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EVALUATION OF NEW SMALL-SCALE COMPOSTING PRACTICES WITH ENERGY RECOVERY

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ABSTRACT
This study involves the evaluation of new composting systems for the treatment of organic solid waste (OSW) that has low environmental impact. Two composting devices were developed, with four types of management, and their behavior was analyzed regarding temperature, gas production, moisture, leachate and percolated water production, compost maturation, nutrient presence, pH and water heating, which can be seen as an energy gain in addition to the economic viability of the process. The proposed composting techniques kept the waste at thermophilic temperatures for more than 20 days, with no significant emission of CH_4, under aerobic conditions by passive aeration, without leachate generation. These results can be partially attributed to the suspension of the compost on pallets, the residue composition chosen in the experiments and the boundary conditions of the compartments. The energy recovery test, through water recirculation inside the compost, presented temperatures that reached 51°C after 24 h of recirculation, and were maintained throughout the process, 20 days, demonstrating its effectiveness. The proposed composting models are environmentally viable, minimizing gas emissions and leachate generation compared to landfill or industrial composting plants. They can be used in industrial kitchens, residential complexes, shopping malls and other small and medium solid waste generators. In addition, the solution presented in this study avoids the transportation of waste over medium and long distances, which also brings a significant reduction in energy expenses, and in the case of landfills, it avoids occupation for long periods, thus reducing emissions of gases and leachate, whose control and treatment are expensive.

1. INTRODUCTION

On site composting of organic solid waste (OSW) is an advantageous alternative to landfill disposal due to its aerobic feature, minimizing emissions by transport and degradation in the landfill, as well as leachate production and the corresponding need for treatment (Pires, Martin and Ni-Bin, 2011). However, scaling issues are relevant, as discussed by Martinez-Blanco et al. (2010) through life-cycle analysis, showing the environmental advantages of small-scale composting in comparison to industrial scale, because even predominantly aerobic composting can be a source of CH_4, NH_3, NO_3, N_2O and SO_2.

In this context, unwanted emissions can be minimized or avoided depending on the operation, as reported in Amlinger and Peyr Cuhls (2008), Andersen et al. (2010a), Zuokaite and Zigmontiene (2013) and Ermolaev et al. (2014). For example, home composting with higher frequency of disturbance compared to lower frequency increases GHG emissions (Andersen et al., 2010a; 2011; 2012). The same was observed by Ahn et al. (2011) with respect to CH_4 in waste from a system that integrates agriculture with pasture and forest. This latter finding was a surprise, because the authors believed that the greater the number of turnings, the more aerobic the condition would be, leading to less formation of CH_4.

This phenomenon can be explained by the difficulty of keeping homogeneity of the ideal environmental conditions during solid state fermentation, contributing to the formation of sites with lower oxygenation and production of CH_4, whose release is facilitated by revolving the compost material (Durand, 2003). On the other hand, when minimizing the frequency of disturbance or operating under controlled static conditions, methanotrophic microorganisms oxidize up to 98% of the CH_4 produced in the composting, as observed by Jackel, Thummes and Kampfer (2005) and Ignatius and Miller (2009). This is economically and technically viable in small-scale operations.

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Ignatius Bettio and Miller (2009a) also drew attention to emission mitigation potential and obtaining carbon credits, considering the sum of the different small-scale static composting projects. The generated organic compound also has ecological advantages over traditional chemical fertilizers (Andersen et al., 2012), adds value to the process and acts as a soil conditioner (Kiehl, 1998).

The economic difficulties and the fragility of public policies for waste management in Brazil are reflected by the fact that around 70% of municipalities still dispose of waste in dumps (IBGE, 2010). There is also a shortage of equipment appropriate for on-site treatment of OSW generated by apartment buildings, industrial kitchens, supermarkets, schools and others. In this study, we developed and tested the performance of new composter models and composting strategies with minimal impact, easy installation and operation, without proliferation of vectors or odors, focusing on the treatment of food scraps and plant trimmings. We also tested the energy use of composting for water heating, seeking to add value to the process.

2. METHODOLOGY

Two composter models were tested for 60 days, called 1 and 2, using two gabions measuring 4 m long x 1 m wide and 1 m high, each divided into four compartments (A, B, C and D), each with volume of 1 m³ (Figure 1). The composters were covered with HDPE tarps to control moisture from rain and the compartments were covered on two sides by drainage mats, composed of geotextile filters, and had a three-dimensional plastic drainage core with 90% voids. The composters were also supported on pallets, increasing the passive aeration on all sides, including the base via thermal convection (chimney effect), as described in Münnich et al. (2006) and Andersen et al. (2010b). A HDPE membrane was installed below the pallets for soil protection and collection of leachates.

Composter 1 was also fitted with a drainage tube with diameter of 200 mm and holes along its entire length, arranged vertically in the center of each of its compartments, simulating a chimney to increase passive aeration of organic solid wastes (Figure 1).

The residues added in compartments A, B, C and D of each composter were inoculated as described in Table 1 and covered with a 5 cm layer of dried leaves after each OSW supply, to help maintain temperature and moisture as well as combat vectors such as flies.

The waste material was formulated experimentally of 33.3% food waste, 33.3% grass or leaves and 33.3% ground tree trunks (by volume), totaling approximately 500 kg of OSW per compartment.

The composters were operated statically, without disturbance. In other words, with each new input, only the top layer of dried leaves was removed, to allow the new material to contact the material already composted.

The compartments were monitored for temperature and moisture at points 10, 25 and 50 cm away from the wall or 40, 25 and 0 cm from the center and 25, 50 and 75 cm deep in each compartment, using a thermometer and Reotemp analog moisture meter with 90 cm rod for a total of 1.800 readings during 60 days of monitoring.

FIGURE 1: Composters 1 and 2 and their compartments A, B, C, D.

The percentages of CH_4 and O_2 gases were measured at 10, 25 and 50 cm from the wall or 40, 25 and 0 cm from the center and 30 and 60 cm depth in each compartment, using a Dräger X-AM7000 gas analyzer connected to a 1 meter metal rod (1,200 readings).

The same gas analyzer was used to determine the emissions from each compartment, associated with an Agilent Technologies model ADM200 flowmeter and a pyramidal flow chamber, covering the entire surface area of each compartment, as described in Andersen et al. (2010a).

The data were grouped into treatment pairs, considering the mean values of compartments A, B, C and D of composters 1 and 2, namely, 1A and 2A, 1B and 2B, 1C and 2C, and 1D and 2D. These were treated as repetitions since the differences between composters 1 and 2 concerning the presence of the central aeration (composter 1 only) were the same for all four treatments, henceforth simply called compartments A, B, C and D. Data were also evaluated considering composter 1 and 2 individually to identify variations between them, comprising the averages of data obtained from compartments A, B, C and D of each composter together, since the differences between these

TABLE 1: Management strategies of the compartments.

Compartments	Inoculation Strategy
A	OSW inoculated with 10% of its volume of compost after each input.
B	OSW inoculated with 10% of its volume of compost in the first input.
C	OSW inoculated with 10% of its wet weight with liquid inoculum EM® in every contribution (EM®: lactic acid bacteria, phototrophic bacteria and yeasts).
D	Control compartment receiving OSW without external inoculant.

compartments were also common to both composters. The pH, carbon/nitrogen ratio (C/N) and nutrients P, K, Na and Mg in the waste before intake and after 60 days of composting were evaluated, in duplicate samples, following the methods described in Andrade and Abreu (2006). Leachate generated in composters 1 and 2, independent of the compartment, was evaluated for pH and COD after 60 days, with samples in duplicate, following the Standard Methods D520 (Standard Methods, 1997).

Comparisons between the above parameters were made by analysis of variance (ANOVA) at a significance level of 95%, with prior verification of normality and homoscedasticity of the variables, as suggested by Sokal and Rohlf (2012). Since most of the data did not meet these requirements, we used base-ten logarithmic transformation [Log (x + 1)] prior to ANOVA, followed by the Tukey test to compare the means, at 95% confidence level ($p < 0.05$).

Data on variations of depth and distance from the wall of the compartments were analyzed separately for all compartments and composters, for a better understanding of their behavior considering the differences between treatments and composters.

To test the energy use for water heating, a composter with total volume of 2 m³ was used. Two waste compositions were studied, expressed in volume: (i) composition: 33.3% food waste, 33.3% grass and leaves (dry and green) and 33.3% ground trunks; (ii) composition: 50% ground trunks and 50% green grass.

This composter was equipped with a 44 m copper coil with diameter of 12.70 mm, immersed in the OSW to a depth of 50 cm from the bottom, through which 300 liters of water was circulated by an electric pump 24 hours after the intake of OSW, between the composter and a boiler with thermal insulation. The temperature was measured outside (air temperature) and at the water outlet of the composter.

3. RESULTS AND DISCUSSION

3.1 Temperature

Compartments A, B, C and D exhibited average temperatures that were mesophilic and reached maximums that were thermophilic, close to 70°C (Figure 2a), which were maintained for more than 20 consecutive days, enough for waste hygiene (USEPA, 1992). Significantly lower temperatures were observed in compartments A compared to C and D, which may have been caused by the 10% compost added as inoculum in these compartments, lowering their temperature to improve the porosity and consequently the oxygenation of OSW, in the same manner as observed in soils, where the addition of compost favors the formation of granules (Kiehl, 1998).

Among the composters, significantly higher temperatures were observed in composter 2 (Figure 2b), attributed to the absence of a central chimney.

Inside composter 1's compartments, the highest temperatures were observed 25 cm away from the wall or 25 cm from the center, against 50 cm in the compartments of composter 2, showing the influence of the chimney present in compartments 1 as a differential element with respect to passive cooling. In vertical evaluation, there was a common pattern in the compartments of composters 1 and 2 regarding the highest average temperature at 25 cm depth, compared to 50 and 75 cm. This result is probably related to the positioning of the composters on pallets, in contrast to traditional layouts, as noted by Jackel, Thummes and Kampfer (2005) and Ignatius et al. (2009b). This design helps establishment of the chimney effect and consequent redistribution of heat by the system, positively influencing the passive oxygenation and minimizing the formation of anaerobic sites, which result in the generation of CH_4 and leachate (Münnich et al., 2006) (Figure 3).

3.2 Gases

The percentage of CH_4 was between 0.0 and 2.6% in the waste, with the highest average being lower than 0.2% in treatment D (Figure 4a). This minimization of CH_4 generation contrasts with the findings of Ignatius et al. (2009b), who studied composters with sizes, OSW composition and input regimes very similar to those of the present study. They found an average value of up to 15% CH_4 in central areas of their compost piles, about 6 times more than

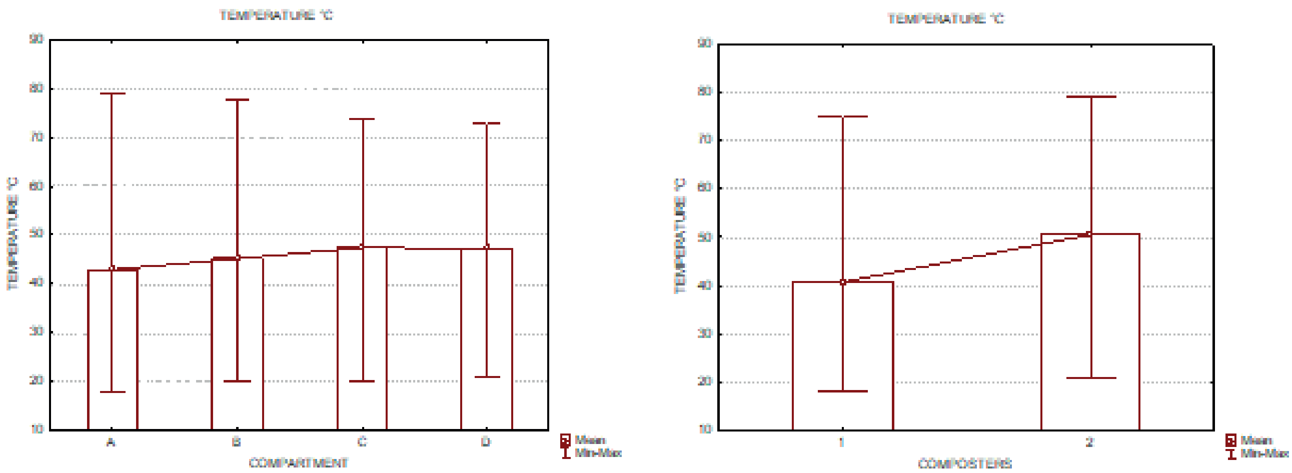

FIGURE 2a/2b: Average, minimum and maximum temperature per compartment and composter, respectively, in °C.

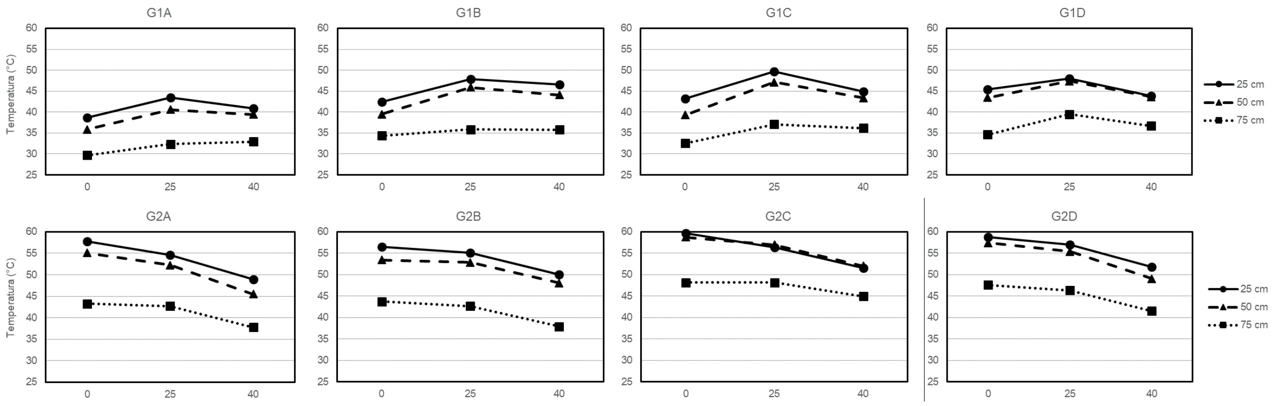

FIGURE 3: Average temperature in °C within the compartments 40, 25 and 0 cm from the center, and 25, 50 and 75 cm depth.

the highest maximum result in the central areas of this study. This positive result can be related to the efficient passive aeration, the result of the adopted materials and management strategies, ensuring aerobic conditions in all compartments, even those without chimney, since the generation of CH_4 is directly related to the establishment of anaerobic conditions in the OSW (Munnich et al., 2006), usually related to high moisture and low penetration of O_2 (Jiang et al., 2011; Kiehl, 1998).

However, even with little generation of CH_4, we observed significantly lower percentage of the gas in treatment A compared to C and D. This can be attributed to the addition of compost in maturation as inoculum at each input in treatment A, suggesting the efficiency of micro methanotrophic organisms present in the OSW to colonize and oxidize the CH_4 produced. This was also noted by Jackel, Thummes and Kampfer (2005) and Rose et al. (2012), investigating minimization of CH_4 emissions in composting and landfills with final compost coverage.

Regarding composters, both generated low percentages of CH_4 (Figure 4b), although composter 1 showed significantly lower values than composter 2. This can be attributed to increased oxygenation and predominance of mesophilic temperatures in 1, since methanogenic microorganisms grow best at thermophilic temperatures and methanotrophic ones find better conditions for growth and CH_4 oxidation at mesophilic temperatures (Jackel et al., 2005).

Horizontally, within composter 1 the highest average CH_4 values were observed in the waste 25 cm from the center of the composter, due to the central aeration of these compartments. In composter 2, without central aeration, the highest percentages of CH_4 predominated at the center of the composter. Variations in CH_4 according to depth did not exhibit a characteristic pattern, with larger values changing between 30 and 60 cm deep, although higher values predominated at 60 cm (Figure 5).

CH_4 emissions were sparse and minimal in all measurements, close to the minimum detection limit of 0.01%, and 5% reading error of the gas analyzer used. So, since all treatments proved to be effective in minimizing the production of CH_4 and/or metabolizing the gas, we considered the emissions from all compartments to be negligible. This finding is similar to those reported by Jackel at al. (2005) and Ignatius et al. (2009b), where up to 98% of the produced CH_4 was oxidized by methanotrophic communities. Further corroborating this assumption is that the average temperatures varied between 40 and 50°C in all compartments, the optimal range for activity of methanotrophic microorganisms, as already discussed. Thus, considering

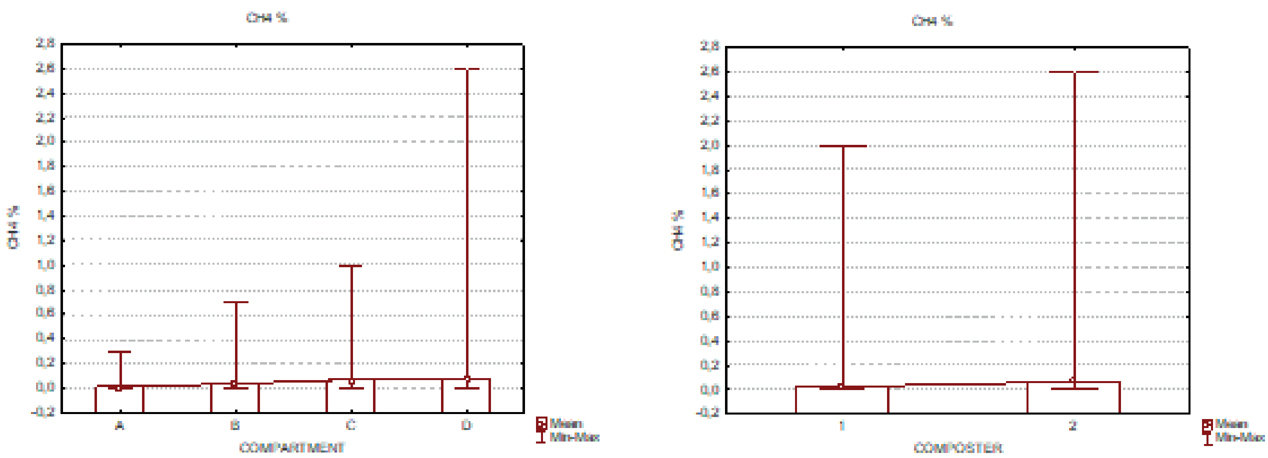

FIGURE 4a/4b: Maximum, minimum and average percentage of CH_4 by compartment and composter, respectively.

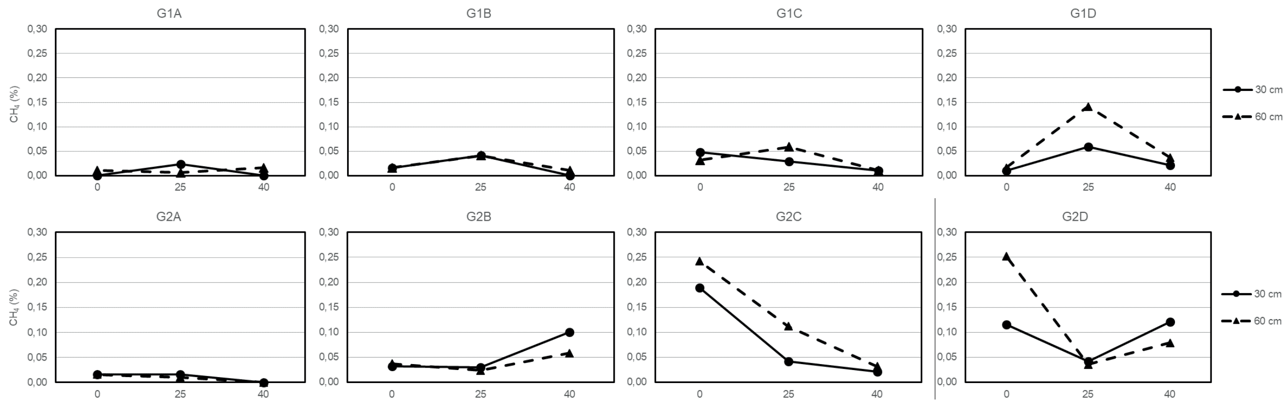

FIGURE 5: Average percentage of CH_4 at 40, 25 and 0 cm from the center, and 30 and 60 cm depth.

the emission of 600 kg of CO_2 eq./metric ton of ground OSW (USEPA, 2005), the 4 tons of OSW composted in this experiment avoided the emission of 2.4 tons CO_2 eq.. Furthermore, the absence of the need to transport the waste to a landfill prevented the emission of 87 kg of CO_2 eq., considering the emission of 2.9 kg CO_2 / l of diesel oil and the consumption of 7.5 L of diesel oil per ton of transported waste (Mahler, 2012). When discounting emissions that could theoretically be avoided in landfills by capture, burning and/or use for energy generation of CH_4, and assuming maximum efficiency between 30% and 40% of emissions avoided, as observed by Viana (2011) and Maciel and Juca (2011), respectively, the emissions avoided by on-site composting would diminish by 34%.

Many aspects contribute together to minimize the generation of CH_4 from composting. Size, density, input intensity and presence of methanotrophic microorganisms are the most relevant parameters (Jackel et al, 2005). They are directly related to the oxygenation and temperature of the system and inversely proportional to the variation of the generation of CH_4.

Since the present study investigated static operation, we believe the combination of a high proportion of structuring material and the positioning of the composters on pallets were important, by helping to establish efficient passive aeration, as evidenced by the mean O_2 between 17 and 20% among compartments and composters (Figures 6a and 6b). These values were sufficient to ensure that all treatments presented suitable aerobic conditions in the composting process, defined as above 5% O_2 by Kiehl (1998) and above 10% by Miller (1993).

However, the solid organic waste present in treatments A and B exhibited significantly higher average O2 percentages than in treatments C and D. This can be attributed to addition of compost as inoculum, which assists entry of O2 by increasing the porosity of the waste, especially in treatment A, as discussed in the item on temperature.

In static windrow piles, the O2 concentration also depends on the intensity of consumption by microorganisms and their replacement via passive aeration, which is influenced by the porosity of the material in the pile, moisture and the internal heat (Randle and Flegg, 1978). In this regard, it is noteworthy that the lowest average temperature and the highest average percentage of O_2 were observed in compartment 1A, which to some extent minimized the influence of temperature difference with respect to increased passive aeration and maximized the influence of possible increase in the porosity of the OSW due to the use of compost as inoculum. Also confirming the influence of the compost on the oxygenation of OSW is the fact that

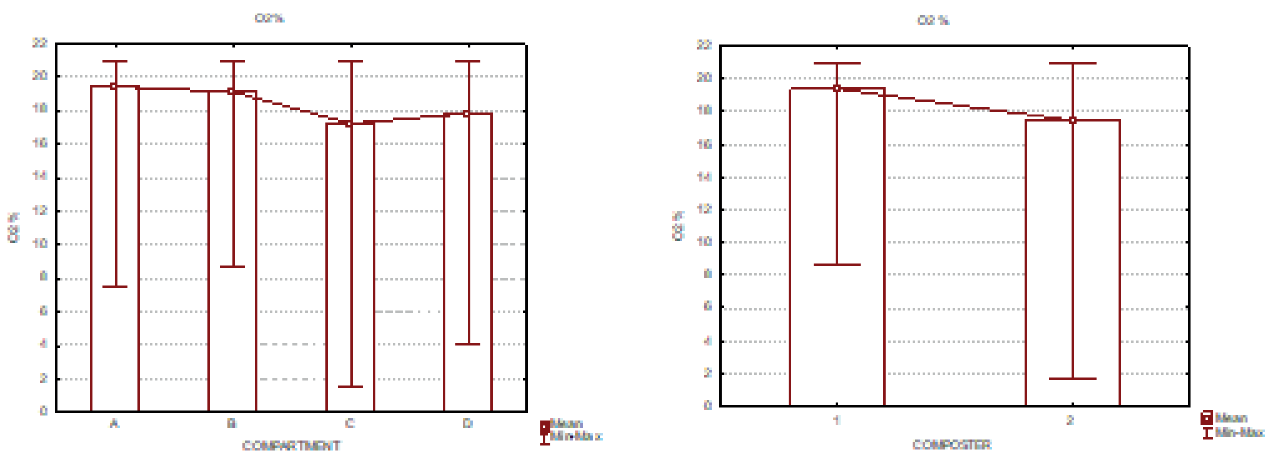

FIGURE 6a/6b: Maximum, minimum and average percentage of O_2 by compartment and composter, respectively.

compartment 2A, without chimney and inoculated with compost, presented an average O_2 value compatible with those observed in compartments 1C and 1D, equipped with central chimney, despite the higher moisture in 2A.

Between composters, higher O_2 percentage was expected in composter 1, due to the presence of the central chimney, facilitating oxygenation and moisture loss. This effect is supported by the higher moisture observed in composter 2, which is discussed below.

3.3 Moisture

Taking all the compartments together, the average moisture was near 60%, with significantly smaller differences for treatment A compared to the other treatments. This can be attributed to the use of compost as inoculum, since the increase in oxygenation attributed to the presence of compost favored drying even with the lower temperatures observed in A in comparison with the other treatments. Between the composters, the lowest average moisture in the waste was observed in composter 1, about 50%, versus about 70% in composter 2, attributed to the central aeration in composter 1.

Thus, the average moisture levels in the compartments and composters were between the minimum and maximum levels considered ideal for composting, of 50 and 70%, as suggested by Jiang et al. (2011), Kiehl (1998) and Brazil (2009), indicating proper maintenance of this parameter. Composting with moisture above 70% reduces O2 by excess water in waste macropores, while moisture below 50% reduces microbial activity, which ceases entirely below around 40% (Kiehl, 1998).

From an environmental point of view, Jiang et al. (2011) suggested that 65% moisture is the optimal value to minimize GHG emissions, the closest value to those attained by treatments B, C and D and composter 2, although compartment A in composter 2 was closest to 65% moisture.

It is noteworthy that the B compartments, although not differing in moisture significantly in relation to C and D, achieved significantly better performance with respect to O2 than C and D, similar to the A compartments. This aspect confirms again the importance of the type of inoculation applied to the compost mass regarding the adequacy of environmental parameters.

3.4 Leachate and percolated water

There was no generation of leachate in the composters and only a small amount of percolated water was produced, resulting from the external supply of water for wetting the compartments. This characteristic is attributed to the same aspects of maintenance of aerobic conditions discussed above, since the generation of leachate and CH_4 is directly related to the establishment of anaerobic conditions (Munnich at al., 2006).

The leachates generated presented average COD of 116.5 mg L^{-1}, so they were suitable for reuse to wet the composters or as liquid fertilizer. They could also be discarded, considering that according to the average COD/BOD ratio of 2/1, suggested by Jordan and Person (2005), the average value of DBO for the leachate in question would be 55.5 mg L-1, meeting the effluent discharge standards set by CONAMA (2005) for BOD of up to 60 mg l-1 (there are no limits for wastewater discharge based on COD in Brazilian federal regulations).

Such COD values contrast with 9,870 mg L^{-1} obtained in traditional residential composting (Andersen et al., 2011). Obviously, such differences are understandable, since the comparison is between percolated water from wetting compost piles and leachate.

The average pH values of the leachate from composters 1 and 2, after 60 days, were 7.1 and 7, respectively, meeting the pH limit for disposal of waste according to CONAMA (2005).

3.5 Maturation of the compost

The C/N ratio <20 is an indicator of stability for organic fertilizer class C according to Brasil (2009). In this regard, most of the treatments had C/N ratio indicating stability after 60 days, except for the D compartments, where the C/N averaged nearly 21, significantly smaller than D, suggesting the advantage of inoculation with compost with respect to degradation of organic solid wastes.

Between the composters, both had C/N <20, indicating stability of the material after 60 days. But composter 1 had C/N ratio significantly higher than composter 2, a result which may have been influenced by higher temperatures reached in composter 2. The average initial value of the C/N ratio of fresh OSW was 26/1.

3.6 pH

The pH of the wastes from treatments A, B and C, which received no inoculum, reached average values higher than 7 after 60 days, which was not observed in D, with pH below neutral (see Table 2). This aspect suggests composting without addition of inoculum is slower, although usually this process demands 90 to 120 days (Kiehl, 1998).

Treatment A presented significantly higher pH than C and D, which reinforces the idea that adding inoculum improves compost maturation.

However, residues in all compartments reached the reference value of pH> 6.5, described in Brasil (2009) and Giró (1994), suggesting that the material could complete its process of degradation in contact with the ground.

Both composters reached neutral pH after 60 days, with no significant differences, indicating that the differences in the temperature and oxygenation, derived from their mor-

TABLE 2: pH of OSW (before composting) and after 60 days of composting.

Sample	pH
Fresh OSW	5.6
Compartment A	7.5
Compartment B	7.3
Compartment C	7.1
Compartment D	6.7
References	<6.5a
	6.5/8b

References: a) Brasil (2009), organic fertilizer from municipal solid waste; b) Giró (1994), mixed organic waste (public parks, gardens and homes) phology (presence or absence of central chimney) did not affect the pH value.

3.7 Vectors

All treatments were effective in preventing the proliferation of flies and mice, a fact related to the maintenance of thermophilic temperatures, management strategy based on periodic OSW input and daily coverage with dry material, as suggested by Ignatius and Miller (2009). However, composter 2 was more efficient than 1 in combating flies, probably due to the higher temperatures. Particularly noteworthy is compartment 2A, which remained completely free of flies. This may be related to the use of compost every contribution, also suggesting its effectiveness in minimizing odors that attract vectors.

3.8 Water heating

The use of composting for heating water was appropriate because the 300 liters of water recirculated through the OSW reached 51°C after 24 h and remained at this temperature for 8 consecutive days in composter 1, with average ambient temperature of 21°C and maximum temperature of 71°C inside the composter. In composter 2, the same volume of water reached a temperature of 42°C after 24 hours in circulation and remained at that temperature for 15 consecutive days, with a mean ambient temperature of 23°C and maximum temperature of 62°C inside the composter.

However, the recirculation strategy depended on energy for pumping water and use of composter 1 would require frequent load changes. On the other hand, Jean Pain (1972) and Native Power (2013) suggested the passage of water only once through OSW, in long plastic hoses, and the use only of shredded trunks due to the longer degradation time of this material, (up to six months), which cheapens and facilitates the implementation of such systems, known in Germany as "Biomeiler".

CONCLUSIONS

Two composting devices were developed, with four different types of management in each, and their behavior was studied regarding temperature, gas production, moisture, leachate and percolated water production, compost maturation, nutrient presence, pH. and water heating.

Both composters and all four treatments studied were effective considering health and environmental aspects, more so for composter 2 (without central chimney) and treatment A (10% compost added) (see Table 1) in relation to combatting vectors and degradation of OSW as well as for neutralization of CH4 more efficiently, suggesting the use of model 2A in practical applications.

Overall, the maturation of the compound was satisfactory, with a C / N ratio <20 in almost all cases, indicating system stability after 60 days.

As for the pH, in all compost neutral values were reached after 60 days. In addition, the composters did not attract vectors, such as flies and mice.

The eight studied cases of composters reached temperatures of up to almost 80°C in some cases, and had negligible CH_4 gas emission and release of leachate and percolated water.

There were no oxygen deficiencies in composter 2, making it unnecessary to use central aeration.

The good results of the experiments can be attributed mainly to the suspension of composters on pallets, the waste composition and boundary conditions adopted.

The energy recovery process showed that the water heating worked very well, reaching temperatures up to 51°C after 24 h of recirculation, for long periods, more than 20 days, with temperatures near 70°C, showing that this process can be a potential energy source.

The proposed composting model is environmentally feasible, because it minimizes gas emission and leachate generation compared to the landfill deposition or industrial composting plants.

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