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Aeration frequency on accelerated composting of animal carcasses

Frequência de aeração em compostagem acelerada de cadáveres de animais

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ABSTRACT

Rotary drum reactors (RDRs) for accelerated carcass composting are being installed in animal production units as an alternative for the disposal of pig and poultry carcasses in Brazil. The aim of the present study was to investigate the influence of aeration frequency on gas emissions (CO_2-C, CH_4-C, NH_3-N and N_2O-N) during composting of pig and poultry carcasses in RDRs. RDRs with a volume of 3.6 m^3 (50% useful volume) were used. Aeration time was 24 minutes. Four intervals between aeration periods were tested (treatments) as follows: 1 hour (T1), 2 hours (T2), 3 hours (T3) and 4 hours (T4). Gas emissions were continuously monitored using a photoacoustic gas monitor (INNOVA 1412). Temperature was monitored using iButtons mixed with the biomass. Mathematical models of CO_2-C and NH_3-N emissions relative to the observed biomass temperature were proposed. Biomass temperature was affected by the treatments. The highest aeration frequency had the shortest thermophilic phase (>50 °C). No significant differences in total gas emissions were observed between treatments ($p>0.05$). CO_2-C and NH_3-N emissions were better fitted by non-linear models ($R^2=0.75$ and $R^2=0.78$, respectively). A minimum 2-hour interval should be adopted between aeration periods of 24 minutes to guarantee a longer thermophilic phase and elimination of possible pathogenic contaminants.

Index terms: Rotary drum reactor; poultry and pig; gas emission.

RESUMO

Como alternativa, para destinação de cadáveres de suínos e aves, no Brasil, estão sendo implantados nas unidades produtivas Reatores Cilindros Rotativos (RCRs) para compostagem acelerada dos cadáveres. O objetivo do presente estudo foi verificar a influência da frequência de aeração na emissão de gases (C-CO_2, C-CH_4, N-NH_3 e N-N_2O) em compostagem de cadáveres suínos e frangos em RCR. Foram utilizados RCR, com volume de 3.6 m^3 (50% de volume útil). Os intervalos estudados entre os períodos de aeração, o qual era 24 de minutos, foram de 4 tempos (tratamentos): T1 (1 hora); T2 (2 horas); T3 (3 horas) e T4 (4 horas). A emissão de gases foi monitorada continuamente utilizando equipamento fotoacústico (INNOVA 1412). A temperatura foi monitorada com uso de *ibuttons* misturados a biomassa. Foram propostos modelos matemáticos que representassem a emissão de C-CO_2 e N-NH_3 em função da temperatura observada na biomassa. Foi verificado que a temperatura da biomassa é afetada pelos tratamentos, quanto maior a frequência, menor será o período na fase termofílica (>50 °C). As emissões totais dos gases avaliados não apresentaram diferença ($p>0.05$) entre os tratamentos. Os modelos que melhor representaram a emissão de C-CO_2 e N-NH_3 foram não lineares, R^2=0.75 e 0.78, respectivamente. Por fim, contata-se que seja utilizado no mínimo duas horas de intervalo entre os períodos de 24 minutos de aeração, para garantir um melhor intervalo de tempo de repouso da biomassa na fase termofílica e eliminação de possíveis contaminantes patogênicos.

Termos para indexação: Reator cilindro rotativo; frangos e suínos; emissão de gases.

INTRODUCTION

The high poultry and pig production in Brazil generates a significant number of carcasses resulting from routine deaths in animal production systems. For example, 84 thousand tons of pig carcasses are estimated to be produced per year (Caron et al., 2018). These carcasses should be disposed of in a biologically safe manner (Cummins; Wood; Delaney, 1994) because otherwise they may result in environmental (Kalbasi-Ashtari; Schutz; Auvermann, 2008) and public health risks.

Some of the main methods of carcass disposal are burying in well or trenches and incineration, which do not allow the use of the material resulting from the treatment; composting (Blake; Donald, 1992; Caron et al., 2018; Cummins; Wood; Delaney, 1994), dehydration and industrialization (flour production) (Caron et al., 2018), in which the material originated in the treatment

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can be reused for different purposes. Composting is a well-established method of organic waste treatment (Ahn; Richard; Glaville, 2008; Oliveira; Higarashi, 2006; Oliveira et al., 2015), and it is based on aerobic degradation of organic matter via chemical and microbial reactions (Bernal; Alburquerque; Moral, 2009; Cáceres; Malinska; Marfà, 2018) without the need of adding microorganisms to the process (Tran; Mimoto; Nakasaki, 2015). Composting mostly generates carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which are greenhouse gases (GHGs), as well as ammonia (NH_3) (Arriaga et al., 2017; Chowdhury; Neergaard; Jensen, 2014b; Wang et al., 2018; Zeng et al., 2018). The biomass is converted into a biologically stable material (Kim et al., 2017) with fertilising power (Bernal; Alburquerque; Moral, 2009; Kim et al., 2017) that can be used as organic compost in agriculture (Oliveira; Higarashi, 2006).

The composting process as a method of eliminating animal carcasses can be considered one of the most ecologically correct alternatives for carcass disposal, allowing the elimination of animals throughout the year at low cost (Price; Carpenter-Boggs, 2008). Mukhtar et al. (2004) indicate that animals can be cut into smaller or even comminuted sizes, facilitating biodegradation reactions.

Morrow et al. (1995) studied the composting process of pig carcasses, verifying the safety of this method for biological contaminants. The authors found that the composting process disintegrated most carcasses, including most of the bones, and reached enough temperatures to kill all Erysipelothrix rhusiopathiae and pseudorabies, partially eliminating Salmonella.

Due to the practicality of composting, it is increasingly used more as an alternative for the disposal of dead animals (Bass, 2012). Most pig and poultry production farms in Brazil use pile composting for carcass disposal. However, this method is unfeasible for large producers due to the substantial amount of waste, which requires a sizeable area and considerable labour for its preparation and maintenance because the process requires months to be completed (Bass, 2012).

As an alternative, in-vessel composting systems using rotary drum reactors (RDRs) are being adopted for accelerated composting (Fillingham et al., 2017; Kalamdhad; Kazmi, 2009). Composting time in RDRs is reduced due to periodic biomass aeration, which is achieved by turning the drum and, thus, mixing the degrading material (Bhatia et al., 2013; Fernández et al., 2010; Fillingham et al., 2017; Hazarika et al., 2017; Kalamdhad; Kazmi, 2009; Singh et al., 2009; Singh; Kalamdhad, 2013; Rodríguez et al., 2012). In addition, the use of RDRs decreases labour time because of the ease of their operation (Fillingham et al., 2017).

However, there is little information about the operating conditions of RDRs, especially for reactors with large volume capacity. Most studies about composting in RDRs have been performed using laboratory-scale reactors with reduced volumes of 100 L (Fernández et al., 2010; Rodríguez et al., 2012), 250 L (Kalamdhad; Kazmi, 2009; Kalamdhad; Pasha; Kazmi, 2008), 500 L (Hazarika et al., 2017) and 550 L (Singh; Kalamdhad, 2013).

An important factor for good efficiency of this type of reactor is the frequency of drum rotation, i.e., the rest interval between turning, responsible for biomass mixing and aeration during composting (Rodríguez et al., 2012). The aim of the present study was to evaluate the effects of different aeration frequencies on biomass temperature and gas emissions during composting of pig and poultry carcasses and, to construct mathematical models that correlate the parameters temperature and emission of gases.

MATERIAL AND METHODS

Experiments

The experiments occurred between November/2016 and January/2017, carried out at Embrapa Swine and Aves (Concordia, Brazil: 27° 18’ 46’’S, 54° 59’ 16’’W). The research was carried out in two replicates of the treatments, using carcasses of different animal species for each replicate: I) accelerated composting of pig carcasses; II) accelerated composting of poultry carcasses.

The study was performed in two replicates due to the volume of the reactor in commercial size, which requires a large number of animals and substrate for composting. The study consisted in evaluating 4 treatments regarding the time in which the reactor remains at rest between the aeration periods (drum rotation). The times interval between the aeration periods studied were: Treatment 1 (T1): 1 hour; Treatment 2 (T2): 2 hours; Treatment 3 (T3): 3 hours; Treatment 4 (T4): 4 hours. Drum rotation time was 24 minutes for all treatments at 0.16 rpm. Sawdust, a by-product of the local wood industries, was used as the carbon source and bulk agent.

In the first replica, where these treatments were evaluated for accelerated composting of pig carcasses, a carcass mass:sawdust ratio of 0.63:1 was used for all treatments. In the second replicate, in which the same treatments were repeated, but with accelerated composting of poultry carcass, a carcass of poultry:sawdust ratio of 2:1 was used for the 4 treatments studied. Table 1 shows the physical-chemical characteristics of the animal carcasses and sawdust used in each of the replicates. For each replica, the characterization of the carcasses used in each treatment is presented, showing small variations among the treatments due to the heterogeneity of the carcasses. Also, the characteristics of sawdust are presented which, because it is more homogeneous, did not make it necessary to characterize it for each treatment. Finally, the biomass mixture (animal carcass + sawdust) used in each treatment is presented, the biomass characteristics being the result of the weighted average between the carcass and sawdust characteristics used. Carcasses were previously ground, homogenised and weighed, and they were manually added to the reactors mixed with sawdust, which was also weighed.

Reactors

Four reactors were used for each experimental stage (replicate), and one was used for each treatment. The RDRs were made of carbon steel with a length of 1.7 m, diameter of 2.3 m and total volume of 3.6 m^3. Fifty percent of the useful volume of the RDRs was used for the biomass, and the control of the rotation frequency was automated. A schematic diagram of the reactor is presented in Figure 1.

The reactors were equipped with fans that worked intermittently during the experiments, ensuring air renewal inside the reactors and contributing to biomass aeration. The air flow rate ($m^3.h^{-1}$) in each reactor was as follows: T1) 290.82; T2) 216.44; T3) 226.21; and T4) 262.17.

Physicochemical analyses

Physicochemical analyses of the material were performed at the Laboratory of Physicochemical Analysis of Embrapa Swine and Poultry. Animal carcass (pig and poultry) samples were collected during carcass grinding for carcass characterisation. Ten subsamples were collected and mixed, and four samples of approximately 1 kg were collected from the mixture and analysed. The samples were frozen and freeze-dried using a JJ Científica LJI-030® freeze drier. All biomass samples collected from the RDR during the experiment were collected at the end of drum rotation to ensure proper mixing of the material. Ten subsamples were collected from each reactor from different points inside the reactor, mixed and homogenised, and one sample was then collected from the mixture and sent to the laboratory.

Table 1: Materials added to each of the four reactors (n=2, Laboratory error<5%).

Replica	Material	Treat	NM (kg)	DM (%)	N (%)*	C (%)*	K (mg/kg)*	pH
I	Pig carcass	T1	188	28.41	8.99	55.0	8954.59	5.29
		T2	188	31.67	11.07	61.80	8929.95	6.25
		T3	188	30.52	10.28	59.44	9376.98	5.32
		T4	188	31.45	10.42	54.95	12411.12	5.51
	Sawdust	-	300	55.94	0.160	47.76	909.25	5.65
	Mix (Pig Carcass + Sawdust)	T1	488	45.33	2.30	49.52	4008.68	5.51
		T2	488	46.59	2.79	51.15	3999.19	5.88
		T3	488	46.14	2.60	50.58	4171.41	5.52
		T4	488	46.50	2.64	49.5	5340.30	5.59
II	Poultry Carcass	T1	300	34.82	7.80	56.22	6479.04	5.85
		T2	300	34.44	9.15	52.33	8170.73	5.78
		T3	300	35.61	9.35	55.46	7346.25	5.85
		T4	300	34.83	8.34	55.11	7499.28	5.78
	Sawdust		300	54.88	0.13	47.89	352.42	5.79
	Mix (Poultry Carcass + Sawdust)	T1	600	44.85	3.97	52.05	3415.73	5.78
		T2	600	44.66	4.64	50.11	4261.58	5.75
		T3	600	45.24	4.74	51.67	3849.34	5.78
		T4	600	44.85	4.23	51.50	3925.85	5.75

*On dry basis.

NM (natural matter); DM (dry matter); N (nitrogen); C (carbon); K (potassium).

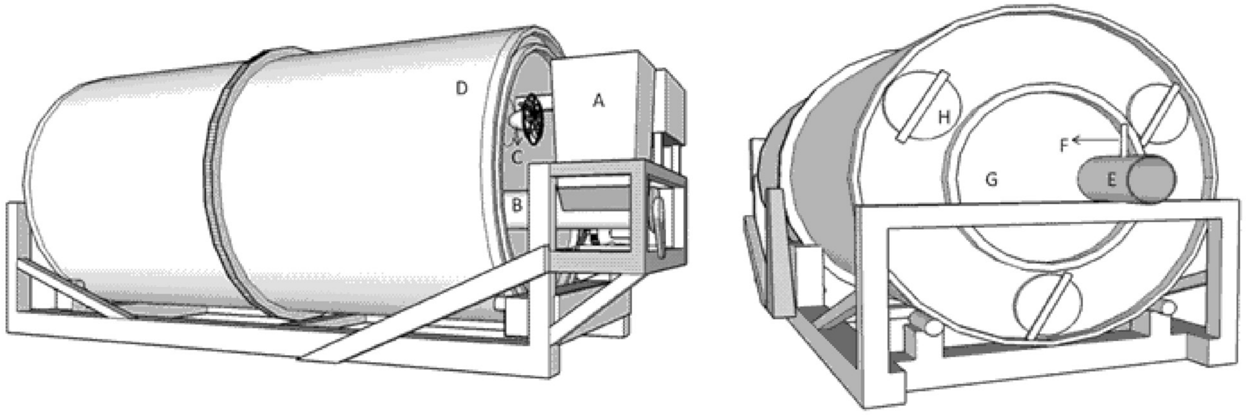

Figure 1: Rotary drum reactor; (A) Feeding compartment; (B) Helical conveyor that transfers the material into the reactor; (C) Ventilation system and air inlet; (D) Rotary drum; (E) Air outlet; (F) Air outlet for analysis; (G) Fixed lid; and (H) Portholes for biomass removal.

The following physicochemical parameters were analysed in the laboratory: pH, dry matter (DM), carbon (C), nitrogen (N), nitrogen nitrate (N-NO$_3^-$), nitrogen nitrite (N-NO$_2^-$), nitrogen and potassium (K). pH was determined by potentiometry. DM was determined by heating to 105°C for 18 hours. K was determined according to the Association of Official Analytical Chemists (AOAC, 1995). C and N concentrations were determined using a Thermo-Scientific™ Flash 2000 CHNS/O elemental analyser. O N-NO$_3^-$and N-NO$_2^-$ were determined according to the official procedure APHA 4500- as described by the American Public Health Association (APHA, 2012). All analyses were performed in duplicate, and only errors lower than 5% were accepted.

Biomass temperature during composting was determined by placing four iButton thermometers in each reactor, which were mixed with the biomass, and the thermometers recorded the temperature every 30 min. Because it was not possible to determine the position of the iButtons inside the RDRs, daily temperatures were estimated as the average maximum temperatures recorded daily by the iButtons.

Gas emissions

RDR outlet air was collected continuously from the air outlet tube at intervals of approximately 5 minutes for each treatment. External air samples were collected at a single point of the external environment (inlet air). The following gases were evaluated in the inlet and outlet air: CO_2, CH_4, NH_3 and N_2O. Automated gas monitoring was performed using a multipoint sampler INNOVA 1309 coupled to a photoacoustic analyser INNOVA 1412 (Lumasense Technologies, Denmark).

Gas emissions during composting were determined as the difference between inlet and outlet gas concentration (Angnes et al., 2013) using the following Equation 1:

$$E_i^m = Q \times (C_{i,out}^m - C_{i,in}^m) \qquad (1)$$

where $E_i^m = (\mathrm{mg.m^{-3}})$ is C emissions (as CO_2-C and CH_4-C) and N emissions (as NH_3-N and N_2O-N); $Q(m^3.h^{-1})$ is the outlet flow rate; $C_{i,out}^m\,(\mathrm{mg.m^{-3}})$ is the outlet concentration; and $C_{i,in}^m\,(\mathrm{mg.m^{-3}})$ is the inlet concentration. Emission values for each gas were presented as the ratio between median daily gas emissions and carcass mass.

Statistical analysis

Biomass composition and mean daily maximum temperature were analysed using repeated measures analysis, considering the effects of block (pig and poultry carcasses), treatment, composting time, interaction between treatments, and 16 types of variance and covariance matrix structures, using PROC MIXED in Statistical Analysis System© (SAS, 2012). The structure used for analysis was selected based on the lowest Akaike Information Criterion (AIC). Restricted maximum likelihood estimation was used. When significant differences were detected by the F test, a protected t-test was used to compare the treatments ($p \leq 0.05$).

A total of 27 linear and non-linear models were fitted to the experimental data to evaluate the effect of temperature on CO_2-C and NH_3-N emission. The analyses were performed using the GENMOD and NLMIXED procedures in SAS (2008). The best models were selected based on the AIC. Coefficients of determination (R^2)

were calculated for all models. All models are valid for a biomass temperature range from 19 °C to 72 °C.

For estimated gas emissions using mass balance, a variance analysis of the model was performed considering block (pig and poultry carcasses) and treatment effects.

The results presented in the present study are the mean adjusted for least squares between the two replicates for each of the treatments.

RESULTS AND DISCUSSION

Temperature and pH

Temperature curves characteristic of composting processes, presenting mesophilic, thermophilic, cooling and maturation or curing phases, were observed (Luo et al., 2014; Singh; Kalamdhad, 2013). All treatments reached the thermophilic phase (>50 °C) on day 3, indicating rapid microbial activity (Kalamdhad; Kazmi, 2009).

During composting, temperature is recommended to remain within the thermophilic range long enough to eliminate all pathogens present in the degrading material. In the present experiment, the temperature remained within the thermophilic range for 4, 8, 11 and 11 days for treatments T1, T2, T3 and T4, respectively. Therefore, higher turning frequencies resulted in less time in the thermophilic range because more frequent aeration speeds up the composting process (Rodríguez et al., 2012) and promotes heat dissipation.

The maximum biomass temperatures were 61.05 ºC (day 5), 62.71 ºC (day 6), 69.83 ºC (day 7) and 69.81 ºC (day 7) for T1, T2, T3 and T4, respectively. These values were higher than previously reported maximum temperatures of 58 °C (Kalamdhad; Kazmi, 2009) and 60 °C (Singh; Kalamdhad, 2013). This difference may have been due to the small volume of the RDRs used in the previous studies (250 L and 550 L, respectively), which promoted energy dissipation.

Comparing the temperature profile among the four treatments, the temperature in T1 was significantly different from T3 and T4 between days 7 and 14 ($p<0.05$) and from T2 between days 8 and 14. No significant differences in temperature were observed between T2 and T3 ($p>0.05$), and a significant difference between T2 and T4 was only observed on day 14. No significant differences were observed between T3 and T4 ($p>0.05$) during the entire experiment.

The pH behaviour was also characteristic of composting processes (Figure 2b) (Fernández et al., 2010). The pH increased to alkaline values in the beginning of composting, indicating that the acids produced in the beginning of the degradation process were quickly consumed (Jiang et al., 2015), and then decreased to values close to neutral, which is characteristic of the biological process (Fernández et al., 2010). Also, the decrease of the pH at the end of the composting can be related to the nitrification process, caused by a release of H^+ during this related process and the low capacity of buffering of the biomass (Cáceres et al., 2016; Cáceres et al., 2018).

The pH of the mix was initially 5.7, 5.82, 5.66 and 5.66 for T1, T2, T3 and T4, respectively, reaching maximum values of 8.45 (T1), 8.36 (T2), 8.32 (T3) and 8.30 (T4) followed by final values of 7.15 (T1), 7.25 (T2), 6.91 (T3) and 7.11 (T4) at the end of the composting process. Significant differences between treatments were only observed between T1 and the remaining treatments on day 9 ($p<0.05$).

CO_2-C and CH_4-C emission

CO_2-C emissions during composting results from biochemical reactions by the anaerobic microbiota. T1 presented higher daily CO_2-C emissions than the remaining treatments in the beginning of the composting process, reaching values higher than 17500 $mg.kg_{carcass}^{-1}.d^{-1}$ (Figure 3a). This result may be explained by the higher turning frequency, which promoted microbial activity and the resulting high gas production. For the remaining treatments, CO_2-C emissions also peaked in the beginning of the composting process (T2, 9881.06 $mg.kg_{carcass}^{-1}.d^{-1}$; T3, 13033.96 $mg.kg_{carcass}^{-1}.d^{-1}$; and T4, 12023.51 $mg.kg_{carcass}^{-1}.d^{-1}$) and then decreased until the end of the experiment. This result was in agreement with previous reports that CO_2 emissions are highest during the first stages of composting (Ahn et al., 2011; Arriaga et al., 2017; El Kader et al., 2007; Wang et al., 2014) due to high temperatures, which results in higher emissions during the thermophilic phase (Wang et al., 2014).

Total CO_2-C emissions were not significantly affected by the treatments (0.0968, 0.0847, 0.0853 and 0.1005 $kg.kg_{carcass}^{-1}$ for T1, T2, T3 and T4, respectively). Although T1 presented the highest daily emissions in the beginning of the composting process, the remaining treatments presented longer thermophilic phases, resulting in similar total losses for all treatments.

Comparing the treatments throughout the experiment, aeration frequency significantly affected CO_2-C emissions, resulting in significant differences between T1 and the remaining treatments on day 5 ($p<0.05$). On days 6, 9, 11, 12 and 13, significant differences were only observed between T1 and treatments

T2 and T4. Significant differences in CO_2-C emissions between T2 and T4 were only observed on day 5. Zeng et al. (2018) observed no significant differences ($p>0.05$) in CO_2-C and CH_4-C emissions among treatments with different aeration intervals, which may have been due to the fact that the aeration intervals tested by these authors were shorter (10, 30 and 50 minutes as well as a treatment with continuous aeration) than in the present study.

Although CH_4 is characteristic of anaerobic processes, it can also be generated during composting due to formation of small anaerobic zones, resulting from high O_2 demand during biodegradation (Hazarika et al., 2017). The highest CH_4-C emissions for T1 (215.08 $mg.kg_{carcass}^{-1}.d^{-1}$), T2 (91.58 $mg.kg_{carcass}^{-1}.d^{-1}$) and T3 (143.97 $mg.kg_{carcass}^{-1}.d^{-1}$) was observed on day 4, and the highest CH_4-C emissions for T4 (110.44 $mg.kg_{carcass}^{-1}.d^{-1}$) was observed on day 5. Significant differences in daily CH_4-C emissions ($p<0.05$) between T1 and the remaining treatments were only observed on day 6.

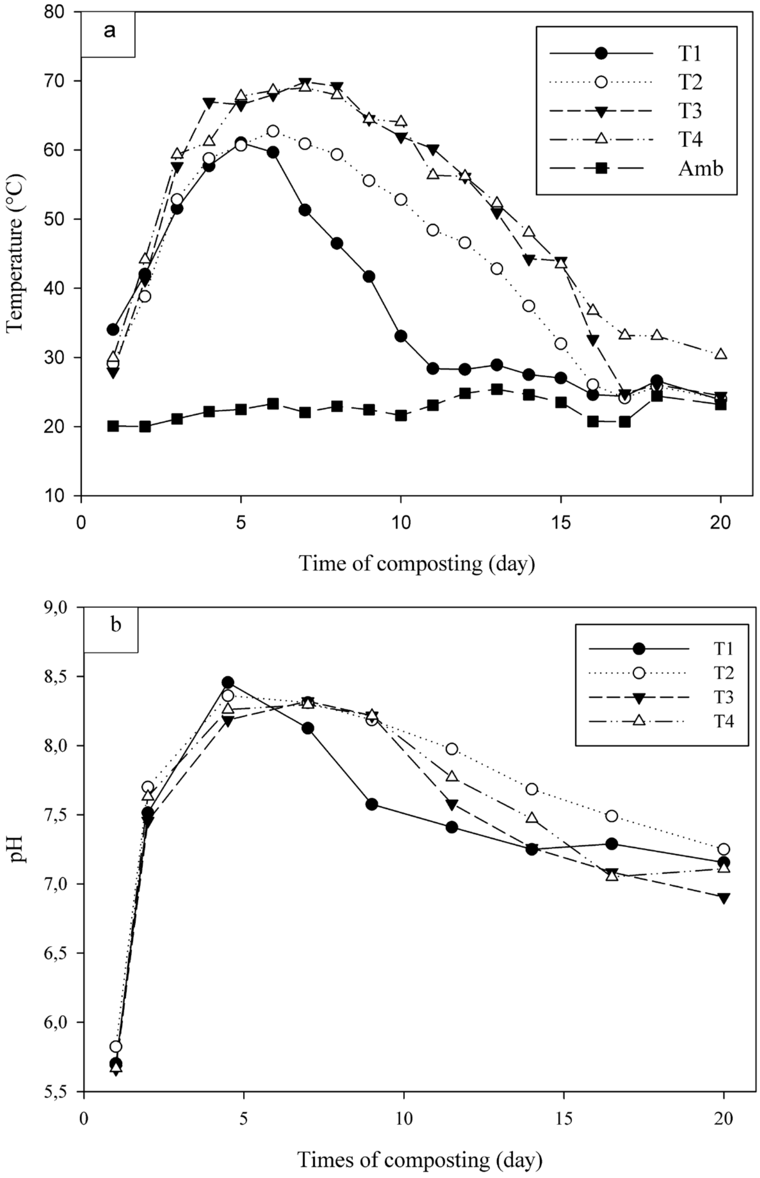

Figure 2: Temperature (a) and pH (b) during the evaluation period.

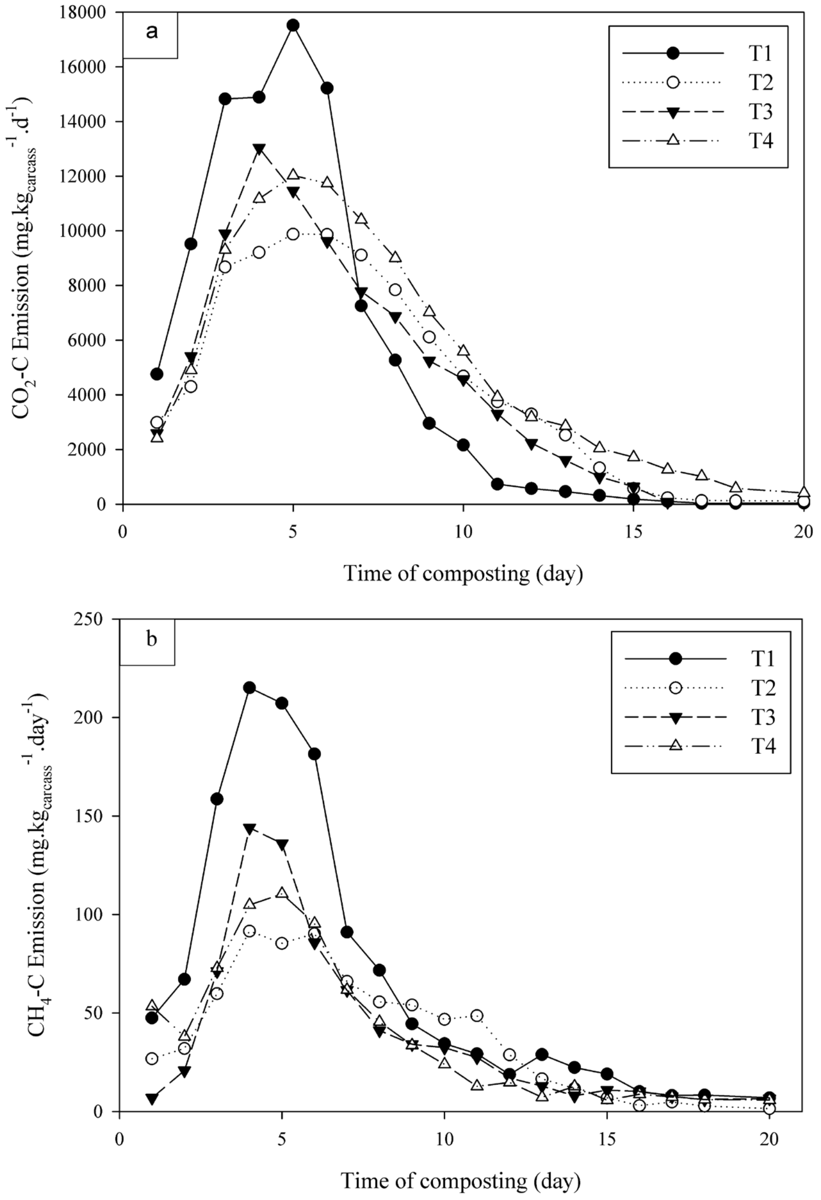

Figure 3: CO_2-C emissions (a) and CH_4-C emissions (b).

The highest CH_4-C emissions were observed during the thermophilic phase when microbial activity was higher, resulting in higher oxygen consumption, thereby promoting the creation of anaerobic zones. This phenomenon was also observed in a previous study (Chowdhury; Neergaard; Jensen, 2014b).

Although T1 was the treatment with highest number of rotations, it presented the highest total CH_4-C emissions (1270 mg.kg$_{carcass}$$^{-1}$) because aeration promotes CH_4-C release from the biomass (Zeng et al., 2018). The total CH_4-C emissions for the remaining treatments were 732.7 mg.kg$_{carcass}$$^{-1}$ for T2, 739.84 mg.kg$_{carcass}$$^{-1}$ for T3, and 720.64 mg.kg$_{carcass}$$^{-1}$ for T4, but they were not significantly different from T1.

From the total C mass measured as gas emissions (CO_2-C + CH_4-C), 98.7% (T1), 99.1% (T2), 99.1% (T3) and 99.2% (T4) resulted from CO_2-C emissions. These levels may be considered adequate because they indicate CH_4-C emissions of 1-4% of the initial C (Arriaga et al., 2017).

N_2O and NH_3 emission

The N present in the organic matter mainly originates from proteins, cellular compounds and DNA, and these are biodegraded during the first days of composting and transformed into NH_4^+, which may be converted to and volatilised as NH_3 (Cáceres; Malinska; Marfà, 2018) or converted to nitrite and nitrate (Wang et al., 2018).

NH_3-N emissions peaked on day 5 (Figure 4a), and it was highest at T1 (2049.62 $mg.kg_{carcass}^{-1}.d^{-1}$). Total N emissions was also highest at T1 (8493.86 $mg.kg_{carcass}^{-1}$), which may be explained by the higher turning frequency, promoting NH_3 volatilisation. Similarly, a previous study has shown that NH_3 loss is also highest for the compost pile with the highest number of turnings (Parkinson et al., 2004). Another study has also observed higher NH_3 emissions for a treatment with aeration compared to a treatment without aeration (Jiang et al., 2015). The high NH_3 emissions observed for all treatments during the first days of composting may be attributed to the high NH_4^+ availability, temperature and pH (Angnes et al., 2013; Chowdhury; Neergaard; Jensen, 2014b; Luo et al., 2014; Jiang et al., 2015), especially during the thermophilic phase because NH_3 is not soluble in water at high temperatures (Wang et al., 2018).

Although nitrogen losses due to N_2O-N emissions were lower, special attention should be given to this gas because it can potentially contribute considerably to the greenhouse effect. N_2O is mainly produced during nitrification/denitrification, originating from intermediate reactions. The highest N_2O emissions were observed on day 5 for T1, T2 and T4, and the highest N_2O emissions were observed on day 4 for T3 (Figure 4b). T1 presented the highest emissions (17.23 $mg.kg_{carcass}^{-1}.d^{-1}$). Maximum emissions for the remaining treatments were 9.45, 11.3 and 11.36 $mg.kg_{carcass}^{-1}.d^{-1}$ for T2, T3 and T4, respectively. Similarly to NH_3-N volatilisation, N_2O-N emissions practically zeroed after day 15. NO_3^- was not observed in the biomass during the experiment, indicating that nitrification was the main pathway of N_2O emission. This result has been previously observed (Chowdhury; Neergaard; Jensen, 2014a; Chowdhury; Neergaard; Jensen, 2014b; Zhu-Barker et al., 2017) because turning/aeration promotes nitrification and consequently N_2O emissions (Arriaga et al., 2017).

Significant differences in NH_3 emissions between T1 and the remaining treatments were only observed on day 6 (T2, T3 and T4; $p<0.05$), and significant differences in N_2O emissions between T1 and the remaining treatments were only observed on day 10 (T2 and T4; $p<0.05$). No significant differences were observed among T2, T3 and T4 ($p>0.05$). Zeng et al. (2018) tested different aeration intervals and observed no significant differences in N_2O and NH_3 emissions among treatments ($p>0.05$).

Mathematical models of NH_3-N and CO_2-C emissions

Because temperature is a parameter that is easy to control during composting, mathematical models were built to estimate gas emissions relative to the temperature of the material during biodegradation. Models were built for CO_2-C and NH_3-N emissions because these were the main gas losses of C and N, respectively, measured in the present study.

CO_2-C emissions relative to temperature was better fitted by a non-linear model, showing the same partitioning temperature for all treatments and different coefficients for each treatment (Table 2). The partitioning temperature was estimated at 31.27 °C. At this temperature, the model predicted constant CO_2-C emissions of 299.4 $mg.kg_{carcass}^{-1}$. Above this temperature, CO_2-C emissions may be estimated using a specific linear equation for each treatment.

NH_3-N emissions were also best fitted by a non-linear model with two partitioning temperatures (28.79 and 50.93 °C). NH_3-N emissions were constant under 28.79 °C (48.03 $mg.kg_{carcass}^{-1}$). At temperatures greater than 50.93 °C, there was a specific model for each treatment. Between these two temperatures, the emissions were best fitted by the same linear model for all treatments.

The behaviour of the CO_2-C and NH_3-N gas emissions models is presented in Figure 5. As previously discussed, T1 presented the most pronounced differences in gas emissions compared to the other treatments during the experiments. In the presented models, T1 stood out from the remaining treatments due to its higher slope.

Mass balance

Carbone (C) mass balance was determined to validate the composting process and determine the experimental error in gas emissions measurements. C mass balance was determined by calculating C gas emissions (GE) and C mass loss (ML). ML is the difference between the C biomass at the beginning and at the end of the composting process, and GE is the C mass calculated as the sum of CH_4-C and CO_2-C. Although N gas emissions (NH_3-N and N_2O-N) were also evaluated, N mass balance was not determined because N_2 emissions, resulting from denitrification and responsible for a part of the N loss, was not determined, which would impair the determination of errors using the mass balance.

The error between ML and GE was highest for T2 (25.82%) and lowest for T3 and T4 (≤2.5%) (Table 3). The highest error found was similar to that found for all treatments in a composting study by Arriaga et al. (2017), which was explained by heterogeneity between subsamples, a problem that was also observed in the present study. The overall mean ML for all treatments was 0.091 $kg.kg_{carcass}^{-1}$, and the mean GE was 0.097 $kg.kg_{carcass}^{-1}$ with a mean error of 14.09%. This error can be considered adequate and may due to possible experimental errors, especially to likely variations in the speed of air traversing the reactor caused by different distributions of the material inside the reactors following each turning, thereby resulting in ML variations throughout the day. Linear regression between ML and GE resulted in the following equation: GE = 1.059 × ML ($R^2 = 0.77$).

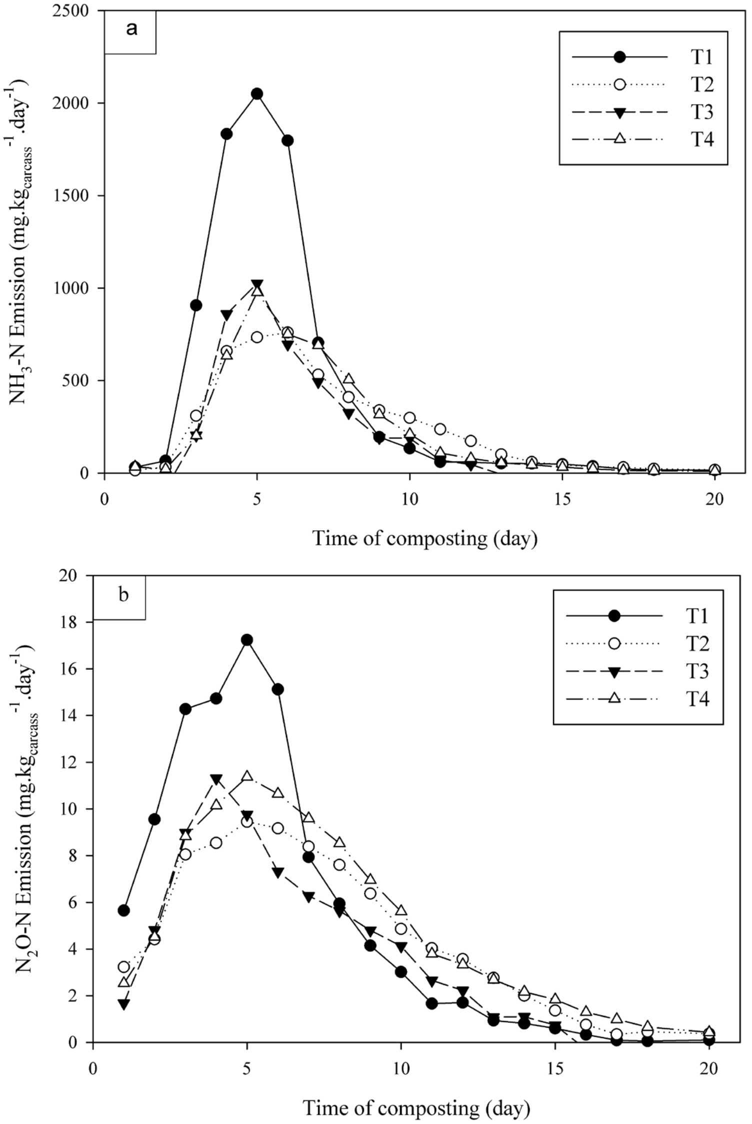

Figure 4: NH_3-N emission (a); N_2O-N emissions (b).

Table 2: Mathematical models for CO_2-C and NH_3-N emissions relative to temperature.

Gas	AIC	R^2	Proposed Model
CO_2-C	2455.25	0.75	$\hat{y}_{CO_2-C}=\begin{cases}299.4; if\ t\le 31.27\\ 430.98.t-13178.2; if\ t>31.27\ and\ Treat=T1\\ 325.98.t-9894.61; if\ t>31.27\ and\ Treat=T2\\ 309.30.t-9372.99; if\ t>31.27\ and\ Treat=T2\\ 296.97.t-8987.41; if\ t>31.27\ and\ Treat=T4\end{cases}$
NH_3-N	1757.1	0.78	$\hat{y}_{NH_3-N}=\begin{cases}48.03; if\ t\le 28.79\\ 5.09.t-125,40; if\ 28.79<t\le 50.93\\ 200.05.t-10055.2; if\ t>50.93\ and\ Treat=T1\\ 50.01.t-2413.33; if\ t>50.93\ and\ Treat=T2\\ 30.04.t-1396.16; if\ t>50.93\ and\ Treat=T3\\ 29.79.t-1384.56; if\ t>50.93\ and\ Treat=T4\end{cases}$

$\hat{y}_{CO_2-C}$: Estimated CO_2-C emissions ($mg.kg_{carcass}^{-1}.d^{-1}$); $\hat{y}_{NH_3-N}$: Estimated NH_3-N emissions ($mg.kg_{carcass}^{-1}.d^{-1}$); t: biomass temperature (°C); Treat: Treatment.

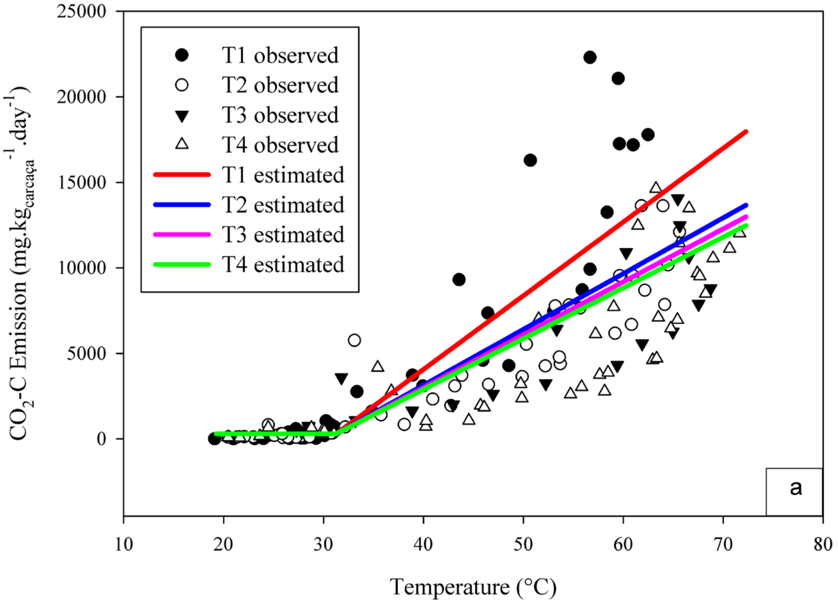

Figure 5: Mathematical models proposed for CO_2-C emissions (a) and NH_3-N emissions (b).

Continue...

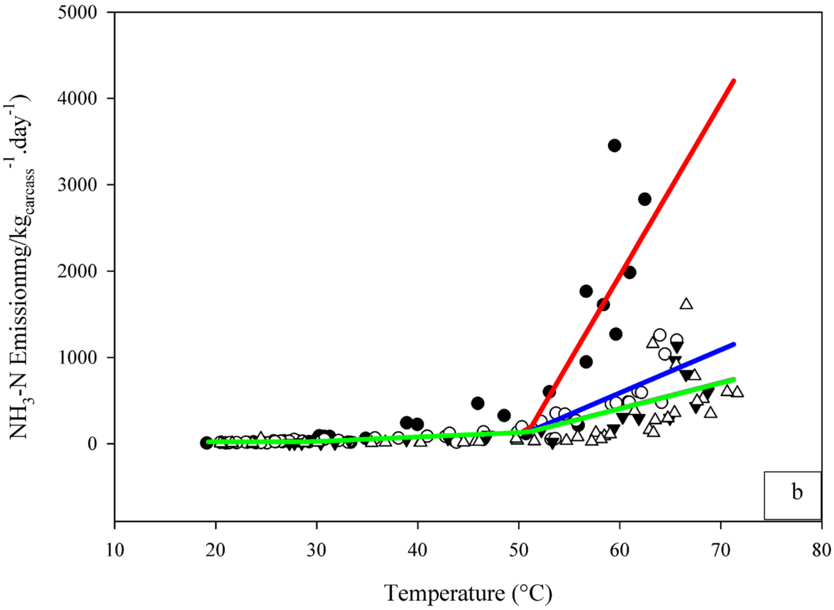

Figure 5: Continuation...

Table 3: Mass balance for carbon and potassium.

Treatment	ML (kg.kg$_{carcass}$$^{-1}$)	GE (kg.kg$_{carcass}$$^{-1}$)	C Error (%)	K Error (%)
1	0.084	0.098	19.76	19.62
2	0.081	0.085	25.82	14.48
3	0.099	0.86	2.49	18.54
4	0.099	0.101	2.50	12.28

ML: difference between C biomass at the beginning and at the end of the composting process; GE: C mass (CH_4-C + CO_2-C) measured by gas emission; C Error: (GE-ML)/GE; K Error: difference (in percentage) between K mass at the beginning and at the end of the composting process.

Although mass balance for non-volatile elements has not been determined in some composting studies (Arriaga et al., 2017; Mulbry; Ahn, 2014; Zhu-Barker et al., 2017), this parameter is important to check for possible sampling and subsampling errors in the collection of material for physicochemical analyses. In the present study, K mass balance was calculated and found to be lower than 20% for all treatments, which was considered satisfactory due to the heterogeneity of the composting material, especially due to the difficulty in characterising poultry and pig carcasses. A mean error of 14.48% was observed for K, a non-volatile element, for all treatments. This value was similar to those found in other studies of gas emissions during composting (Angnes et al., 2013; El Kader et al., 2007).

CONCLUSIONS

A minimum period of 2 hours between aeration times of 24 minutes resulted in a longer thermophilic phase. Total gas emissions were not affected by turning frequency. Therefore, turning frequency does not have to be considered when selecting total gas emissions. The proposed mathematical models are considered adequate to estimate CO_2-C and NH_3-N gas emissions during carcass composting based on the temperature of composting biomass.

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