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Process Dynamics and Parameter Variations during Co-Composting of Mixed Vegetables, Broiler Litter, Cow Dung and Textile Sludge

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ABSTRACT

The co–composting behaviours of a mixture of vegetable wastes and three other different substrates (broiler litter, cow dung and textile sludge) were investigated through the evolution of temperature, respiration rate (RR), pH, volatile solids (VS), electrical conductivity (EC), moisture content (MC), bulk density (BD) and free air space (FAS) for 32 days. The three experimental mixes were set up separately in three 200L in–vessel rotary batch composters. The mass of vegetable wastes was kept fixed at 10 kg in all mixes but the amount of other substrates varied, and bagasse (10 kg) was used as bulking agent. 10 kg broiler litter, 17 kg cow dung and 36 kg textile sludge were added to Mix 1, Mix 2 and Mix 3 respectively. The average initial C/N ratio and initial wet MC were 24.0 and 53.2, 32.1 and 66.4% and 33.3 and 65.7% for Mixes 1, 2 and 3, respectively. Temperature peaks were recorded on day 2 for Mix 1 at 68.9 and 49.2°C on day 4 for Mix 2 and 68.5°C on day 4 for Mix 3. The average matrix temperatures for all mixes remained above the threshold of 55°C for an average period of 4 days. An increase in wet BD of 84.64% was noted for Mix 1, 57.12% for Mix 2, and 34.28% for Mix 3. The VS typically reduced from 72.35 to 55.9% in Mix 1, 72.27 to 62.10% in Mix 2, and from 66.11 to 58.39% in Mix 3, indicating that adequate microbial degradation of the organic fractions had taken place in the mixes. The average RR peaked at 73 mg CO_2.C/day on day 2 for Mix 1 and decreased to 10.9 mg CO_2.C/day on day 32. The corresponding peak and final stable values for Mixes 2 and 3 were 54.2 mg CO_2.C/day and 14.0 mg CO_2.C/day on day 32, and 50.2 mg CO_2.C/day and 14.5 mg CO_2.C/day on day 32. The typical temperature trends obtained for all mixes supported that the major composting stages had taken place but the different pH, EC, VS and temporal RR variations highlighted that the microbial decomposition rates were dependent on the nature of the substrates.

Keywords: broiler litter, composting, cow dung, parameter variations, respiration rate, textile sludge

Abbreviations: BD, bulk density; **EC**, electrical conductivity; **FAS**, free air space; **MC**, moisture content; **RR**, respiration rate; **VS**, volatile solids

INTRODUCTION

During recent years, Mauritius has experienced a growth in population as well as a rise in the standard of living as a result of rapid development. This had led to an increase in consumption patterns, as well as significant production of wastes. The solid waste generation rate in Mauritius is estimated to be 1500 tons of waste per day, 50% of which is biodegradable. The daily amount of waste sent to Mare Chicose, the island's sole landfill, has rapidly become an overwhelming situation. Mare Chicose can no longer present itself as the sole solid waste management option of the island and in this scope, the composting of organic wastes might prove to be a resourceful option in the future. Other than addressing the problem of solid waste management, the use of compost as a fertiliser can be an economical alternative to the highly costly artificial fertilisers. Experimental investigations carried out by Montanari *et al.* (2003) have demonstrated that plant diseases in fields may be repressed by the application of compost.

Bio-recycling of the nutrient value of animal wastes and manure, through composts, would not only help alleviate the stress on the landfill but also reduce the energy and fertiliser inputs to farming. Textile sludge is significantly rich in organic matter and nutrients but toxic contaminants and heavy metals present in textile sludge jeopardise its potential as a soil improver. In this regard, the composting potential of mixed vegetable wastes with three different substrates (broiler litter, cow dung and textile sludge) was investigated, not only to produce compost but also as a means of bio-stabilisation of waste. Composting is generally carried out in the presence of oxygen. In aerobic systems, the organic matter is decomposed by microorganisms in the presence of large amounts of oxygen. Carbonaceous matters present serve as an element in cell protoplasm and as well a source of energy for the microorganisms and is respired as carbon dioxide. Aerobic decomposition does not give rise to foul odours and the conversion of carbon to carbon dioxide is largely exothermic. Microorganisms play a large role in the degradation of organic matter into a stable amendment during the process of composting. They are naturally present in the environment, the compost feedstock, water, air, soil and machinery to which the composting mixture is exposed to during the composting process. These sources provide a high diversity of microorganisms which helps to maintain an active microbial population during the chemical and physical processes of composting such as shifts in pH, temperature, water, organic matter and nutrient availability. Different communities of microorganisms are found at different stages of the composting process and can therefore be classified by virtue of the temperature ranges associated to their activity (Trautmann and Olynciw 1996). During the aerobic composting process, microorganisms degrade organic matter in the presence of oxygen by breaking down the large complex molecules to intermediate then simpler and more stabilised compounds. The compost produced is rich in humus and plant nutrients and the by-products are carbon dioxide, water and heat (Gajalakshmi and Abbasi

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Table 1 Carbon, nitrogen and moisture contents of substrates.

Substrate	%N (dry wt.)	%C (dry wt.)	C:N ratio (wt./wt.)	Moisture content % (wet wt.)
Cow dung	1.29 ± 0.1	23.4 ± 0.2	18.14 ± 0.8	62.87 ± 1.1
Broiler litter	3.0 ± 0.3	50.0 ± 0.6	16.7 ± 0.8	22.85 ± 1.1
Bagasse	0.35 ± 0.01	36 ± 0.9	102.9 ± 0.8	46.30 ± 1.2
Vegetable wastes	2.4 ± 0.1	46.1 ± 0.8	19.2 ± 0.8	92.00 ± 2.3
Textile sludge	0.74 ± 0.01	15.98 ± 0.8	21.59 ± 0.8	65.00 ± 1.8

(n = 3, mean values are shown, SD was always less than 15%).

2008). Under optimal conditions, the biological decomposition process proceeds from the initial ambient stage through four main phases: the mesophilic stage or moderate temperature phase, the thermophilic stage or high temperature phase, the cooling phase, and the maturation stage (Gajalakshmi and Abbasi 2008). The rate of decomposition of organic matter and the type of final product obtained are governed a multitude of closely interrelated physical and chemical.

The aim of this study was to monitor the variations in the composting parameters (moisture content, bulk density, temperature, volatile solids content, free air space, pH and electrical conductivity) and rate of respiration during the in-vessel composting process of mixed vegetable wastes with broiler litter, cow dung and textile sludge at pilot-scale. Knowledge of the variations of the latter parameters will provide a better understanding of the biodegradation dynamics in the composting mixes.

MATERIALS AND METHODS

Substrates

Five different substrates were employed in this study: vegetable waste, broiler litter, cow dung, textile sludge and bagasse. Dry broiler litter and cow dung were collected from local farms. Textile sludge was obtained from the drying beds of Denim De l'Ile textile factory's wastewater treatment plant (a factory in the northern part of Mauritius) while bagasse was collected from Beau Champ sugar factory (found in the western region of the island). Vegetable wastes were collected at the city Port Louis central market. Since the composition of vegetable wastes depends largely on the seasonal variation, the sampling and collection of vegetable wastes were done in such a way so as be well representative of the seasonal composition. Grab samples of 40-60 g from each substrate were analysed for their initial moisture content (**Table 1**) in triplicates. The carbon and nitrogen content of the dried and then finely ground samples were used determined through a Carbon Hydrogen Nitrogen and Sulphur determination (CHNS-932).

1. Bagasse

Bagasse is a residual fibrous matter obtained from the milling tandem after the extraction of juice from sugar cane stalks. Bagasse consists mostly of cellulose, hemicelluloses, lignin, water and waxes. The high carbon content of bagasse makes the latter an excellent bulking agent for allowing aeration and providing structure in the composting system. Moreover, Mauritius has a well established sugar industry producing an estimated value of 1,532,000 ton of bagasse per year which makes bagasse an easily available substrate for composting.

2. Broiler litter

Broiler litter is a material which is used as bedding in the poultry industry to make the floor more manageable. Common litter materials which are usually used are wood shavings, sawdust, bagasse and other dry absorbent, low cost organic materials. After use, the litter consists of a large amount of poultry manure, feathers and waste food. However, the factors influencing the chemical composition of poultry litter are numerous, such as the nature of the bedding material, density of birds per unit, level of nutrition and type of storage. It has been found that broiler litter in Mauritius has high nitrogen content and low ash content.

3. Cow dung

Cow dung consists mostly of water, faeces (solid matter) and urine combined, sometimes also materials used for bedding such as straw and peat. The composition of cow manure varies largely according to the food consumed, therefore affecting the nitrogen, phosphorus and potassium passed into the excrements. The solid fraction consists mostly of undigested matter retaining the same constituents in the food while having a finer condition. Urine often mixed in cow dung consists of soluble nutrients readily available for plant growth.

4. Textile sludge

Textile sludge has been reported to contain abundant amount of organic matter as well as plant nutrients such as nitrogen and phosphorus, and could be regarded as potential soil improvers (Islam *et al.* 2009). However, the presence bleaching agents, aromatic dyes and heavy metals such as aluminium, copper, zinc, iron and chromium in textile sludge, compromise its direct application to soil and plants (Mathur *et al.* 2005).

Rotary batch composter

The experiments were carried out in rotary batch composters having a capacity of 215 L. The composters were made of 4mm thick plastic with an internal diameter of 550 mm and a length of 880 mm. Two PVC pipes, each of length 1090 mm, thickness of 1 mm and having an internal diameter of 50 mm were fitted at the base of each composter. The pipes were perforated with holes of 5 mm in diameter at every 20 mm interval along the circumference and every 40 mm interval along the length of the pipes. The role of the perforated pipes was to allow the proper aeration of the composting system, as well as to evacuate leachate which might have been formed during the decomposition process so as to ensure aerobic conditions. An opening with an attached flap, with dimensions 300 mm by 210 mm was located in the middle of each composter. The opening allowed the loading and unloading of the compost materials and as well for the collection of samples. Four other perforations of 50 mm diameter were present on the composter, two of which were located on the upper side of the composter, one in the middle of the flap and a last one at the bottom of the drum. Perforations on the upper side on the drum allowed the temperature measurements to be taken with the help of a thermocouple while the hole at the bottom allowed the evacuation of leachate.

Experimental set ups

The influence of three substrates, (broiler litter, cow dung and textile sludge) on the composting process of mixed vegetable waste, using bagasse as bulking agent, was investigated. The mass of mixed vegetable waste was kept constant in each mix and the optimum amount of the added substrates and bulking agent were calculated based on their average moisture content and respective C/N ratio, keeping in mind that the overall average moisture content and C/N ratio of the mixes were to fit the optimum ranges. The optimum mix ratios of each composting mix are given in

Table 2 Optimum mix ratios of composting substrates.

Composting Mixes	Broiler Litter Mix	Cow Dung Mix	Textile Sludge Mix
Substrates		**Mass used (kg)**	
Mixed vegetable wastes	10 ± 0.1	10 ± 0.1	10 ± 0.1
Bagasse (bulking agent)	13 ± 0.1	10 ± 0.1	10 ± 0.1
Broiler litter	10 ± 0.1	-	-
Cow dung	-	17 ± 0.1	-
Textile sludge	-	-	36 ± 0.2
Total	33 ± 0.3	37 ± 0.3	56 ± 0.4
Overall C/N ratio	24 ± 0.4	32 ± 0.4	33 ± 0.4
Overall moisture content (%)	53 ± 0.3	66 ± 0.6	66 ± 0.6

(n = 3, mean values are shown, SD was always less than 15%).

Table 2.

The mass of mixed vegetable wastes was weighed, and then roughly shredded into pieces not exceeding 10 cm x 10 cm and spread on the floor. Three thin piles of equal mass of shredded vegetable wastes made. The respective amount of substrates and bulking agents (**Table 2**) were uniformly spread on the piles. 3 kg of finished (mature broiler litter/bagasse) compost was added to each composting mix for inoculation purposes. Each composting mixture was then thoroughly mixed with a space to break down large clumps and enhance homogeneity in the mix. The respective mixes were then carefully filled into batch composters with the help of a spade.

Monitoring of parameters

Three grab subsamples of 30-45 g were taken on a daily basis at an average depth of 10 cm from the top layer of each sides and the middle of each composter. The subsamples were mixed in a 1 L beaker to form a composite sample which would be well representative of the variation in the composter and were analysed right away after sampling for moisture content, volatile solids, bulk density, pH, electrical conductivity, and respiration rate in triplicates. The parameters were monitored over a period of 35 days since the setup of the composting experiments. However, since laboratory facilities were not available on Saturdays and Sundays, no parameters were monitored during that period. The daily monitored parameters were temperature, average bulk density, moisture content. The experimental setups for the investigation of compost was done on every Mondays and the rate of respiration was monitored on a daily basis. Compost pH was monitored three times a week while volatile solids, particle density and electrical conductivity were monitored twice a week. The dry bulk density and free air space of the composting matrix were obtained from calculations shown later in this section. The water holding capacity of the final compost was determined at the end of the composting process. The composters were turned through two revolutions on a basis of every 7–10 days in order to ensure proper aeration. The turning frequency and the number of revolutions were kept constant so as to minimise the disruption of the free air space in the composting matrix and to keep consistency in results. All raw data were average and the corresponding standard deviations calculated.

Analytical test procedures

Samples were analysed daily for the following parameters: wet bulk density (determined gravimetrically), moisture content (oven-drying at 105°C for 24 h). The pH of the samples were analysed thrice a week (1: 10 w/v waste:water extract). The following parameters were analysed twice a week: electrical conductivity, volatile solids content (loss on iginition in furnace at 550°C for 2 h), particle density [hexane submersion method by Weindorf and Wittie (2003)]. The rate of respiration of each mix was investigated through the alkaline trap method (24 h incubation at room temperature, during four days following setup of jars). Details of these tests are given below.

Temperature

Temperature was measured at three different locations (T1, T2, T3) within the composting reactors; twice a day during the first week, and daily thereafter using a temperature probe (Comark Ni Cr/Ni Al, ± 0.1°C). The probe was dipped slowly through a few centimeters and the temperature was allowed to stabilise on the monitor of thermocouple. The same procedure was carried out several times across the depths of the pile until the maximum temperature was recorded vertically down the initially point of temperature reading.

Bulk density (BD)

The initial wet bulk density of the samples was determined according to Agnew and Leonard (2003). A pre-weighed 1000-mL plastic container was filled with the compost sample material loosely up to the brim and the final weight was recorded. The bulk density was calculated by dividing the mass of the compost sample by the volume of the container. Masses were recorded to the nearest 0.1 g on a Mettler PM3000 top balance.

Moisture content (MC)

70–100 g of sample was weighed in oven-dried aluminium plates and then placed in a preheated forced-convection oven at 105°C for 24 h and heated to constant mass. The samples were then equilibrated to room temperature in a dessicator for about an hour before recording the final weight. The moisture content was calculated by subtracting the final and initial masses of the plate with the compost sample and dividing it by the wet mass of the subsequent sample. Masses were recorded to the nearest 0.1 g on a Mettler PM3000 top balance.

Volatile solids (VS)

1–2 g of oven-dried samples were weighed in pre-weighed dry porcelain crucibles and then placed into the muffle furnace and burnt to 550°C for about 2 h (BS1377 method). The volatile solids of each sample was determined by the equation

$$VS(\%) = \frac{M_{dry} - M_{burnt}}{M_{dry} - M_{crucible}} \times 100\%$$

where M_{dry} = mass of sample and crucible before burning (g), M_{burnt} = mass of sample and crucible after burning (g), $M_{crucible}$ = mass of empty crucible (g). The masses for *VS* determination were recorded to the nearest 0.001 g on the Mettler PM400 top balance.

pH

The pH was determined electrometrically in a slurry of the homogeneously ground oven-dried compost and calcium chloride solution. The original sample was sieved to <10 mm. 200 mL of 0.01 mol/L of calcium chloride solution was added to 20 g of the sample in a clean dry beaker. The mixture was stirred with a clean glass rod and the pH determined after one hour over the collected filtrate using a calibrated *EcoScan* pH (buffer 4, 7 and 10) meter. Excessive vigorous homogenisation was avoided in an effort to avoid gas exchanges which might alter slurry pH.

Electrical conductivity (EC)

20 g of fresh compost sample, sieved to less than 10 mm, was added to a beaker containing 200 mL of distilled water and stirred constantly for about 2 h. The mixture was then filtered. The filtrate was used to determine the electrical conductivity using a calibrated electrical conductivity meter (Model Lutron pH-201 Hand Held Digital pH meter).

Respiration test

The respiration rate (RR) was measured as per the experimental method described by Mohee *et al.* (2008). If the level of carbon dioxide measured remained fairly constant, this would indicate that the compost has stabilised. The respiration test was performed in four jars. Three of the jars contained a known mass of fresh compost derived from the main compost pile and the fourth jar was a blank (no compost). The moisture content of the compost taken from the pile was determined prior to filling in the jars. 25.0 to 25.5 g of as-received compost was weighed, carefully deposited inside the jar and then thinly spread at the bottom. 20.0 mL of freshly prepared 1.0 mol/L potassium hydroxide was pipetted and transferred into a 100 mL beaker that fitted exactly through the neck of the jar. With the aid of a hook, the beaker was gently lowered into the jar and securely deposited alongside the compost. Care was taken not to cover any compost material under the beaker. The jar was then tightly sealed with a rubber bung. The date, time and mean air temperature were also recorded. This procedure was repeated for two other jars while a blank was prepared with the same volume of alkali.

The four jars were stored at room temperature (25.0 to 27.0°C). The amount of carbon dioxide released and absorbed by the potassium hydroxide trap was monitored over the next three days using simple titrimetric methods with standardised hydrochloric acid (HCl) acid. Standardisation was performed using aqueous sodium carbonate and methyl orange indicator following the standard procedures. The acid concentration used had a concentration of 0.979 mol/L.

Every 3 days, the potassium hydroxide containing beakers were carefully removed, an equal volume of fresh 1.0 mol/L potassium hydroxide replaced and the jars resealed. The titrations were carried out immediately. The burette was filled with the HCl and zeroed. Two to three drops of phenolphthalein indicator were added to the potassium hydroxide solutions. The potassium hydroxide was titrated with the acid until the endpoint was reached whereat colour of solution changed from pink (or purple) to colourless. The volume of acid required for each of the four potassium hydroxide samples was recorded to the nearest 0.2 mL. The date and time of the experiment were also recorded. Based on direct stoichiometric analysis, the higher the amount of carbon dioxide released from the compost sample and absorbed by the potassium hydroxide trap, the less acid will be needed for titration to endpoint. The mass of CO_2 generated by the compost sample may be calculated using the expression

$$CO_2.C(mg) = 12 \times (HCl_b - HCL_s) \times [HCl]$$

where HCl_b = mL HCl used in titration of blank, HCl_s = mL HCl used in titrating sample from jar containing compost, [HC*l*] = concentration of hydrochloric acid used (mol/L), and $CO_2 .C$ = mass of CO_2 – Carbon generated (mg). The value for mg CO_2.C/g organic carbon/day was determined using the relationship mgCO_2.C/g organic carbon/day = mass of CO_2.C (mg/day)/organic carbon (g), where the organic content (g) was itself deduced from the equation Organic carbon (g) = (wet weight of sample) (100-%wet moisture) (%Carbon). The %Carbon was estimated from the equation %C = 0.55 (%VS) (Haug 1993).

Water holding capacity

A glass cylinder 120 mm high, 35.7 mm inside diameter, with a closed-meshed plastic net bottom was used in this experiment. The sieve bottom of the glass cylinder was covered up with moistened filter paper. The mass (M_0) of the whole assembly was recorded on a Mettler PM3000 top balance. The fresh and naturally moistened compost sample (<10 mm) was then filled into the cylinder with light shaking and the new mass (M_c) recorded. The glass cylinder was then carefully placed into a beaker and tap water was slowly added so that the material could soak itself full with water from the bottom. Water will actually move by capillary action. When the sample was moistened up to the surface, the same amount of water was added until the sample was overdamped by 0.5 cm. The cylinder was left to stand for 24 h. After that, the cylinder was taken out, dried from the outside and placed on a water saturated cellulose base covered with watch glass. Subsequent weights (M_{moist}) after 2 h were taken until constant weight was obtained. The water holding capacity test was run in triplicate. Simultaneously, the wet basis water content of the fresh sample used was determined (W_c). The maximum water holding capacity (WK_{max}) is determined using the equation

$$WK_{max} = \frac{E_{moist} - E_{dry}}{E_{dry}}$$

where E_{dry} = Mass of dry sample (g) = (M_c - M_o)(1-0.01 W_C), E_{moist} = Mass of wet sample (g) = M_{moist} - M_o, M_c = mass of cylinder + mass of wet filter paper + mass of weighed-in sample (g), M_{moist} = mass of cylinder + mass of wet filter paper + mass of wet sample (g), M_o = mass of cylinder + mass of wet filter paper (g), and W_C = wet basis moisture or water content of fresh sample (%).

Particle density

Particle density values are needed in order to use the FAS equation. The physical properties of compost are similar to those of highly organic soils. As such the method used has been adapted from Weindorf and Wittie (2003), a commonly employed method for determining soil particle density. While soil particles, with particle densities commonly in excess of 1.000 g/cm^3, are easily submerged in distilled water, many compost particles are somewhat buoyant and as a result will not settle out of a suspension so that an accurate measurement of displaced volume can be made. Given this, hexane was selected as a relatively inexpensive, low density (0.665 g/cm^3) liquid that easily allows for compost particle settling. Taking into consideration the highly volatile and flammable nature of liquid hexane, the specific gravity tests were conducted in a fume hood with plastic gloves and safety goggles worn at all times.

Concisely stated, the method used to find compost particle density employs the submersion of a known mass of compost in the hexane to determine the volume of the compost solids. About 4 to 8 g of the dried ground compost was placed in a dry and clean 100 mL volumetric flask and weighed on a Mettler PM3000 top balance to an accuracy of 0.1 g. To displace the gases from the compost sample, the flask was brought to volume with hexane, and completely submersing the compost. While tilted at an angle, the flask was gently swirled until no further air bubbles were seen to emerge. After mixing, the flask was again brought to volume, the volumetric flask allowed to stand for about 5 min, and the weight of the compost-hexane mixture recorded on the Mettler PM400 balance of accuracy ±0.001 g whilst the normal procedure calls for use of 10 to 20 g of compost sample and all measurements being made to an accuracy of ±0.0001 g. All mass measurements were made with the volumetric flask always capped. This procedure was repeated for the remaining samples. The compost material specific gravity G_c was calculated using the equation below.

$$G_c = \frac{\rho_h M_c}{\rho_w (M_c - (M_{ch} - M_h))}$$

where ρ_h = density of hexane (0.665 g/cm^3), M_c = mass of oven–dried compost (g), M_{ch} = mass of compost and hexane (g), M_h = mass of 100 mL pure hexane (g), and ρ_w = density of water (normally 1.000 g/cm^3 at 26.5°C).

Free airspace (FAS)

The equation below in terms of wet basis moisture content, wet bulk density and specific gravity of compost particles (ρ_s) and which is similar to Haug's formula for FAS (Haug 1993) was used to determine the FAS from each wet bulk density, the average wet basis moisture content and compost particle density for the mixtures under study (all density values should have the same units for consistency).

$$\text{FAS} = 1 - \rho_t \left(\frac{\theta_{ww}}{\rho_w} + \frac{1 - \theta_{ww}}{\rho_s} \right)$$

[ρ_t = total (wet) bulk density (M_t / V_t) (g/cm^3), ρ_s = average absolute specific gravity of the compost particles (dimensionless), ρ_w = density of water (usually taken to be 1 g/cm^3), and θ_{ww} is volume wetness or wet moisture content (decimal fraction and dimensionless).

RESULTS AND DISCUSSION

Temperature

Temperature readings were recorded on a daily basis at three different locations, T1, T2 and T3 in the composting reactors until near ambient temperature values were reached. The average ambient temperatures had mostly varied between 25.2–26.7°C. The average temperature profiles for the broiler litter, cow dung and textile sludge systems are shown in **Fig. 1**.

The average starting temperatures of the composting mixtures were in the range of 21.8–22.6°C. From **Fig. 1**, a sharp increase in temperature was recorded for the broiler litter mix within one day after the setup of the experiment, indicating rapid oxidative action of microbial activity in the conversion of organic matter (Peigne and Girardin 2004). Similar rapid rise in temperature was reported by Mohee *et al.* (2008) for the composting of broiler litter with shredded paper and Lhadi *et al.* (2004) for the co-composting of separated municipal solid waste and poultry manure. In the case of the cow dung mix and textile sludge mix, the rise in temperature was relatively gradual. This may be attributed

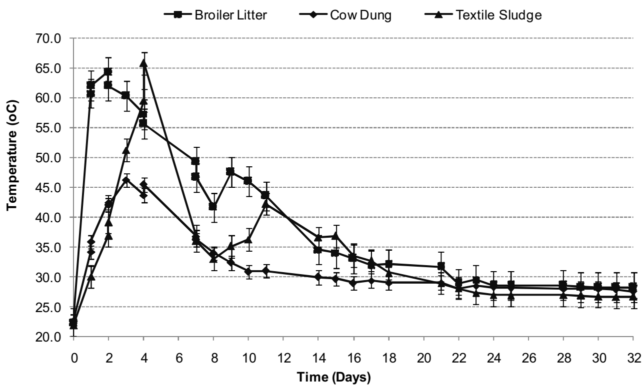

Fig. 1 Average temperature profile for composting mixes.

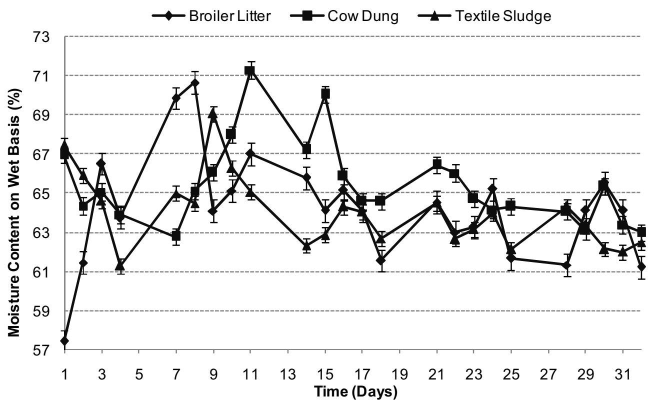

Fig. 2 Variation of moisture contents.

to the initial readiness of nitrogen source available to microorganisms being higher in the broiler litter mix than the two other mixes. Peak temperatures were attained in the centre of compost pile (location T2) on day 2 for the broiler litter mix at 68.9 and 49.2°C on day 4 for the cow dung mix and 68.5°C on day 4 for the textile sludge mix. The average temperature profile of the broiler litter mix lasted in the thermophilic range for a period of 4 days before decreasing sharply to 41.6°C on day 8. The textile sludge mix exhibited a drastic fall in average temperature from its peak on day 4 to 36.9°C on day 7. According to the US EPA standards, effective pathogen inactivation can be achieved only if the composting system is subjected to a minimum operating temperature of 40°C for a period of five days with temperatures exceeding 55°C for at least 4 h of this period. It is therefore deduced that the conditions in the broiler litter mix and textile sludge mix were satisfactory for the sanitation and destruction of pathogens. However, the peak temperature in the cow dung mix did not cross the thermophilic plateau and consequently, it may be inferred that that proper conditions for sanitation might not have been achieved in that reactor. The low temperature peak might be a result of the high initial FAS (81.22%) promoting heat dissipation faster than heat generation as a result of microbial activity from the reactor.

The reactors were turned through two revolutions on day 8. Consequently, it was observed that the turning caused a net rise in temperature in the mesophilic range for a short lapse of time in the broiler mix and textile sludge reactors. This might be attributed to the renewal of the concentration of air in the system as well as exposing more nutrients to the microorganisms. However, the cow dung mix did not exhibit a similar behaviour; no rise in temperature was observed as in the other reactors. This might be due to the depletion of immediate nutrients since the moisture content was around 65% and the FAS was decreasing to a value of about 72%, indicating normal composting conditions. From that point, the temperature in all three reactors maintained a gradual decline to a temperature averaging 27.5°C, indicating stabilisation of organic matter and the beginning of compost maturation process. It was observed that peak temperatures occurred in the middle locations (T2) in each of the reactors while temperature was lower at each end (T1 and T3) of the reactors. This behaviour demonstrated the existence of several pockets within the composting system at which degradation is occurring at different rates. Also, the compost found at extremities of the reactors is subjected to a larger surface area, hence promoting dissipation of heat faster than the middle.

Moisture content

The initial moisture content of the starting mixes were theoretically calculated to be 53, 66 and 66% for the broiler litter mix, cow dung mix and textile sludge mix, respectively. It can be considered that the initial moisture content for the broiler litter mix was in the acceptable range of 50–60% while the two other were slightly on the higher end (Gajalakshmi and Abbasi 2008). Experimental study carried out by Richard *et al.* (2002) revealed that a moisture content of 55–60% compromised the rate of biodegradation for the composting of dairy manure, paper mill sludge and seed screenings. This was most likely due to the initial high moisture content of the substrates (cow dung and textile sludge). The average moisture content profiles of each composting system are given in **Fig. 2**.

From **Fig. 2**, the broiler litter mix showed an increase in moisture content to a critical limit of 70.7% on day 9. The moisture content of the cow dung mix and textile sludge mix decreased from the initial amount and later peaks at 71.31 and 69.06%, respectively. The increase in moisture content of the mixes during the active phase of composting despite the high temperatures attained can be attributed to the fact that the samples were taken from the surface of the piles on which water droplets condensing on the inner surface of the reactor dripped back into the composting system. After their respective moisture content peaks, a general decreasing trend in moisture content was obtained for all the three mixes, reaching a range of approximately 61–63% at the end of the experiments. Most of the analysed samples were higher generally agreed optimum moisture content of 50–60%. However, owing to the fact that FAS in each composting mix were higher than 60% throughout the experiments, it can be said that the high moisture content did not affect the structural strength of the composting matrices through the means of compression and diffusion of air within was not compromised. Significant fluctuations in the moisture content measurements were also obtained. This might be explained by the presence of non-homogenous pockets of substrates inherent to the composting system.

Bulk density

Figs. 3 and **4** illustrate the variations in the average wet bulk density and average dry bulk density of the composting mixes with time, respectively. From the wet bulk density profiles, a general increasing trend can be observed from initial starting values. Tiquia and Tam (2002) observed that the compost bulk density is inversely related to the total compost volume and particle size, increased during the composting of poultry litter. Ruggieri *et al.* (2008) reported an increase in wet bulk density for the co-composting of raw sludge with commercial fats and proteins during the thermophilic phase. Mohee and Mudhoo (2005) made the same observation for the composting of chicken manure with mixed vegetable wastes and woodchips.

As the results indicate, the broiler litter mix had the highest net increase in wet bulk density of approximately 84%, followed by the cow dung mix – 57% and lastly the textile sludge having an increase of 34%. However, the highest wet bulk density (354 kg/m^3) was reached by the textile sludge mix but this might be resulting from the pre-

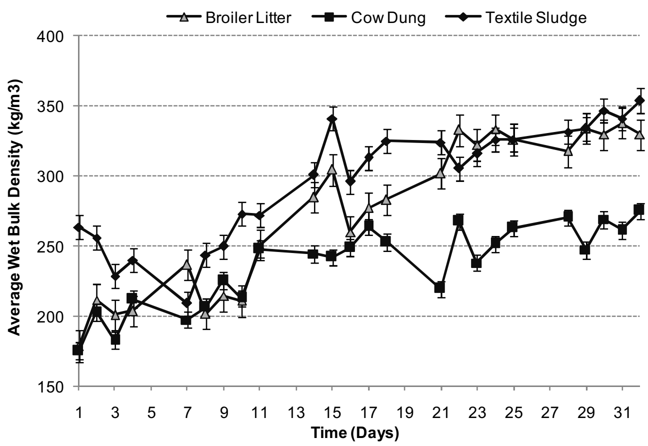

Fig. 3 Variation of average wet bulk density of each mix with time.

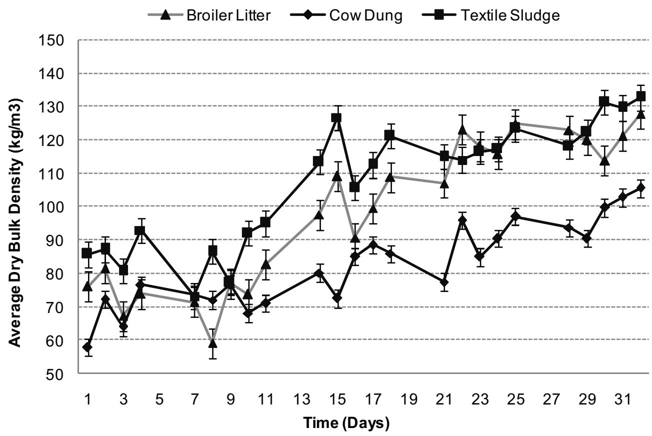

Fig. 4 Variation of average dry bulk density of each mix with time.

Table 3 Wet bulk density of various substrates and composts.

Substrate	Wet Bulk Density (kg/m^3)	Reference
Cattle manure	190	Kunene and Ossom 2010
Bagasse	40	Kunene and Ossom 2010
Topsoil	260	Kunene and Ossom 2010
Broiler litter and shredded paper	463 - 497 on 32nd day	Mohee *et al.* 2008
Chicken manure, wood chips and mixed green vegetable	628 on 36th day	Mohee and Mudhoo 2005
Poultry litter, wood shavings, feathers and waste feed	330 - 348 on 35th day	Tiquia and Tam 2002
Broiler litter, mixed vegetable and bagasse	Initial – 179 ± 10, Final – 330 ± 17	This study
Cow dung, mixed vegetable and bagasse	Initial – 175 ± 17, Final – 275 ± 18	This study
Textile sludge, mixed vegetable and bagasse	Initial – 264 ± 19, Final – 354 ± 20	This study

(n = 3, mean values are shown, SD was always less than 15%).

sence of compacted textile sludge particles in the starting mixture. Values of wet bulk density have been reported from various sources in **Table 3**.

From **Table 3**, it is seen that the range of wet bulk density values obtained by Tiquia and Tam (2002) for the composting of poultry litter with wood shavings and waste feed closely corresponds to the one obtained for the broiler litter mix in this study (330 kg/m^3). However, wet bulk density values obtained by Mohee *et al.* (2008) and Mohee and Mudhoo (2005) almost double the value obtained for the broiler litter mix in this study. This disparity may be accounted by the type and proportions of substrate used, the composting technologies employed and the locations of sampling in those studies. It is possible that the compressibility and the extent of settlement of substrates used in the broiler litter mix might have been lesser than those used in the former studies. Furthermore, the methods employed for the measurement of bulk density was found to be subjective. Tiquia and Tam (2002) reported using a 500 ml wide-mouthed jar for the determination of bulk density, Mohee *et al.* (2008) reported using a 1000 mL graduated cylinder while no precisions were made regarding bulk density measurements by Mohee and Mudhoo (2005). Due to practical limitations, it is difficult to establish which of these procedures could accurately mimic the conditions within the composting reactors.

The dry bulk density values of the composting mixes were calculated as from measured wet bulk density values and measured moisture content values. As a result, a linear increase in average dry bulk density with time is seen for each composting mix, owing to the direct proportionality relating dry bulk density to wet bulk density and moisture content values. This general increasing trend in dry bulk density may be arising as a result of a decrease in particle size due to organic matter degradation (Young *et al.* 2001). From the analysis of the results, the highest net increase in dry bulk density, 82.4% was obtained for the cow dung mix; followed by the broiler litter mix with an increase of 68.3% and lastly an increase of 54.97%. The changes in dry bulk density are an indication of extent of bio-physical degradability of the substrate particles.

The random nature of the bulk density profiles might be resulting from the non-homogenous mixing of the substrates at start. Since the behaviour of non homogenous pockets of substrates to the plethora of physical and biological factors cannot be exactly predicted, it can only be advanced that the grab samples taken tended to vary according significantly from locations they have been taken from the reactors. A similar deduction was proposed by Van Ginkel *et al.* (1999), in which it was observed that wet bulk density of chicken manure and wheat straw compost varied according to the vertical position in the compost pile from which the sampling was carried out.

Particle density

The variation of the average particle density of each composting mix with time is given in **Fig. 5**. While no explicit trend can be deduced for the broiler litter mix, the particle density of the latter ranged from 0.857 to 1.190 g/cm^3 with a mean value of 0.975 g/cm^3. In reference to the mean particle density value (1.58 g/cm^3) reported by Mohee and Mudhoo (2005) from **Table 4**, the mean particle density for the broiler litter mix in this study is almost half than that reported. This difference may be explained by inherent attributes of differing substrates used in the study. Moreover, Mohee and Mudhoo (2005) similarly reported fluctuations in particle density values over time, as observed in this study for the broiler litter mix. Van Ginkel *et al.* (1999) reported an increase in particle density from 1.8 to 1.9 g/cm^3 but considered that the increase was insignificant due to a low standard deviation of 0.04 g/cm^3.

A net decreasing trend of particle density was observed in the textile sludge mix. The results ranged from 1.147 to 0.792 g/cm^3 with a mean value of 0.901 g/cm^3. The particle density result peaked on day 7 (1.147 g/cm^3) from the initial values and gradually decreased thereafter to 0.768 g/cm^3 on day 31. Since a decreasing trend to constant values towards the end of the experiments was more prominent in the set of results, it is possible that the first two values were subjected to experimental errors. Whilst the particle density of the samples were determined using the standard procedure des-

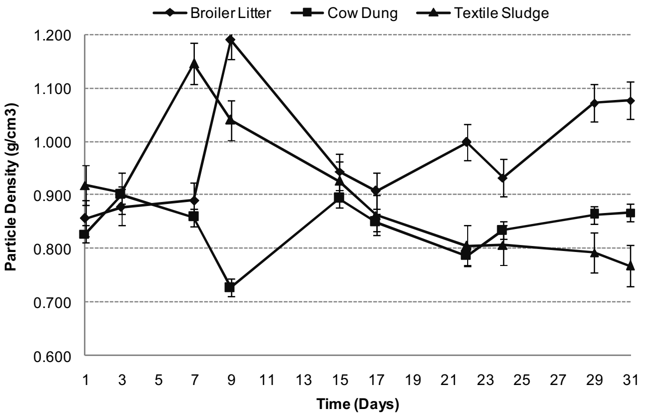

Fig. 5 Variation of particle density with time.

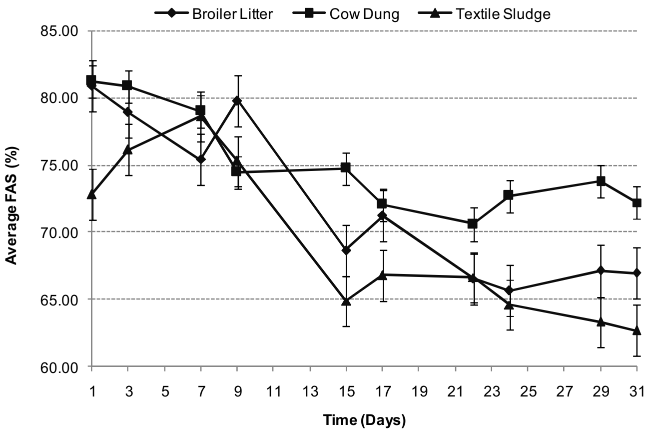

Fig. 6 Variation of mean FAS with time.

Table 4 Particle density values from literature.

Substrate	Value (g/cm^3)	Reference
Bagasse	0.4	Kunene and Ossom 2010
	0.5	
Top soil	2.5	Kunene and Ossom 2010
Cattle manure	1.6	Kunene and Ossom 2010
Mixed vegetable, chicken manure and woodchips (10%) compost	1.10 – 2.33	Mohee and Mudhoo 2005
Chicken manure and wheat straw compost	1.80 – 1.90	Van Ginkel *et al.* 1999
Dairy manure compost	2.19 – 2.39	Weindorf and Wittie 2003
	1.38 – 0.08	Das and Keener 1996
	1.23 – 1.27	Levanon *et al.* 1988
Manure compost	1.55 – 1.69	Agnew *et al.* 2003
Broiler litter, mixed vegetable and bagasse	Initial – 0.857 ± 0.01, Final – 1.078 ± 0.02	This study
Cow dung, mixed vegetable and bagasse	Initial – 0.828 ± 0.04, Final – 0.867 ± 0.06	This study
Textile sludge, mixed vegetable and bagasse	Initial – 0.919 ± 0.07, Final – 0.768 ± 0.02	This study

(n = 3, mean values are shown, SD was always less than 15%).

cribed in Weindorf and Wittie (2003), bagasse particles were seen to float at the surface of the hexane used. This occurrence affected the net displacement of hexane and eventually the particle density results might have been prone to experimental errors to some extent. The decreasing trend indicate the possible degradation of the organic constituents from textile sludge particles as well as from the other substrates present to more constant values at the end of the experiments. Inorganic constituents such as heavy metals are detached from the textile sludge matrix and are mainly responsible for keeping the particle density values constant since they cannot be biodegraded by microorganisms (Zhang *et al.* 2009).

The particle density of the cow dung mix was found to be relatively constant as compared to the variation of the other two mixes. The values ranged from 0.727 to 0.901 g/cm^3 with a mean value of 0.814 g/cm^3. The results for the cow dung mix tally with those reported by Das and Keener (1996) and Levanon *et al.* (1988). Das and Keener (1996) have also reported the variation of particle density values to be fairly little about the mean particle density. The fluctuations in the results obtained may be arising due to the difficulty in ensuring homogeneity in composition of each aliquot despite standard sampling procedures. Moreover, it was almost impracticl to ensure that all pockets of air from the oven dried and ground samples were removed by slight tapping during the hexane displacement test. Occasional tiny air bubbles (less than 1 mm in diameter) were seen to rise after swirling the hexane and compost mixture and allowing it to rest, hence causing an underestimation of the volume of hexane required. Another source of error was that fine particles of bagasse were seen to float in some aliquots, on the top of the liquid layer, resulting in a lower displacement of hexane than it should. The standing time after swirling the volumetric flasks could have also affected the results through the absorption of hexane by dried compost particles, leading to an increase in particle volume by swelling and hence a decrease in particle density. Assessing the relative contribution of each of these aforementioned factors remained a difficult task and as a result, corrective factors were not applied to the particle density results

Free air space

The free air space values were determined from the formulaic method given by Haug (1993). The variation of the mean FAS of each composting mix with time is shown in **Fig. 6**. From the FAS profiles, a general decreasing trend was noted in all three composting mixes, in agreement to the results obtained by Mohee *et al.* (2008) and Mohee and Mudhoo (2005) with different composting substrates. This observed behaviour may have resulted from the biodegradation of organic matter in the composting system, causing a decrease in particle size, leading to the settlement of particles.

The initial mean FAS of the broiler litter mix was found to be 80.86% and decreased to 66.98% at the end of the experiments, corresponding to a net decrease of 17.17% over the composting period. The obtained net decrease in this study was found to be lower than the value reported by Mohee and Mudhoo (2005) who obtained an overall decrease of approximately 48% for the composting of chicken manure with mixed vegetables and woodchips. The FAS values, being dependent on measured variables (wet bulk density, moisture content and particle density) largely reflect the variations of the latter. The rise observed in FAS on day 9 is attributed to a high particle density and low moisture content of the compost sample that day. The compost reactor was turned through two full revolutions on day 8 but the expected decrease in FAS was not reflected in the results obtained on day 9.

The FAS was initially found to be 81.22% for the cow dung mix which decreased to 72.22% at the end of the composting process. This corresponded to a net decrease of 11.08% over the composting period of 32 days. In comparison to the optimum FAS range of 30–60% suggested by

Table 5 Free air space results.

Substrate	Free Air Space (%)	Reference
Chicken manure, wood chips and mixed green vegetable	Initial – 75, Final - 40	Mohee and Mudhoo 2005
Broiler litter, mixed vegetable and bagasse	Initial – 80.86 ± 2.5, Final – 66.98 ± 2.6	This study
Cow dung, mixed vegetable and bagasse	Initial – 81.22 ± 3.1, Final – 72.22 ± 3.6	This study
Textile sludge, mixed vegetable and bagasse	Initial – 72.83 ± 4.0, Final – 62.71 ± 3.7	This study

(n = 3, mean values are shown, SD was always less than 15%).

Table 6 pH values compared from other studies.

Substrate	Starting pH	Final pH	Reference
Broiler litter	8.5	-	Lavergne *et al.* 2006
	7.7 – 8.3	-	Tasistro *et al.* 2004
Broiler litter and shredded office paper	7.2 – 7.8	8.6	Mohee *et al.* 2008
Poultry manure and municipal solid waste	7.9 – 8.0	8.2 – 8.3	Lhadi *et al.* 2004
Poultry manure, wood shavings, waste feed and feathers	8.18 – 8.33	7.01 – 7.10	Tiquia and Tam 2002
Vegetable wastes, cattle manure and saw dust	8.0	7.92	Kalamdhad and Kazmi 2009
Tannery sludge, sawdust, chicken manure and rice bran	7.3	6.6	Ahmed *et al.* 2007
Textile sludge and green waste	8.1 – 8.4	7.5 – 7.6	El Hammadi *et al.* 2007
Broiler litter, mixed vegetable and bagasse	8.52 ± 0.1	7.41 ± 0.1	This study
Cow dung, mixed vegetable and bagasse	7.20 ± 0.1	7.85 ± 0.1	This study
Textile sludge, mixed vegetable and bagasse	6.69 ± 0.1	6.11 ± 0.1	This study

(n = 3, mean values are shown, SD was always less than 15%).

Annan and White (1999), it can be deduced that the initial FAS of the cow dung mix was on the higher end. This might be the possible cause for the inability of the composting system to reach a temperature plateau higher than 55°C during the active composting stage. It is likely that the excessive air flow through the compost matrix had caused a cooling effect significant enough compared to the heat generated from the matrix.

The initial FAS of the textile sludge mix was the lowest among the three composting mixes in this study. This might be resulting from the high wet bulk density and high moisture content of the starting mix as compared to the broiler litter mix and cow dung mix. However, the initial FAS was still above the optimum range stated by Annan and White (1999). A net decrease of 13.89% from an initial FAS value of 72.83 to 62.71% was obtained at the end of the composting process. The summary of FAS results from this study is given in **Table 5**.

Annan and White (1999) also found that the formulaic expression for the calculation of FAS proposed by Haug (1993) and employed in this study, provided a close estimate of the FAS content as compared to FAS values obtained through air pycnometry, deemed to be the most reliable method for FAS determination in composting systems. In this regard, it can be said that the FAS values obtained in this through Haug's equation are reliable. However, one limitation in the determination of FAS was arisen from the sampling procedure. Due to the confined nature of the composting reactors, compost samples were mostly taken from an average depth of 10 cm from the surface in order to minimise disruption of the composting matrix. Consequently, the obtained results might not be fully representative of the actual FAS in the composting system. A study carried out by Das and Keener (1996) demonstrated that FAS not only decreased with increasing moisture content but also declined with increasing compost bed depth. This might explain the relatively low net decrease results obtained in each three mixes during the composting time.

pH

The variations of the mean pH in each of the composting reactors monitored during the composting period are shown in **Fig. 7**. The pH of the broiler litter mix at the start of the experiments was found to be 8.52; hence indicating that the starting mix was initially alkaline. Experiments carried out by Lavergne *et al.* (2006) and also by Tasistro *et al.* (2004) revealed that the pH of broiler litter varied in the range of approximately 7.7 to 8.5 due to the presence of uric acid in the broiler litter being converted to ammonia upon contact with air. Therefore, it can be inferred that the presence of broiler litter in the mix might be the principal substrate contributing to the alkaline nature of the composting mix.

The pH value gradually decreased from the 8.52 to 7.41 on day 11. This decrease could be resulting from the production and accumulation of organic acids during the decomposition of polysaccharides in the active decomposition phase (Iwegbue *et al.* 2006; Gao *et al.* 2010). Thereafter, a relative rise in pH was observed on day 16 and stabilised itself to a near neutral value of 7.41 at the end of the experiments. The rise in pH may be accounted by further metabolic degradation or volatilisation of organic acids. Another possible cause is the further decomposition of nitrogenous compounds, leading to the formation of ammonia which in turn reacts with the moisture present and hereby neutralising the present organic acids. The volatilisation of ammonia is favoured at a pH greater than 7 and hence it could also contribute to the rise (Gao *et al.* 2010). The results obtained in this study agree with the observations found by Tiquia and Tam (2002). **Table 6** presents pH values obtained for various composting substrates from various sources.

The starting cow dung mix was found to be quasi neutral with a pH of 7.20 and slightly increased to a maximum pH of 8.02 on day 16, possibly as result of an increase in ammonia released following protein degradation. From there onwards, the pH of the cow dung mix remained more or less constant till the end of the experiments with a final pH of 7.85. The pH results obtained by Kalamdhad and Kazmi (2009) closely follow the same trend as the one obtained for the cow dung mix in this study. Initially, the pH of the textile mix was slightly acidic as compared to the two previous mixes. Also, from **Table 6**, various sources have reported the initial pH of sludge mixes to be ranging from neutrality to slightly alkaline. The possible divergence from these sources is the presence of organic acids in the textile sludge at the disposal site prior to collection. It is also possible that the grab samples used for the experiment poorly represented the proportion of textile waste present in the reactor and contained more vegetable wastes. Nakasaki and Ohtaki (2002) found that vegetable wastes are mainly acidic in nature. Therefore a predominant presence of vegetable wastes in the grab samples might have affected the overall pH to being slightly acidic. A drastic increase from the initial pH to a maximum pH of 8.01 was recorded on day 7. This might have occurred from the production of ammonia at the thermophilic stage. From then on, the pH progressively decreased to a pH of 6.11 till the end of the experiments. This slight acidification of the compost might be due to the production of organic acids resulting from micro-

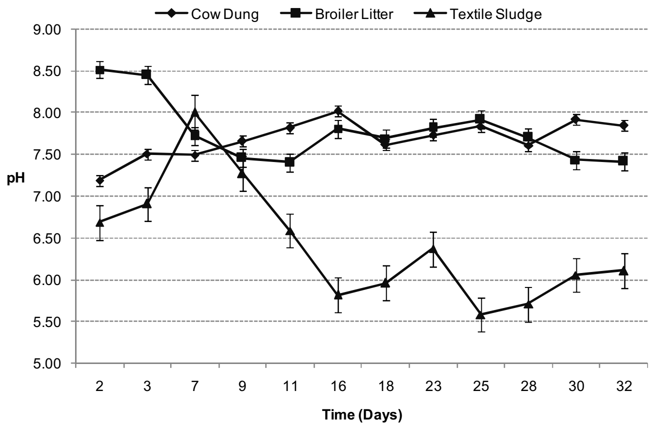

Fig. 7 Variation of average pH with time.

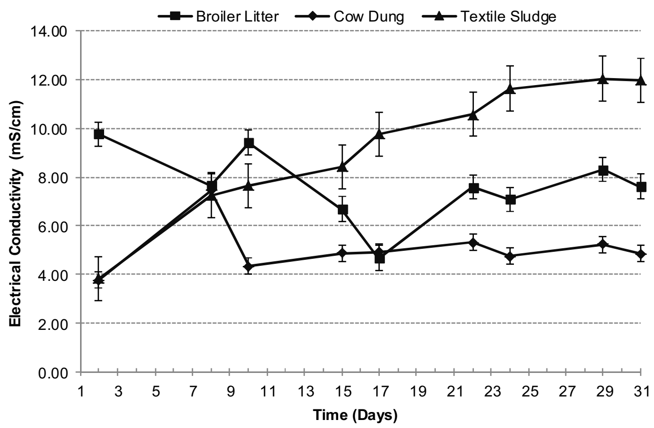

Fig. 8 Variation of electrical conductivity with time.

Table 7 Reported electrical conductivity values from various studies.

Substrate	**EC (mS/cm)**		**Reference**
	Initial	**Final**	
Mixed vegetables, chicken manure and wood chips	-	8.22 – 8.58	Mohee and Mudhoo 2005
Poultry manure and sawdust	2.36 – 3.02	2.05 – 2.61	Gao *et al.* 2010
Textile effluent	9.56	-	Prasad and Rao 2011
Broiler litter, mixed vegetable and bagasse	9.76 ± 0.1	7.61 ± 0.1	This study
Cow dung, mixed vegetable and bagasse	3.77 ± 0.1	4.84 ± 0.1	This study
Textile sludge, mixed vegetable and bagasse	3.83 ± 0.2	11.98 ± 0.1	This study

(*n* = 3, mean values are shown, SD was always less than 15%).

bial degradation of complex carbohydrates and organic matter in the composting mix.

From **Fig. 7**, it can be seen that the variation in pH for the cow dung mix and the broiler litter mix are quite similar as compared to that of the textile sludge mix. This might be likely due to the highly biodegradable organic content of the former mixes in contrast to the recalcitrant nature of dyes present in textile sludge. However, since the pH results obtained throughout the experiments were within an acceptable pH range of 6–7.5 for the development of bacteria, 5.5–8.0 for fungi and 5–9.0 for the action of actinomycetes (Ahmed *et al.* 2007), it can be concluded that at any point, the pH in the composting mixes were not a limiting factor during the experiments.

Electrical conductivity

The electrical conductivity value of compost gives an indication of the amount of ions present, its possible stability and phytotoxicity on plant growth if applied to soil. The variation of electrical conductivity monitored for each composting mix over time is given in **Fig. 8**.

A net decrease in the electrical conductivity values was observed for the broiler litter mix. The starting mix had a high initial electrical conductivity of 9.76 mS/cm and decreased to a value of 7.61 mS/cm at the end of the experiments. In a study performed by Santamaria-Romero and Ferrara-Cerrato (2001), it was found that an electrical conductivity higher than 8 mS/cm m adversely affected the microorganism population as well as the degradation of organic matter. However, despite the initial high electrical conductivity values obtained for the broiler litter mix, successful production of carbon dioxide was obtained during the active composting phase. The extent to which the high electrical conductivity value might have limited the degradation process cannot be evaluated within the scope of this study and would require further investigation. Since significant variations in the values were obtained for the electrical conductivity values, no clear cut trend can be deduced. Substantial differences in the final conductivity values were observed in the values reported in literature, as shown in **Table 7**. Gao *et al.* (2010) reported an initial increase in electrical conductivity values during the active phase of composting. Later, the values gradually decreased till the end of the experiments as a result of precipitation of mineral salts and volatilisation of ammonia. However, the final conductivity values obtained in this study seem to be closer to that obtained by Mohee and Mudhoo (2005) for the composting of mixed vegetables, chicken manure and woodchips.

The initial electrical conductivity of the cow dung mix was found to be 3.77 mS/cm, followed by an increase to a value of 7.44 mS/cm on day 8. This increase might be resulting from the release of mineral salts such as phosphates and ammonium ions during the decomposition process. Sánchez-Monedero *et al.* (2001) reported that the formation of nitrates also lead to an increased in electrical conductivity. The electrical conductivity then decreased to 4.33 mS/cm on day 10 and remained almost constant till the end of the experiments with a final value of 4.84 mS/cm. A clear increasing trend was obtained for the electrical conductivity values of the textile sludge mix. The electrical conductivity value was initially found to be 3.83 mS/cm and the final value of the textile sludge compost was 11.98 mS/cm. The initial electrical conductivity value obtained for the textile sludge mix was lower than expected as one would assume the presence of heavy metals in textile sludge. The rise in the electrical conductivity values till the end of the experiments may have been triggered by the lowering of pH below 6 in the composting media. Studies carried out by Zhang *et al.* (2009) have demonstrated that below a pH of 6, solidified sludge, disintegrating from natural weathering conditions, can release heavy metals at high concentration, therefore increasing the mobility of ions in the media.

The electrical conductivity profiles of the studied composting mixes significantly varied from each other. The divergences of final conductivity values from reported values from literature can be accounted by the factors such as the type of material composted, the duration of the composting process and also the technology employed. It is therefore difficult to use electrical conductivity as a reliable evaluator of compost stability. Since the final electrical conductivity values of each composting mixes in this study exceed the range of 2 mS/cm – 3.6 mS/cm and also the Mauritius standards limits of < 3.6 mS/cm (Mohee *et al.* 2008), the utilisation of the composts for agriculture might be detri-

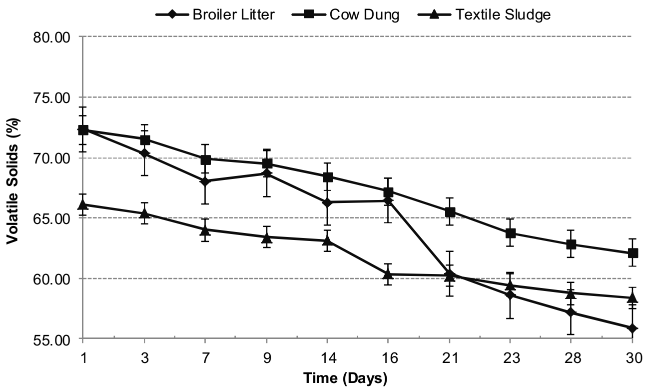

Fig. 9 Average volatile solids profile with time.

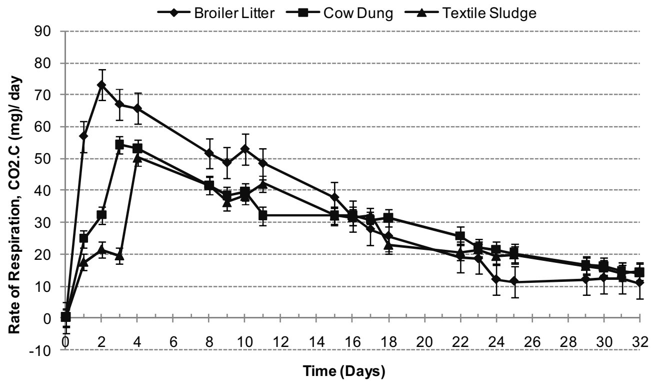

Fig. 10 Variation of average rate of respiration with time.

Table 8 Volatile solids results for various studies.

Substrate	Volatile Solids (%)			Reference
	Initial	Final	Decrease (fixed ash basis)	
Broiler litter and shredded office paper	82.7 – 85.0	72.9 – 76.6	56.3 – 57.1	Mohee *et al.* 2008
Dairy manure and straw	83	62	67	Changa *et al.* 2003
Broiler litter, mixed vegetable and bagasse	72.35 ± 1.6	55.90 ± 2.1	58.29 ± 1.9	This study
Cow dung, mixed vegetable and bagasse	72.27 ± 1.9	62.10 ± 2.4	47.97 ± 1.9	This study
Textile sludge, mixed vegetable and bagasse	66.11 ± 1.7	58.39 ± 1.9	41.64 ± 2.0	This study

n = 3, mean values are shown, SD was always less than 15%).

mental to plant growth and also to the environment through possible salt leaching.

Volatile solids

The evolution of volatile solids with time, within a composting system often gives good indication of biological degradation occurring in the reactor when absolute values are not considered (Lasaridi and Stentiford 1998). The plot of volatile solids (%VS) against time is given in **Fig. 9**. A general decreasing trend was observed in all three composting mixes.

The broiler litter mix demonstrated the most significant and rapid decrease in volatile solids. The values decreased from 72.35% at the start to 55.90% at the end of the experiments. This represented a net decrease of 58.29% on a fixed ash basis, comparable to the value obtained by Mohee *et al.* (2008) as shown in **Table 8**. Significant drop in volatile solids between day 16 and day 21 might indicate the presence of non homogenous pockets in the composting reactor, in which the rate of degradation might be differing from the rest of the composting system. Another possibility is the delayed degradation of hemicellulose, cellulose and lignin by microorganisms that might have caused the drop in volatile solids % at the later stage. This justification is supported by the results obtained by Eiland *et al.* (2001) for the composting of liquid pig manure and straw.

The cow dung mix, though having a volatile solids content (72.27%) almost equal to the broiler litter mix, had known a smaller decrease (to the value of 62.10%) at the end of the experiments than the latter. This represented a net reduction of 47.97% on a fixed ash basis. The textile sludge mix had the lowest initial volatile solids content with a starting value of 66.11% and a final value of 55.90% at the end of the experiments, indicating a net decrease of 41.64% on a fixed ash basis.

From the above results, the broiler litter mix underwent highest biological degradation of organic matter as compared to the two other mixes. This might have been aided by its initial parameters (C/N ratio of 24 and moisture content of 53), being closer to optimum conditions than the two other mixes, despite larger particle size. The relatively higher initial moisture content (66%) of the cow dung mix and the textile sludge mix might have inhibited oxygen diffusion within the composting mixes, therefore affecting the rate of decomposition. It is also possible that the broiler litter mix contained organic matter which was more easily degradable by the microbiological fauna present, than in the other two mixes. The results also indicate that the textile sludge mix contained more complex compounds and was less biodegradable, characterised by the lowest reduction in volatile solids. However, since all the composting mixes demonstrated a reduction of higher than 40%, it can be deduced that a fair deal of decomposition had occurred.

Respiration rate

The rate of respiration of the composting process was monitored for each mix (through the alkaline trap method), in the attempt to reflect microbial activity and organic matter decomposition with regard to the influence of substrates in each reactor. The variations of the respiration rate of each composting mix with time exhibited a trend shown in **Fig. 10**.

The respiration rate of the broiler litter mix rapidly increased on the very first day and peaked on day 2 with an average value of 73.0 mg CO_2.C/day. This sharp increase can be attributed to the presence of easily degradable organic matter in that could have stimulated microbial communities in the composting mix (Gao *et al.* 2010). As the degradation of most easily available organic matter occurred, the respiration value gradually decreased till day 9. Following the turning of the compost reactors on day 8, a slight increase in the respiration rate (52.9 mg CO_2.C/day) was observed on day 10. Turning of the reactor might have exposed more organic matter to microbial communities and increased the concentration of oxygen within the composting mix. Then onwards, the rate of respiration gradually decreased till the experiments to a final value of 10.9 mg CO_2.C/day.

The cow dung mix exhibited a lower respiration rate at the start of the experiments, in contrast to the broiler litter mix. It is possible that the initial high moisture content (66%) of the starting cow dung mix might have inhibited oxygen diffusion through the pore spaces and also cause the present microbial community to require more time to adapt to the high moisture conditions, thereby explaining the lag relative to the broiler mix whose starting mix had an initial moisture content of 53%. This reasoning is supported by the findings obtained by Richard *et al.* (2002) which revealed that respiration rate rapidly drops in the range of 55–60% (on a wet basis). The rate of respiration peaked on day 3

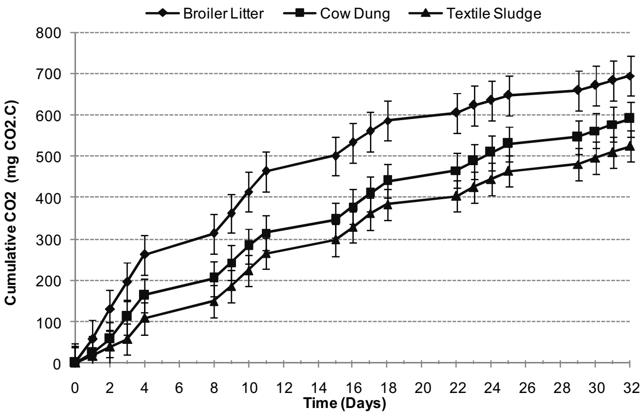

Fig. 11 Cumulative carbon dioxide evolution with time.

Table 9 Water holding capacity of composts produced.

Composting Mix	Water Holding Capacity (%)
Broiler litter	359 ± 11
Cow dung	332 ± 11
Textile sludge	346 ± 13

n = 3, mean values are shown, SD was always less than 15%).

with an average value of 54.2 mg CO_2.C/day. The value remained almost constant the next day, implying active degradation of the organic matter. The values gradually decreased through successive plateaus indicating the taking over of the composting process by more adaptable microbial communities as the most easily degradable organic matter exhausted and more complex ones were exposed and assimilated. A final respiration rate of 14.0 mg CO_2.C/day was obtained for the cow dung mix.

The rate of CO_2 evolution in the textile sludge mix was the lowest at the start of the experiments. An initial low plateau was obtained during day 1 to day 3 indicating sluggish microbial activity as compared to the other two mixes. This can be attributed to the toxicity caused by the presence of heavy metals, azo-dyes and complex molecules in the textile sludge and secondly, to the acclimatisation of the microbial community to the experimental conditions. The rate of respiration then increased to a peak of 50.2 mg CO_2.C/day on day 4. The values then gradually decreased till day 9, after which a lower peak was observed on day 11, following the turning of the reactor on day 8. The reason of this delayed peak could be the acclimatisation of the microorganisms to the renewed supply of labile organic matter which the turning effect incurred. There onwards, the rate of respiration gradually decreased till the end of the composting process to a final value of 14.5 mg CO_2.C/day. The cumulative carbon dioxide evolution of each composting mixes with time is given in **Fig. 11** to illustrate the extent of biodegradation in the studied composting mixes.

From **Fig. 11**, it can be observed that the highest amount of carbon dioxide production occurred in the broiler litter mix (695.7 mg CO_2.C), followed by the cow dung mix (591.5 mg CO_2.C) and lowest in the textile sludge mix (525.5 mg CO_2.C). These figures indicate that not only the rate of respiration was highest in the broiler litter mix but also that the latter was the most favourable to microbial decomposition at the end of the experiments.

Water holding capacity

The maximum water holding capacity of each composting mix was investigated after a composting period of 32 days. The results are as shown in **Table 9**.

The broiler litter mix gave the highest water holding capacity (359%) among the studied composting mixes. Mudhoo (2004) reported a water holding capacity of 231% for mixed vegetable waste, poultry manure and woodchips compost. The US Composting Council (2001) cited a range of 75–200% for municipal feedstock based composts and asserted that the preferred water holding capacity should be above 100%. Therefore, the obtained water holding capacity results in this study fit in the guidelines set by The US Composting Council (2001).

Stability of compost

The carbon dioxide evolution rate per unit volatile solids content was calculated according to the following equation:

$$mgCO_2.C / gVS.day = \frac{mgCO_2.C(mg/day)}{volatiles\_solids(g)}$$

The volatile solids content (g) was deduced from the following equation:

Volatile Solids (g) = (wet weight of sample) × (100 - MC_w) × (% Volatile Solid)

where MC_W = Moisture content of sample on wet basis (%)

Table 10 summarises the final parameters determining the biological stability of each mix at the end of the composting process.

The obtained figures indicate that after a period of 32 days, satisfactory decomposition of organic matter has occurred within each of the composting mixes and the obtained composts were stable according to the California Compost Quality Council (2001) standards.

CONCLUSION

The influence of different substrates namely broiler litter, cow dung and textile sludge on the physical, biological and chemical parameters involved in an in-vessel co-composting process of mixed vegetable waste with bagasse was analysed in this study. Through the analysis of the carbon dioxide evolution rate, this study demonstrated that broiler litter exhibited the highest rate of respiration (73.0 mg CO_2.C/day), followed by cow dung mix (54.2 mg CO_2.C/day), and lastly the textile sludge mix (50.2 mg CO_2.C/day). The peak respiration rate was also achieved earlier in the broiler litter composting system than in the other two mixes. The cumulative carbon dioxide evolution after 32 days indicated that the broiler litter mix had the highest carbon dioxide production of 695.7 mg CO_2.C, followed by the cow dung mix at 591.5 mg CO_2.C and lowest in the textile sludge mix (525.5 mg CO_2.C).The changes in bulk density, moisture content, temperature, free air space, particle density, volatile solids content and electrical conductivity provided an indication of their possible interactions in influecing the rates of respiration. However, these

Table 10 Summary of biological stability parameters.

	Broiler litter mix	Cow dung mix	Textile sludge mix
Final Rate of Respiration (mg CO_2.C/day)	10.9 ± 0.1	14.0 ± 0.2	14.5 ± 0.2
Final Volatile Solids Content (%)	55.9 ± 0.4	62.1 ± 0.8	58.4 ± 0.4
Final Moisture Content (%)	61.21 ± 0.3	61.64 ± 0.8	62.48 ± 0.6
Final Volatile Solids (g)	5.42 ± 0.1	5.96 ± 0.03	5.48 ± 0.04
Final Respiration Rate (mg CO_2.C/g VS / day)	2.01 ± 0.01	2.35 ± 0.04	2.65 ± 0.03
Stability Rating – Carbon dioxide Evolution Rate (mg CO_2.C/g VS / day)*	Stable (2 – 8)	Stable (2 – 8)	Stable (2 – 8)

*Source: (California Compost Quality Council (2001)
n = 3, mean values are shown, SD was always less than 15%).

interpretations linked to the rate of respiration were not always explicit due to the dynamic nature of composts.

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