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CENTRALIZED TREATMENT OF WASTE THROUGH COMPOSTING: INFLUENCE OF THE C/N RATIO AND BULKING AGENT

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Abstract

The objective of this study was to evaluate the feasibility of composting municipal solid waste and agro-waste and the effects of initial C/N ratios of 35/1, 28/1 and 25/1 using 0%, 18% and 28% recalcitrant bulking agent during the composting process and in the final compost. Parameters such as thermal and exothermic profile, losses of organic matter and nitrogen, pH, electrical conductivity and C/N ratio were evaluated during the composting process. The quality of the organic compost was evaluated through the germination test and Brazilian normative instructions. The losses of organic matter were adjusted to a first order kinetic equation and the cluster analysis was applied to assess the similarity between the piles. Temperatures necessary for the elimination of pathogens were reached in all piles. The duration of the thermophilic phase doubled (49 days) in a pile with the initial C/N ratio of 35/1 without recalcitrant bulking agent. In the piles with initial C/N ratios of 28/1 and 25/1 and the addition of 18% and 28% recalcitrant bulking agent, thermal peaks (68 to 72 °C) were achieved more quickly (4 to 5 days) and the degradation of organic matter was more intense (0.071 to 0.173 d^{-1}). The organic composts obtained did not present phytotoxicity (germination index > 90%). Composting proved to be viable for the treatment of solid waste in a centralized way and the C/N ratio of 25/1 combined with 28% recalcitrant bulking agent ensured more significant degradation and better quality of the compost.

Key words: animal manure, biodegradability, food waste, germination index, waste management

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1. Introduction

Population growth and economic development contribute to the expansion of urban centers resulting in an increase of municipal solid waste (MSW) generated every year. The generation of food waste and pruning of green areas increased by 34% between 2000 and 2018 in Brazil, from 83 to 111 million tons per day (Abrelpe, 2019). In addition to MSW, Brazil generates significant amounts of agro-waste (AW) from the production of animal protein. The country was responsible for 13.4% of the world production of chicken meat in 2019 (ABPA Report, 2020) and 4% of the world milk production in 2018 (Embrapa, 2019). MSW and AW must be properly managed to avoid emissions of greenhouse gases, contamination of soil and water with organic materials and nutrients, and proliferation of pathogens (Bernal et al., 2009). However, the correct management of these residues can be often expensive and complex due to their diverse chemical, physical and biological characteristics (Gutiérrez et al., 2017).

Composting is a low-cost technology that allows the centralized treatment of organic waste with diversified characteristics, reducing demands for landfills or even more expensive technologies, such as incineration (Chen et al., 2020; Gutiérrez et al., 2017). Composting is a bio-oxidative process that promotes

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the stabilization of organic matter, leading to the formation of a product free of pathogens and phytotoxicity, recognized as a soil conditioner and a potential organic fertilizer (Bernal et al., 2009). The composting of organic waste is a sustainable alternative that contributes to circular economy strategies, reducing pollution and environmental impacts such as reducing greenhouse gas emissions (Costa et al., 2017; Soto-Paz et al., 2019).-www-

Parameters such as adequate C/N ratio, oxygen and moisture are essential to ensure satisfactory biological activity and stabilization of waste during composting (Bernal et al., 2009). C/N ratios between 25/1 to 30/1 are indicated to ensure the balance of nutrients, enabling energy and microbial growth. An unbalanced C/N ratio can cause problems such as the emission of unwanted gases and odors, attraction of disease vectors and low biodegradability of waste (Chen et al., 2020). Oxygen is essential in the composting process because microorganisms use it as an electron acceptor during the metabolic process to oxidize organic matter (Calisti et al., 2020). The oxygen supply can occur mechanically or automatically and directly affects the rate of waste degradation (Soto-Paz et al., 2019). Adequate moisture (≈ 55%) is important for maintaining biological activity and the satisfactory levels of biochemical reactions (Bernal et al., 2009).

Waste such as tree pruning and grass clippings from urban green areas are made up of cellulose, hemicellulose and lignin, and can assist in balancing the C/N ratio through the supply of carbon. However, lignin forms an amorphous reticulum that surrounds cellulose chains, making it difficult to biodegrade (Ma et al., 2020). A strategy to overcome this limitation and improve the biodegradation of lignocellulosic residues consists of adding AW such as cattle manure and poultry litter in the composting process. AW is rich in easily available organic molecules, have a high contact surface and can inoculate microorganisms in piles (Bai et al. 2020; Rich et al., 2018; Souza et al., 2019). In addition, food waste can also promote adequate C/N ratio and moisture in the composting piles, as they are a source of nitrogen and abundant in moisture (Guidoni et al., 2018).

The effective and centralized composting of MSW and AW requires a bulking agent with greater granulometry to improve the structure of the piles. The bulking agent with greater granulometry are necessary to avoid compaction and promote empty spaces that improve the internal homogenization of oxygen (Zhou et al., 2018). Several studies have been carried out using bulking agents from various plant sources, mainly to supply carbon to the process (Costa et al., 2017; Guidoni et al., 2018; Kebibeche et al., 2019; Zhou et al. 2018). Some studies have also evaluated the influence of non-biodegradable or recalcitrant bulking agents with strictly physical and structural purposes and not as a carbon source. Zhou et al. (2014) used recycled plastics as bulking agents (sludge composting) and observed improvements in oxygen diffusion, in the degradation of organic matter and in the germination index when the particle size the plastic was greater (5.0 cm). Jolanun and Towprayoon (2010) investigated the composting of MSW and rabbit waste with hollow granular clay as a bulking agent in the proportions of 0% to 35%. An increase in the loss of organic matter was observed when 15% of clay was used while 35% increased heat and nitrogen losses. Thus, it is evident that the bulking agent can benefit the composting process, when used in adequate proportions.

The main goal of this study was to evaluate the composting as centralized treatment technology of MSW and AW and the influence of the initial C/N ratio of 35/1, 28/1 and 25/1 using 0%, 18% and 28% of recalcitrant bulking agent during the composting process and in the final compost.

2. Material and methods

2.1. Source and characterization solid organic waste

The composting piles were built with (a) MSW (tree pruning, tree trunk, grass clippings and food waste) and (b) AW (poultry litter, cattle manure and ash waste) (Fig. 1) since these are the most abundant type of waste in the region of study.

Tree pruning was provided fresh and crushed (particle size under 5 cm) and grass clippings were collected fresh from maintenance of green areas. Both were the main carbon sources for the composting piles. The tree trunk had a particle size of 7 - 12 cm and it was used as a recalcitrant bulking agent to provide structure and improve gas exchange in the piles, and not as an energy source. Food waste served as source nitrogen and it was consisted mostly of grains, vegetables, eggs, milk products, meat and paper napkins and it was collected in a university restaurant. Poultry litter was collected in a poultry farm after seven cycles of production. Cattle manure was collected in a grazing system. The poultry litter and cattle manure were used to improve organic matter degradation and inoculation of microorganisms (Rich et al., 2018). The wood ashes were collected in a boiler from a dairy industry. This type of ash is generated in large quantities in agro-industries from the burning of wood to generate heat. When applied in composting, it can influence the process and mineral quality of the final compost (Asquer et al., 2017). All residues were collected in the municipality of Medianeira/Brazil in the urban and rural areas. The physical and chemical characteristics of the bio-wastes are summarized in Table 1.

2.2. Composting process

Three composting piles were built on a concrete floor in a covered area in the composting plant at Federal University of Technology – Parana (Medianeira/Brazil). The composition of each pile is shown in Table 2. Each pile corresponded to a treatment, in which the C/N ratio was varied and the amount of recalcitrant bulking agent being: C/N 35/1 and 0% recalcitrant bulking agents (pile 1); C/N 28/1 and 18% recalcitrant bulking agents (pile 2); C/N 25/1 and 28% recalcitrant bulking agents (pile 3).

The variation of carbon sources (tree pruning and grass clippings) was based on the availability and regional seasonality of these residues. The pile 3 received more recalcitrant bulking agent due to the low porosity of the grass clippings used. The piles were aerated by two turning manual overturns during the first month and once a week thereafter. The temperature in the environment and in the piles had been monitored by means of an alcohol thermometer with daily measurements for the first ten days and, thereafter, every two days at four points 30 cm deep. The humidity of each pile was kept between 50% - 60% by adding water during the turns. The masses of the piles were determined on days 0, 10, 24 and 57 by using a digital scale. Piles were sub-divided into three parts for sampling. Sub-samples were collected at three different points within each part. After being homogenized, the sub-samples formed a single composite sample. The piles were monitored until the end of the bio-oxidative phase when the internal and environmental temperatures were equal.

Fig. 1. Waste used in the composition of the piles

Table 1. Characterization of the waste that made up the composting piles

Parameter	*Waste*				*Carbon sources*		*Bulking agent*
	Food waste	*Cattle manure*	*Poultry litter*	*Ash waste*	*Tree pruning*	*Grass clippings*	*Tree trunk*
Moisture (%)	71.9	79.5	25.9	0.0	53.6	9.4	2.1
TS (%)	28.1	20.5	74.1	100.0	46.4	90.6	97.9
OM (%)	94.1	80.6	64.9	0.0	95.2	90.1	94.3
Ash (%)	5.9	19.4	35.1	100.0	4.8	9.9	5.7
TOC (%)	52.3	44.8	36.1	0.0	52.9	45.3	52,4
TKN (%)	3.73	1.31	1.74	0.03	0.76	0.89	0.37
C/N	14.0	34.2	20.9	0.0	69.6	50.9	141.6
Cellulose (%)	nd	nd	nd	nd	30.0	23.2	35.1
Hemicellulose (%)	nd	nd	nd	nd	14.1	27.0	7.6
Lignin (%)	nd	nd	nd	nd	15.3	9.2	27.7

TS = total solids; OM = organic material; TOC = total organic carbon; TKN = total Kjeldahl nitrogen; C/N = carbon to nitrogen ratio; nd = not determined. (n = 3)

Table 2. Gravimetric composition of piles in dry matter

Treatments	*Waste (kg)*				*Carbon sources (kg)*		*Ratio C/N*	*Total mass (kg)*	*Recalcitrant bulking agent* (%)*
	Food waste	*Cattle manure*	*Poultry litter*	*Ash waste*	*Tree pruning*	*Grass clippings*			
Pile 1	14	4	11	7	48	0	35	84	0
Pile 2	14	4	22	15	28	0	28	83	18
Pile 3	14	4	22	13	0	33	25	85	28

**The carbon of the recalcitrant bulking agent (tree trunk with particle size from 7 to 12 cm) was disregarded in determining the initial C/N ratio of the piles, since the high content of lignin (27.7%) prevents its use as an energy source for microorganisms*

2.3. Analytical methods

Three additional piles (500 g wet weight) in the same proportions of residues also used in the experimental piles were used for the initial characterization. The contents of total solids (TS), ash and organic matter (OM) were determined by drying (105 °C) and ignition (550 °C) of the sample (APHA, 2017). Total organic carbon (TOC) was determined by removing the volatile solids by the ignition process (Cunha-Queda et al., 2007). Total Kjeldahl nitrogen (TKN) was analyzed after heat block sulfuric digestion, followed by distillation and titration (APHA, 2017). The C/N ratio was calculated from the division of TOC by TKN. The pH and electrical conductivity (EC) was determined in aqueous solutions of 1:5 ratio (sample:water) and stirred for 30 min (Tedesco et al., 1995). To measure TKN, the samples were dried at 50 °C and grounded to improve homogeneity (weight values were corrected after drying at 105 °C). Neutral detergent fiber, acid detergent fiber and acid detergent lignin were measured to determine cellulose, hemicellulose and lignin content according to Van Soest et al. (1991).

The exothermic index (EXI²) was determined from the sum of the quadratic differences between the average temperature of the piles and the environment temperature during the bio-oxidative phase of composting (Vico et al., 2018). The dry matter reduction (Eq. 1) during the composting process were calculated from the initial (M_1) and final (M_2) values of the piles. Organic matter losses (Eq. 2) and nitrogen losses (Eq. 3) were calculated from the initial (X_1) and final (X_2) ash, and initial (N_1) and final (N_2) TKN concentrations, respectively, contents according to the Equations of Paredes et al. (2000).

$$\mathrm{Re}\,duction\ dry\ matter(\%) = \left[\frac{(M_1 - M_2)}{M_1}\right]\cdot 100 \qquad (1)$$

$$Organic\ matter\ losses(\%) = 100 - 100\frac{[X_1(100 - X_2)]}{[X_2(100 - X_1)]} \qquad (2)$$

$$N\ losses(\%) = 100 - 100\frac{[X_1 N_2]}{[X_2 N_1]} \qquad (3)$$

2.4. Germination index

To determine the germination index (GI), aqueous extracts of the final composts were prepared. The compost samples were stirred in distilled water (solid/water ratio p/v 1:10) for 24 hours inside a horizontal shaker (150 rpm) at room temperature. The suspensions were centrifuged at 3,000 rpm for 30 min and filtered with a 0.45 µm glass fiber membrane.

The GI was determined through tests with ten replicates of each compound. 3 mL of the extract was added to each Petri dish containing sterile double cellulose paper (Whatman n°. 1). Ten seeds of *Lepidium sativum* (garden cress) were added to the paper. Petri dishes containing the seeds were incubated at 25 °C with no light for 72 hours (adapted from Zucconi et al., 1981) in a germination chamber. Five Petri dishes (same characteristics) with distilled water was used as controls. The GI was calculated with the result of the percentage of viable seeds, the number of germinated seeds and the root growth after 72 hours (Eq. 4).

$$GI(\%) = \left(\frac{NGext.L\,\mathrm{Re}\,xt}{NGcont.LRcont}\right)\cdot 100 \qquad (4)$$

where: *NGext* is the number of seeds germinated in the extract; *NGcont* is the number of seeds germinated in the control; *LRext* is the average root length of the extract (cm); and *LRcont* is the mean root length of the control (cm).

2.5. Statistical analysis

The losses of organic matter during the degradation process were adjusted to a first-order kinetic function (Paredes et al., 2000) (Eq. 5). This mathematical model was chosen due to its satisfactory fit related to the randomized residuals distribution and the lowest residual mean square (RMS), while giving a significant F-value.

$$Organic\ matter\ losses\ (\%) = A(1-e^{-kt}) \qquad (5)$$

where *A* is the maximum degradation of organic matter (%), k is the rate constant (d^{-1}) and t is the composting time (d).

The GI was determined by using 10 replicates per sample. All other analysis were performed in triplicates. The least significant difference (LSD) test with $p < 0.05$ was applied to calculate differences among each parameter during composting. The experimental design applied in the IG test was completely randomized. The data has been evaluated using ANOVA and Tukey's multiple comparison test of means ($p<0.05$). Cluster analysis was used to group treatments based on their similarity. The matrix of Euclidian distances was calculated and the clusters were formed by the average hierarchical linkage method. The observations was standardized (mean 0 and variance 1). After the assumptions of data normality and linearity were met, variables were analyzed using the Pearson rank correlation coefficient ($p<0.05$).

3. Results and discussion

3.1. Thermal profile of the composting

Temperature is one of the most important parameters of composting, as expresses the evolution of process biodegradation (Bernal et al., 2009). The thermal profile of the compost piles showed a typical behavior characterized by a well-defined thermophilic phase (>40°C) followed by a mesophilic phase

(<40°C) until reaching room temperature (Bustamante et al., 2013), as shown in Fig. 2.

The highest C/N ratio (35/1) and the absence of bulking agent in pile 1 prolonged the thermophilic phase by 49 days. However, the thermophilic phase lasted 25 and 26 days with C/N ratio of 28/1 with 18% bulking agent in pile 2 and 25/1 with 28% bulking agent from pile 3 (Table 3). This behavior explains the greater accumulated EXI^2 of pile 1 (21,882.7) when compared to piles 2 (19,990.9) and 3 (18,805.1), because high C/N ratios prolong biological activity and heat release (Bustamante et al., 2013). Thermophilic temperatures indicate intense bio-oxidation of residues and are desired to eliminate pathogens and weed seeds (Vico et al., 2018). All piles had at least seven days of temperature above 60 °C, as required by Brazilian and European Union legislation for sanitizing the compost (Brazil, 2017; Saveyn and Eder, 2014). The thermal peak of pile 2 (68 °C) and 3 (72 °C) occurred in the first week of composting, while pile 1 showed a thermal peak (66 °C) in the second week. The rapid temperature increase in piles 2 and 3 may be related to the greater amount of poultry litter used (Table 2).

The presence of easily biodegradable organic compounds, particles with a high contact area and a possible inoculation of microorganisms of the AW may have contributed to the increase in temperature (Rich et al., 2018; Souza et al., 2019). An increase in temperature was observed during the thermophilic phase after turning the piles (Fig. 2). This behavior has been reported by other authors (Costa et al., 2017; Vico et al., 2018) and is explained by the oxygen supply followed by the intensification of biodegradation of the organic matter (Bernal et al., 2009). The average temperature increase was 3.1, 1.7 and 0.7 °C in piles 1, 2 and 3, respectively. The tenuous increase in temperatures in piles 2 and 3 can be related to the better oxygen distribution provided by the bulking agent with higher particle sizes (7 - 12 cm). This result is particularly important for composting plants, as it indicates that the frequency of pile turnings can be reduced by using structural bulking agents such as the tree trunk, which can reduces operating costs. However, excess of bulking agents with large particle size must be avoided to prevent unwanted heat losses (Jolanun and Towprayoon, 2010).

Table 3. Parameters of the thermal profile of the piles during the bio-oxidative phase of composting

Parameter	***Pile 1***	***Pile 2***	***Pile 3***
Thermophilic phase* (days)	49	25	26
Temperatures ≥ 60°C (days)	7	9	11
Maximum temperature (°C) / Day of occurrence	66/11	68/4	72/5
Bio-oxidative phase (days)	57	57	56
Cumulative EXI^2**	21,882.7	19,990.9	18,805.1
EXI^2 / days of bio-oxidative phase	383.9	350.7	335.8

** Thermophilic phase > 40°C. **EXI^2: Square of the exothermic accumulation index. Pile 1: C/N 35/1 and 0% bulking agents; Pile 2: C/N 28/1 and 18% bulking agents; Pile 3: C/N 25/1 and 28% bulking agents*

3.2. Organic matter losses

The organic matter loss was significant during the bio-oxidative phase in the three piles (Fig. 3), presenting degradation profiles that satisfactorily adjusted ($p < 0.05$) to the first-order kinetic equation (Table 4), indicating the exponential behaviour of the degradation between MSW and AW.

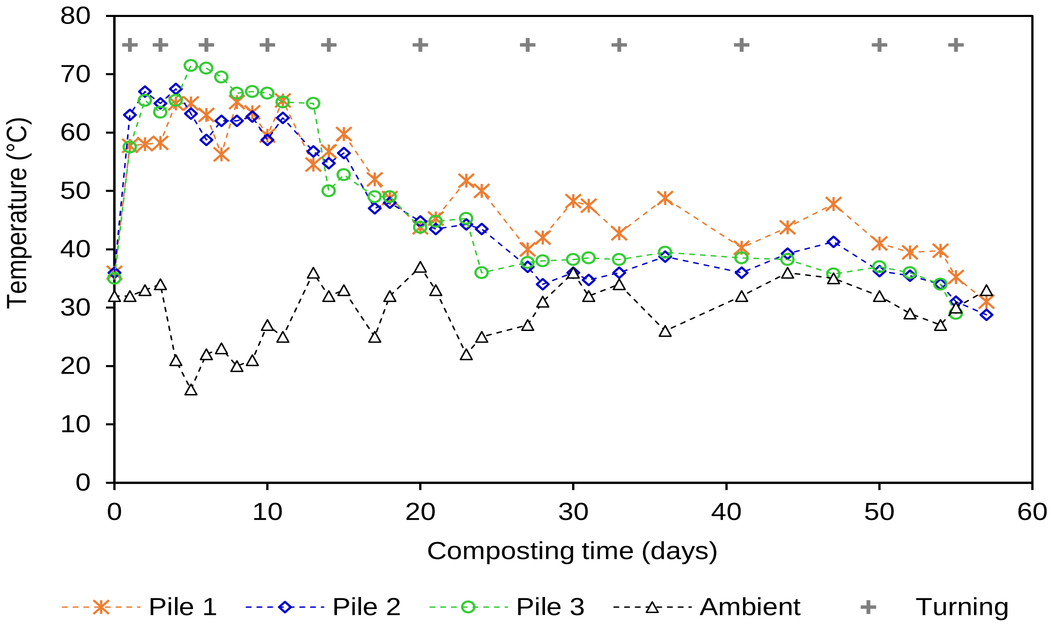


Fig. 2. Temperature profiles of pile 1 (C/N 35/1 and 0% bulking agents), pile 2 (C/N 28/1 and 18% bulking agents) and pile 3 (C/N 25/1 and 28% bulking agents), ambient temperature and turning events throughout the composting process

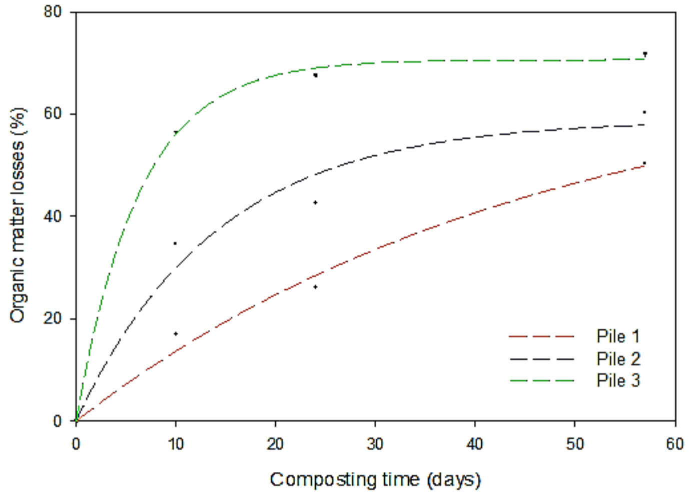


Fig. 3. Organic matter loss during the composting of Pile 1 (C/N 35/1 and 0% bulking agents), Pile 2 (C/N 28/1 and 18% bulking agents) and Pile 3 (C/N 25/1 and 28% bulking agents). *Symbols are the experimental data (n = 3) and lines represent the curve-fitting*

Table 4. Parameter obtained after fitting organic matter losses to a first-order kinetic function

Treatment	***A***	***k***	***F***	***R sqr***	***RMS***	***SEE***
Pile 1	60.5 (5.7)	0.021 (0.008)	164.3***	0.98	7.95	2.82
Pile 2	58.9 (6.2)	0.071 (0.022)	62.8***	0.97	29.60	5.43
Pile 3	70.6 (1.1)	0.157 (0.011)	187.0***	0.99	1.77	1.33

*A: maximum degradation of organic matter (%); k: rate constant (d^{-1}); ***: Significant at $p<0.001$; RMS: residual mean square; SEE: Standard Error of Estimate. Pile 1: C/N 35/1 and 0% bulking agents; Pile 2: C/N 28/1 and 18% bulking agents; Pile 3: C/N 25/1 and 28% bulking agents*

The A and k values were within the range found by different authors in composting experiments: 32 – 74% for A and 0.005 – 0.200 d^{-1} for k (Chiarelotto et al., 2019; Morales et al., 2016; Paredes, 2002). The first-order kinetic model showed similar values of maximum degradation of organic matter (A) between piles 1 (60.5%) and 2 (58.9%), but the degradation constant (k) of pile 2 (0.021 d^{-1}) was significantly higher than pile 1 (0.071 d^{-1}). As tree pruning was the main source of carbon in these two piles, the greater speed degradation of pile 2 is explained by the more balanced C/N ratio (28/1) and the presence of 18% of the tree trunk as a structuring volume agent.

High initial C/N ratio and oxygen deficiency cause a reduction in the degradation rate of organic matter due to the limited microbial performance and slow decomposition related to the lower nitrogen and oxygen availability (Chen et al., 2020; Soto-Paz et al., 2019). Values of A (70.6%) and k (0.157 d^{-1}) were significantly higher in a pile 3 than in piles 1 and 2. This difference can be related to the synergism produced between the more balanced C/N ratio (25/1), the presence of 28% of recalcitrant bulking agent and the carbon source used (grass clippings). The lower lignin content of grass clippings (9.2%, Table 1), may have made cellulose more readily available for biodegradation, causing increases in the values of A and k (Ma et al., 2020). Morales et al. (2016) obtained k = 0.200 d^{-1} by composting biological reactor sludge with 58% of plant sprouts, with a C/N ratio of 24/1.

The similarity between piles 1 and 2 was 38.5%, while the similarity between piles 2 and 3 being 61.5% (Fig. 4). Thus, it can be said that the initial C/N ratio and the recalcitrant bulking agent had a greater influence on the composting process and on the compost than the different carbon sources (piles 1 and 2: tree pruning; pile: grass clippings) used in this study.

3.3. Evolution of traditional compost monitoring parameters

The initial pH of the piles was close to neutrality and within the range of 6 – 8 (Table 5), considered adequate for composting (Bernal et al., 2009). The higher pH values in piles 2 and 3 during composting can be explained by the greater amount of ash used in these piles, since the ashes are recognized for their high content of hydroxyls (Asquer et al., 2017). The reduction of pH values of the three piles at the beginning of composting is explained by the decomposition of easily degradable organic matter into low molecular weight organic acids (Kebibeche et al., 2019; Wu et al., 2017). The pH increase of the three piles from the tenth day of composting can be related to the degradation of carboxylic and phenolic acids, and to the mineralization of proteins, amino acids and peptides in ammonia (Paredes et al. 2002). Chiarelotto et al. (2019) presented similar pH values during the composting waste from the broiler production chain and pruning of crushed trees as a carbon source. The final pH values of the compost are within the recommended range for application to the soil (Brazil, 2009). The increase in the relative concentration of ions due to the organic matter degradation lead to an increased EC in the three piles (Table 5) (Bustamante et al., 2013).

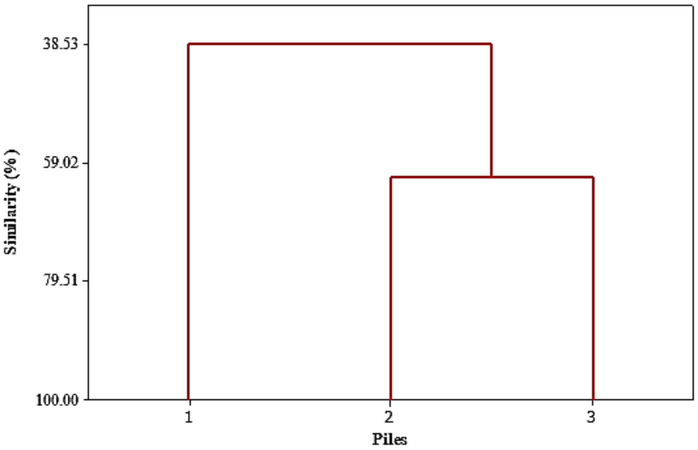


Fig. 4. Dendrogram constructed using average linkage hierarchical clustering and Euclidean distance *Pile 1: C/N 35/1 and 0% recalcitrant bulking agents; Pile 2: C/N 28/1 and 18% recalcitrant bulking agents; Pile 3: C/N 25/1 and 28% recalcitrant bulking agents*

Table 5. Evolution of the principal parameters during composting

Composting time (days)	pH	EC (dS/m)	Dry mass (kg)	COT (%)	TKN (%)	Ratio C/N	TKN losses (%)
Pile 1: C/N 35/1 and 0% recalcitrant bulking agents							
0	7.2	3.1	84.0	42.2	1.20	35.2	0.0
10	6.6	3.5	73.9	40.2	1.17	34.5	15.5
24	7.4	3.9	64.9	38.9	1.17	33.3	22.2
57	8.0	4.4	47.1	33.9	1.38	24.6	29.0
LSD	0.1	0.3	-	1.8	0.13	3.6	10.8
Pile 2: C/N 28/1 and 18% recalcitrant bulking agents							
0	7.7	4.3	83.5	36.9	1.32	27.9	0.0
10	7.1	4.9	60.9	31.3	1.15	27.3	33.2
24	8.0	5.5	47.7	29.5	1.22	24.1	33.6
57	8.5	5.9	39.9	24.4	1.13	21.7	48.8
LSD	0.1	0.3	-	1.3	0.07	1.4	6.5
Pile 3: C/N 25/1 and 28% recalcitrant bulking agents							
0	7.9	4.3	85.1	41.4	1.67	24.7	0.0
10	7.4	5.1	44.1	31.1	1.67	18.7	42.3
24	8.1	5.3	43.5	27.0	1.53	17.6	54.3
56	8.4	5.4	29.2	25.1	1.60	15.7	55.3
LSD	0.2	0.2	-	2.7	0.02	1.9	7.3

EC, electrical conductivity; OM, organic matter; TOC, total organic carbon; TKN, total Kjeldahl. LSD, least significant difference at p < 0.05

The higher EC of piles 2 and 3 can be explained by the greater amount of ash residues added to these piles (Asquer et al., 2017).

The reduction in dry mass during the entire composting period was 44% in pile 1, 52% in pile 2 and 65% in pile 3 (Table 5)This parameter directly affects the space optimization of composting plants (Costa et al., 2017). The C/N ratio between 25 – 28/1 combined with the recalcitrant bulking agent proved to be important for mass reductions in less time, since that in 10 days the mass reductions of pile 2 was 27% and that of pile 3 was 48%, while pile 1 reduced only 12% in the same period.

The initial total organic carbon content decreased in all piles, from 42.2% to 33.9% in pile 1, from 36.9% to 24.4% in pile 2 and from 41.4% to 25.1% in pile 3 (Table 5), which demonstrates the process of mineralization of organic carbon into CO_2 (Morales et al., 2016). The lower initial concentration of organic carbon in pile 2 can be attributed to the greater amount of ash residues added in this pile (Table 2).

The degradation of organic forms of carbon and nitrogen caused reductions in the C/N ratio in all piles during composting (Table 5), especially during the thermophilic phase, coinciding with the maximum degradation of organic matter. The final C/N ratio < 20 is indicative of good stabilization and maturation of the compound (Bernal et al., 2009). However, this parameter should not be used as an absolute in relation to the state of maturity of the compost, but as a parameter for mineralization of organic matter (Bustamante et al., 2013; Morales et al., 2016, Vico et al., 2018). The significant Pearson's linear correlation ($p < 0.01$) between the final C/N ratio and the loss of organic matter in the piles was very strong and negative ($r = -0.931$), therefore, the higher the final C/N ratio, the less was the loss of organic matter.

The initial nitrogen concentrations in the piles followed the pattern: pile3 > pile2 > pile1 (Table 5).

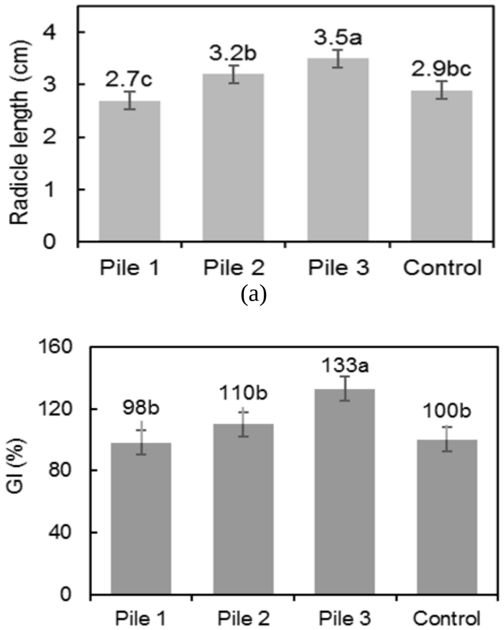
The nitrogen losses were significantly different between the three cells and corresponded to 29.0% in pile 1, 48.8% in pile 2 and 55.3% in pile 3. Nitrogen losses during the composting process can reach up to 70% (Nigussie et al., 2016). Some similar in composting studies obtained nitrogen losses of 42.98% (Costa et al., 2017) and 40.30% (Chiarelotto, et al. 2019). The need to decrease nitrogen losses during the composting process is the focus of many studies, given that nitrogen losses have a negative impact by emitting toxic gases in the atmosphere and reducing the nutritional value and, consequently, the quality of the final compost (Zhang and Sun, 2016).

Nitrogen losses to the environment can occur through leaching, volatilization and denitrification. It is believed that the greatest nitrogen losses in this study were due to volatilization in the form of ammonia, since there was no generation of leachate in the piles and denitrification corresponds to losses < 5% of nitrogen in the forms of N_2, N_2O and NOx (Bernal et al., 2009). The conditions necessary for ammonia to appear are related to some physical-chemical combinations, such as pH > 7.5 and temperature > 65 °C (Zhao et al., 2020). The pH and nitrogen losses in this study showed a significant Pearson linear correlation ($p < 0.01$) and a very strong coefficient of determination ($r = 0.831$), which agrees with the literature cited. In piles 2 and 3, the two borderline levels for ammonia production were exceeded at the beginning of the process, which justifies the greatest nitrogen losses, while pile 1 reached the limit pH when temperatures were below 50 °C.

3.4. GI and quality parameters of compost

The radicle length and germination index (GI) were significantly different ($p < 0.05$) for the composts from the three piles (Fig. 5). The compost from pile 3 favoured radicle growth (3.5 cm) and provided the highest GI (133%) when compared to the results of pile 1, pile 2 and control (distilled water). Pearson's linear correlation between GI and organic matter losses ($r = 0.902$) and final C/N ($r = -0.964$) were very strong ($p < 0.01$), which means that the best biodegradation observed in pile 3 positively influenced GI. The higher amounts of ash used in piles 2 and 3 may have influenced the length of the roots and GI, as they are composed of elements such as P, Ca, Mg, K, among others (Asquer et al., 2017). Considering the safety of the application of the composts, all could be used for agricultural purposes without risks since the GI presented by them were above 80% (Zhou et al., 2018). Organic compounds with GI between 80 – 100% have no phytotoxicity; above 100% are recognized as germination enhancers; and less than 50% are recognized as potentially phytotoxic (Bernal et al., 2009; Zucconi et al., 1981). Chiarelotto et al. (2019) obtained higher GI varying between 150 – 170% of composts from waste of the broiler production chain and tree pruning after 60 days of maturation.

Although all composts had satisfactory GI, the features of the compost of pile 1 and 2 did not meet some the parameters established by Brazilian Normative Instruction 25/2009, of the Ministry of Agriculture, Livestock and Supply (Brazil, 2009), for the sale of organic composts in the country (Table 6). The compost from pile 1 did not meet the parameters of moisture and C/N ratio and the compost in pile 2 did not meet only the C/N ratio regarding the Brazilian standard. Therefore, the maturation process is recommended until the reduction of the C/N ratio (Bernal et al., 2009) to acceptable levels and, later, the compost must be put in the sun in order to reduce excessive moisture. Meeting this parameter is crucial, as the application of composts with a high C/N ratio in the soil can reduce the performance of crops due to competition for oxygen and the possible sequestration of nitrogen from the soil to end the biodegradation of organic matter (Kebibeche et al., 2019). The only compost that met all safety parameters was that from pile 3, which reveals that the composition of this pile guaranteed a more efficient composting process.



(a)

(b)

Fig. 5. Radicle length (a) and GI (b) of organic compounds from the Pile 1 (C/N 35/1 and 0% recalcitrant bulking agents), Pile 2 (C/N 28/1 and 18% recalcitrant bulking agents), Pile 3 (C/N 25/1 and 28% recalcitrant bulking agents) and control (water). *Different letters represent statistically different treatments (Tukey with p<0.05)*

Table 6. Brazilian specifications for organic composts commercialization

Parameters	*IN n° 25/2009*	*Pile 1*	*Pile 2*	*Pile 3*
Moisture %)	≤ 50.0	60.5	36.6	33.8
TKN (%)	≥ 0.50	1.09	1.11	1.60
TOC (%)	≥ 15.0	31.3	24.4	25.8
pH	≥ 6.00	9.34	9.67	8.62
C:N ratio	≤ 20	29	22	16

Source: Adapted from Brazil (2009). Pile 1: C/N 35:1 and 0% recalcitrant bulking agents; Pile 2: C/N 28/1 and 18% recalcitrant bulking agents; Pile 3: C/N 25/1 and 28% recalcitrant bulking agents

4. Conclusions

The composting of municipal solid waste and agro-waste proved to be viable as a centralized treatment strategy. The balanced initial C/N ratio and the presence of the bulking agent positively affected the composting process and the quality of the final compost. Both balanced (25-28/1) and higher (35/1) C/N ratios resulted in a thermal profile (>60ºC over 7 days) reported to remove pathogens. In addition, the adequate thermal profile was not dependent of the recalcitrant bulking agent.

However, the balanced C/N ratio together with the recalcitrant bulking agent accelerated the degradation of the organic material, with degradation constant (k) increasing from 0.021 d^{-1} to 0.157 d^{-1}. Regarding the final compost quality, the GI was over 90% for all treatments, with the best operational condition being C/N of 25/1 and 28% structuring bulking agent, with GI of 133%.

This condition resulted in quality parameters in accordance with the national regulation for the final compost commercialization.

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