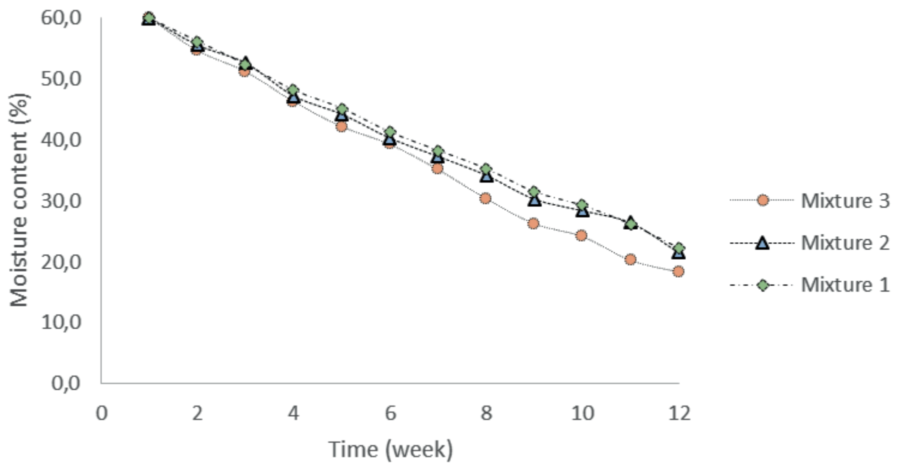

FIGURE 3: Variation of moisture content of composting mixture.

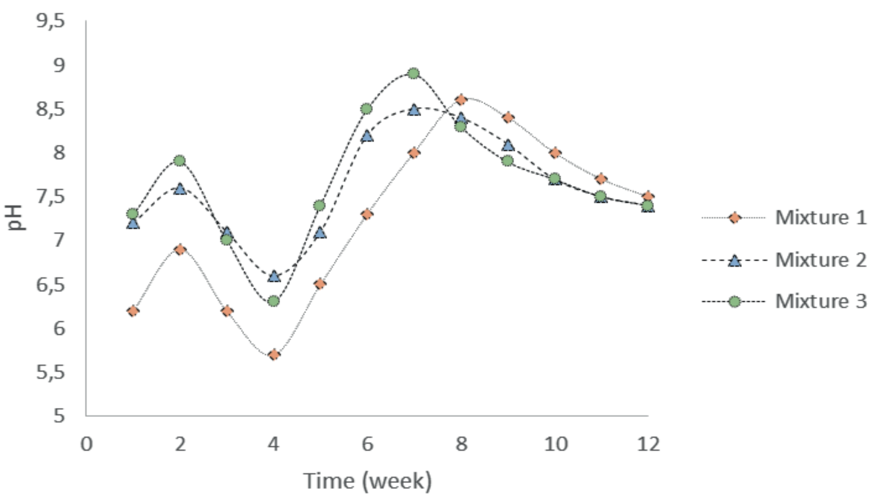

FIGURE 4: pH of the composting mixtures.

than mixtures 1 and 2. After the 8th week of experiment, no significance reduction was observed in EC of compost mixture 3. It still maintained higher EC than mixtures 1 and 2. However, in the early 10th week, all the compost mixtures had similar EC values. The final EC was below 4 mS/cm which is good for plant production (He et al., 2020).

4.4 Total Organic Carbon, Total Nitrogen, and C/N ratio

4.4.1 Total organic carbon

Organic carbon from the bulking agent is consumed by microorganisms as food for metabolic activities, this leads to the degradation of organic matter by microbial activities in the presence of oxygen with the release of CO_2 gas leading to the production of organic matter, therefore, total organic carbon decreases generally during the composting process (Bello et al., 2021). As shown in Figure 6, TOC showed a downward trend in all the mixtures with mixture 3 exhibiting the greatest decrease in TOC, while mixture 1 recorded the lowest decrease in TOC. The greatest reduction in total organic carbon was observed at the thermophilic stage, and the main reason for the decrease in TOC content in mixture 3 was because high temperature and vigorous microbial activities recorded in this mixture, so at the end of the process, TOC was lowest in this mixture. In mixture 2, organic carbon degradation was gradual while it was slowest in mixture 1. The reason for the slowest organic matter degradation in compost mixture 1 was because of the lowest temperature recorded in the mixture. In mixture 1, the composting materials are less compacted leaving more space for air and moisture to penetrate, therefore microbial activities were slowest in this mixture and as a result, the temperature was lowest in this mixture. At the end of the composting process, total organic carbon reduction in compost mixture 1 was the least.

4.4.2 Total Nitrogen

Figure 7 shows the nitrogen variation of each of the mixtures. Total nitrogen was first decreased in all the mixtures during the earlier stage and later increased continuously till the end of the composting period. Several scholars reported similar observations in their study. For example, Yu et al. (2019) observed that nitrogen content first decreased and then increased during the study of changes in carbon,

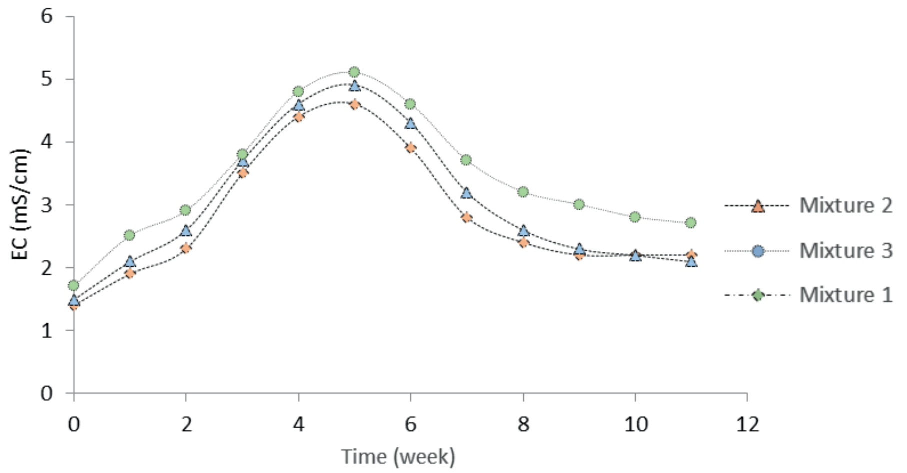

FIGURE 5: Electrical conductivity of the composting mixtures.

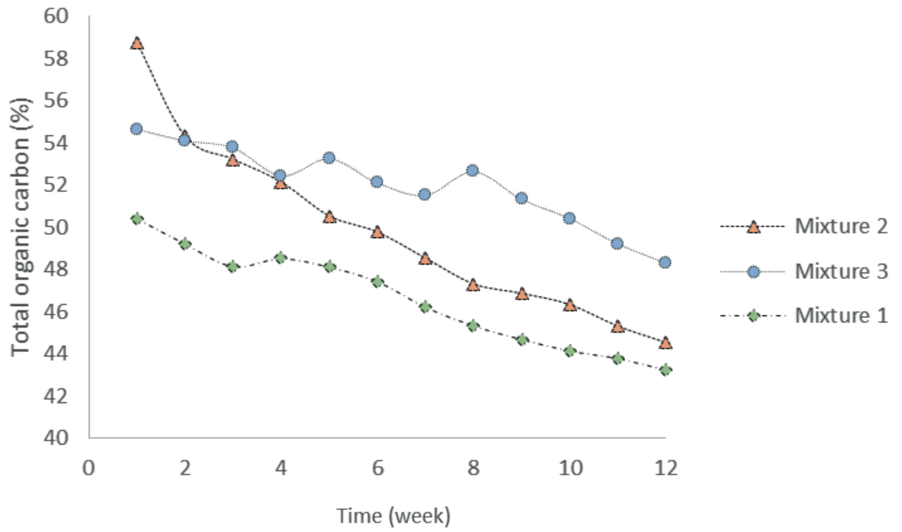

FIGURE 6: Total organic carbon of the composting mixtures.

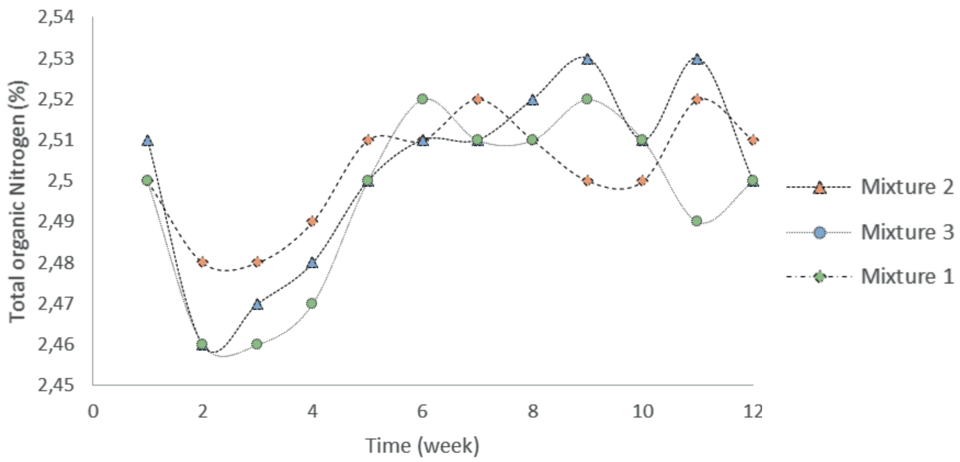

FIGURE 7: Total organic nitrogen of the composting mixtures.

nitrogen components, and humic substances in organic-inorganic aerobic co-composting. The authors claimed that the loss in nitrogen at the early stage of composting could be attributed to volatilization (Yu et al., 2019) and due to some loss in the form of NH_3-N (Cao et al., 2020; Sun et al., 2017; Lu et al., 2016). The loss in nitrogen content at the

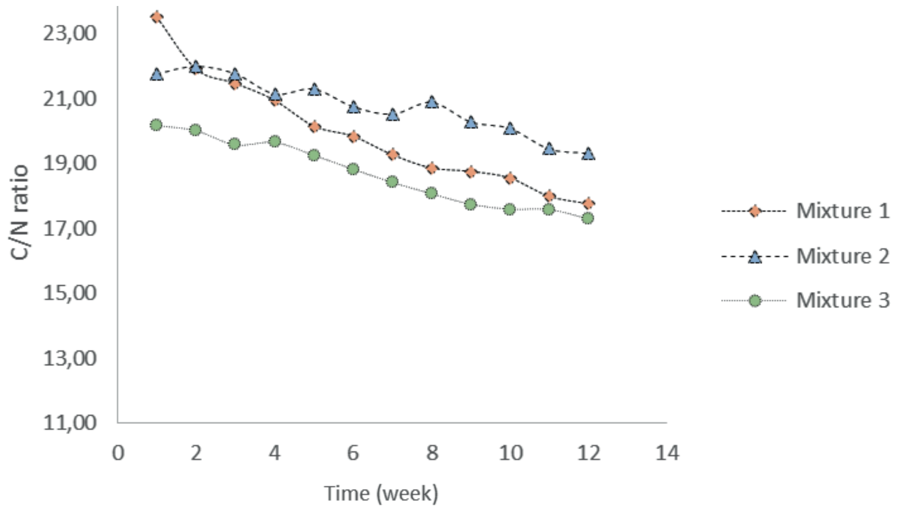

FIGURE 8: N ratio of the composting mixtures.

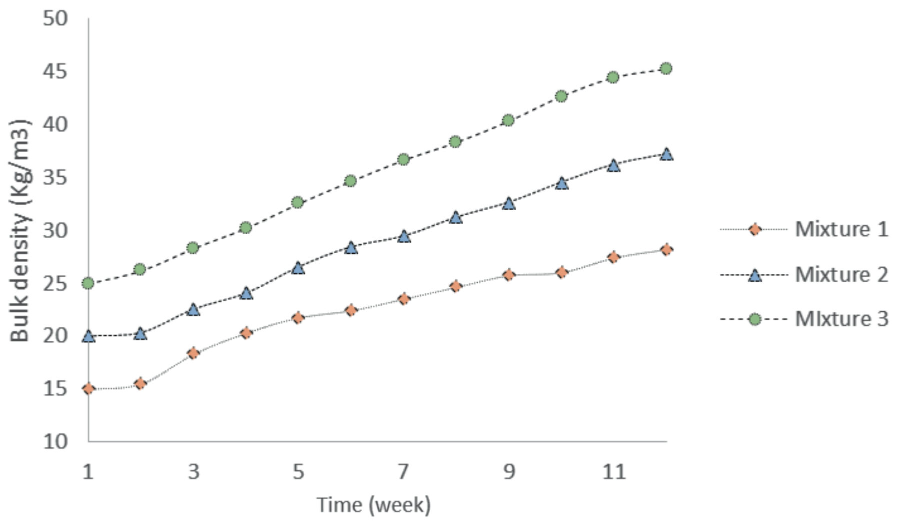

FIGURE 9: Variations of bulk densities during the composting period.

early stage of composting could be due to the consumption of nitrogen content by microorganisms for growth and reproduction (Ren et al., 2016) and due to leaching from the compost. However, as the composting is progressing, a significant increase in nitrogen content was recorded in all the mixtures during the subsequent sampling. An increase in nitrogen may be because of the degradation of organic carbon compounds (He et al., 2017).

4.4.3 C/N Ratio

Another important parameter for the determination of composting time, quality of the final compost, and evaluation of compost maturity is the C: N ratio. It also plays an important role in formulating the nutritional balance of a composting mixture. Carbon and nitrogen are needed by microorganisms as a source of energy for metabolic activities. A proper C: N ratio is favourable to microbial growth and production and also good for soil and plant growth (Kebibeche et al., 2019). As the composting progressed, the C/N ratio decreased throughout the period in all the mixtures as shown in Figure 8. A decrease in C/N ratio was highest in mixture 3, moderate in mixture 2, and lowest in mixture 1. This may be due to variation in temperature as a result of compaction. Mixture 1 had the lowest bulk density (15 Kg/m^3) so, the temperature was lowest in this mixture and it recorded the lowest reduction in C/N ratio value. In compost mixture 3, the changes in total nitrogen and organic carbon were high; therefore, the reduction of the C/N ratio was highest in this mixture. At the end of the process, the highest reduction in C/N ratio was in mixture 3 and the lowest reduction was observed in mixture 1. This result was in line with the result of Getahum et al. (2012) in the composting of municipal solid waste.

4.5 Physical properties variation during composting

4.5.1 Bulk density, particle density, and porosity

Figure 9 shows the variation of bulk density of the mixtures throughout the composting period. The initial bulk density of the compost mixtures was 15 kg/m^3, 20 kg/m^3, and 25 kg/m^3 for mixtures 1, 2, and 3 respectively. During the process, an increase in bulk density was observed in all the mixtures. This may be a result of the settlement of the compost as soon as it was compacted. A similar result was reported by Zhao et al. (2011) during composting of municipal solid waste of different particle sizes. Zhao et al. (2011) reported that an increase in bulk density was a result of the decrease in particle size of the waste. During the compaction of the compost, the volume of the compost is reduced while its mass remains unchanged. The highest bulk density in this study was observed in compost mixture 3, while the lowest bulk density was observed in compost mixture 1. Therefore, an increase in bulk density in mixture 3 may be a result of the compaction effect.

For an effective composting process, air (oxygen) must flow to achieve maximum performance. Bulk density, porosity, and free air space are interconnected and play a critical role in air movement in the compost mix (Iqbal et al., 2010). Free-air-space or air- filled-porosity as cited in literature with a minimum value of 30% and 60% maximum is required to ensure aerobic condition (Mayur et al., 2018). Different studies reported different free air space values. For example, Ahn et al. (2008) and Ruggieri et al. (2009) reported a maximum value of 85-90% without any negative effects on compost. But in this study, a decreasing trend in porosity value was observed with maximum and minimum porosity values of 46.34% and 37.41% were observed. The minimum and maximum porosity value of 37.41% and 39.23% was recorded in compost mixture 1. For mixture 2, 33.64% minimum and 40.36% maximum were recorded. While 46.34% maximum and 30.67% minimum were recorded in mixture 3.

4.6 Evaluation of Final Compost

4.6.1 Maturity and stability analysis of the matured compost

Compost maturity simply refers to the level of decomposition of the poisonous substances formed during the composting phase (Wu et al., 2000). The maturity and stability of the final compost are important for its use in agriculture. If compost is not stable, microbial activities in it can cause adverse effects and can affect plant growth since the final product will be of agricultural use. The properties of the final products are shown in Table 3. The final pH of all the mixtures was within the recommended value (6-8), with the value being close to alkaline (7.4-8.3). Total nitrogen in mixture 3 (1.78%) was slightly higher than in mixtures 1 (1.14%) and 2 (1.45%). The electrical conductivity ranged between 3.15 and 2.13 dS/m, the C/N ratio ranged between 10.56 and 19.59, the CEC value between 13.66 and 26.27, a phosphorous value between 8.29 and 11.08 Cmol/Kg, and final moisture content values between 20.20 and 23.20%.

4.6.2 Phytotoxicity of the matured compost

The matured compost must be free of any poisonous substance before it can be used as soil organic fertilizer. Determination of the level of toxicity is important as it gives insight into the agricultural value of the final product. The most common and economical method used to evaluate the agricultural value of the final compost is the germination index method (Tibu et al., 2019). A germination index test was carried out to evaluate the level of phytotoxicity of the final compost of this study using tomato seed recorded 100% in mixtures 1 and 2 while mixtures 3 recorded 90% germination. Similar observations were reported by Tibu et al. (2019). In his study of phytotoxicity, a germination index between 80 and 100% was reported. The high germination index recorded in this study might be due to the presence of nutrients in adequate proportion in the final compost of each of the mixtures. Tibu et al. (2019) reported that if the germination index values are greater than 80%, then the compost is phytotoxin-free and it is safe and good to use. So, in this study, all the compost mixtures showed germination index values greater than the limit value, and therefore considered phytotoxin-free and safe to use.

4.7 Physical properties of the final compost

4.7.1 Finest and fibrosity content of the matured compost

The physical characteristics of the final compost were also evaluated based on the finest ratio and fibrosity content. As shown in Table 4, mixture 3 had the highest percentage of finest (97%), followed by mixture 2 with 94% finest, and experiment mixture 1 had the lowest percentage finest 89% finest. Fibrosity contents vary significantly among the experimental mixtures, experiment mixtures 3 and 2 recorded zero fibrosity while experiment mixtures 1 recorded 5% fibrosity content. The zero fibrosity recorded in mixtures 2 and 3 shows that all the sawdust in these mixtures were decompose totally while mixture 3 contains some fiber content as a result of incomplete decomposition of the sawdust by microorganisms and heat.

4.8 Regression analysis

The interactions between the physical parameters (bulk density, porosity, particle density, and moisture content) considered in this study were analyzed using correlation analysis (Wu et al., 2019). A strong positive correlation was found between porosity and moisture content and it exceed 0.9. The correlation between bulk density and porosity was negatively correlated (-0.942), and the highest negative correlation was between moisture content and bulk density (-0.978). The reason for the negative correlation between bulk density and porosity is that bulk density increases throughout the composting process the porosi-

TABLE 3: Chemical properties of the final compost.

Composting Mixtures	C: N	pH	EC	CEC (Cmol/Kg)	Phosphorus (Cmol/Kg)	Nitrogen (%)	Moisture content (%)
Mixture 1	19.59 ± 0.25	7.8 ± 2.11	2.13 ± 0.24	13.66 ± 0.08	8.29 ± 1.52	1.14 ± 0.02	23.20
Mixture 2	14.85 ± 0.10	8.3 ± 2.01	2.91 ± 0.22	22.20 ± 0.28	11.08 ± 0.81	1.45 ± 0.01	22.40
Mixture 3	10.56 ± 0.20	7.4 ± 1.07	3.15 ± 0.16	26.27 ± 0.12	8.25 ± 1.44	1.78 ± 0.01	20.50

TABLE 4: Physical properties of the final compost.

Mixtures	Finest (%)	Fibrosity (%)	Bulk density (K/gm³)	
			Initial	Final
Mixture 1	89.0 ±0.01	0.5 ± 0.012	15.0	28.21 ± 0.2
Mixture 2	95.0 ± 0.12	0.0 ±0.00	20.0	37.21 ± 0.5
Mixture 3	97.0 ± 0.11	0.0 ± 0.00	25.0	45.23 ± 0.3

TABLE 5: Effects of treatment on the physicochemical parameters measured during the experiment.

Parameters	Mixture group		
	1	2	3
pH	7.25a	7.6b	7.6b
MC (%)	37.38a	39.85b	40.53b
TOC (%)	49.80a	51.99a	46.59b
TON (%)	2.50a	2.5a	2.19b
C/N ratio	19.91a	20.78a	18.68b

Note: Values are the averages (n = 3). Different letters are related to significant differences tested by Duncan's multiple ranges ($p < 0.05$)

ty shows decreasing trend. The same thing happened between moisture contents and bulk density, as composting progressed moisture was lost and bulk density increases.

5. CONCLUSIONS

The study was carried out to investigate the influence of the physical properties of composting materials on composting of sawdust with food waste. For this reason, sawdust and food waste was composted in a bin at the initial bulk densities of 15, 20, and 25 kg/m³. According to the results obtained and presented above, the three composting mixtures at different initial bulk densities had reached an acceptable degree of maturation and stability at the end of the composting process. The highest temperature of 65.3 o C was recorded in mixture 3 with the highest bulk density and lasted for more than four days. Loss in moisture content was more pronounced in mixtures 3 than in mixtures 1 and 2. The lowest EC was observed in mixture 1 and the highest in mixture 3. The bulk density increases throughout the process, porosity, and moisture content decrease during the composting process. Mixtures 3 and 2 had the highest finest and lowest fibrosity content and mixture 1 had the lowest finest and highest fibrosity content. Based on the result presented above, the best compost was produced at 25 kg/m3 bulk density and 46.34% porosity.

ACKNOWLEDGMENT

The authors are grateful to the Department of Agricultural and Biosystems Engineering, University of Ilorin, Nigeria, without which this study would not have been undertaken.

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