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Determination of Kinetics Parameters for Composting Process of the Organic Fraction of Municipal Solid Waste Separated at Source

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Several mathematical models have been developed to describe the composting process. The degradation rate of the substrate is an important criterion to determine the effectiveness of the process and to design optimization strategies in composting. Kinetic models' development plays an important role in composting process management. The aim of this research was to estimate the kinetic parameters and to develop a kinetic model on the degradation process of organic fraction of municipal solid waste (OFMSW) separated at source in two independent composting facilities located in rural areas near to the city of Medellín (Colombia). The composts obtained showed adequate physical-chemical properties. Existent models based on first-order kinetics were selected and new values of model parameters were found by a nonlinear fitting procedure. The kinetic models of the composting of OFMSW included process parameters such as electric conductivity (EC), temperature and oxygen concentration. The developed model has been adjusted with experimental data obtained from two composting facilities located in different environmental conditions, which allowed a good prediction of the degradation rate of organic matter (OM). Kinetic models and data analysis proposed allowed a better understanding of transformation processes of OM during municipal solid waste composting in areas under tropical climate. The developed analysis could be used as a tool for composting simulation and optimization of process parameters.

1. Introduction

In last decades, the suitable management of municipal solid waste (MSW) became one of the major environmental challenges. Although the landfilling is one of the least recommended disposal methods according to the waste management and environmental sustainability criteria, it is still practiced in both, highly-developed and developing countries (Cuartas et al., 2018). However, the growing generation of MSW and the limited availability of resources in developing countries as in Latin America, lead to greater negative environmental impacts (Jara-Samaniego et al., 2017). Poorly managed MSW and open dumping represent a potential risk to human health and the environment (Inglezakis et al., 2017). In order to minimize the MSW generated worldwide, the development of waste management solutions, and technologies combining physical, chemical and biological treatments are needed.

The organic fraction of municipal solid waste (OFMSW) normally accounts for 40 - 70 wt% (Wei et al., 2017). Of all the OFMSW treatment methods, biological conversion has great potential from an environmental point of view. Properly managed, composting has many benefits regarding the carbon footprint, such as diverting waste from landfill sites and reducing greenhouse gas emission. The composting end-product could be used as an amendment to improve soil properties or as organic fertilizer in agricultural soils (Wong et al., 2017). However, efficient composting techniques should be developed to prevent environmental issues, increase the compost quality and maximize benefits.

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Composting is a complex biological treatment of OM under aerobic conditions, producing stabilized and sanitized valuable products (Wei et al., 2017). As a bioprocess, composting involves several physical, chemical and biological mechanisms, which depends on environmental factors. Ambient conditions cause significant variations on composting parameters and organic transformation (Zailani et al., 2017); processing time, pile size and degradation rate determine the cost-effectiveness of the process (Petric et al., 2012). The kinetic parameters and design of composting facilities must be optimized and aimed to increase the rate of degradation of the organic wastes (Baptista et al., 2010).

The degradation rate of OFMSW composting can be predicted using kinetic models, which are mainly related to process parameters such as temperature, OM content, moisture content, pH, oxygen, free air space, ammonia, carbon dioxide, C/N ratio and particle size (Petric et al., 2012). The kinetic model of OM decomposition is accepted to be a first-order kinetic equation for most of the biodegradable materials (Külcu and Yaldiz 2004). Few studies have assessed the composting procedures on the kinetic parameters (Faverial et al., 2016). The performance of composting depends on understanding the kinetics of biodegradation of the waste type under certain environmental conditions. The aim of this research was to apply kinetic models, to obtain the kinetic parameters and to fit the model suitable for degradation process of organic fraction of municipal solid waste (OFMSW) separated at source in two composting facilities located in rural areas near to the city of Medellín (Colombia).

2. Experimental

2.1 Composting materials

Composting experiments were carried out on a field scale at facilities located in two different places in rural areas near to the city of Medellín, Colombia. Site 1 is located in Altavista neighbourhood (6°13'18.24 N", 75°38'32.95"), an area of an average temperature of 22 °C, and altitude of about 1,600 m above sea level. Site 2 is located in Santa Elena neighbourhood (6°15'05.74 N", 75°25'58.69"), with an average temperature to 14 °C, and 2200 m above sea level of altitude. Both composting facilities were designed of a set of piles of 1.50 m by 1.50 m base, and 1.0 to 1.5 m height. The composting materials consisted of a mixture of OFMSW and garden waste on a 97:3 ratio, about of 1,300 kg in site 1 and 600 kg in site 2. The compost piles were turned over manually twice a week to ensure adequate aeration. During turnover, the material was weighted to determine the mass loss, and after the new pile was built and its new height was recorded.

2.2 Sampling and analysis

For seven weeks, sub-samples from nine different points of the composting pile were taken and homogenized to obtain an approximately 500 g composite sample. Temperature of the pile on each sample points was recorded before sampling. Composting material samples were stored in sealed bags and sent to the laboratory for analysis. The composting process took seven weeks. The conducted analytical methods for composting material analysis followed the NTC-5167 standard, which is a Colombian Standard based on ISO 7851:1983 for fertilizers and soil conditioners. Moisture content (M_C) was determined by dry oven technique at 105 °C for 12 h. Ash content was determined after burning in an oven at 550 °C for 4 h. Electrical conductivity (EC) and pH were determined in the 1:10 (w/v) aqueous extract. Total nitrogen was determined by Kjeldahl standard procedure. Phosphorus content was assessed colourimetrically by molybdovanadate method (Warwick et al., 2013). Cation exchange capacity (CEC) was determined with $BaCl_2$-triethanolamine. Total organic carbon (TOC) content was determined by Walkley-Black titration method. Bulk density was determined by adopting the mass per unit volume method (Ruggieri et al., 2009). Water retention capacity (WRC) was assessed by gravimetric analysis. The solid phase mineralization was determined by respirometric assay (Iannotti et al., 1994). Bacteria and fungi communities were assessed by culture media and serial dilution techniques (Saldarriaga et al., 2018).

2.3 Applied mathematical modelling

For the description of the OM as a function of time, a first order kinetic was used (Haug, 1993), where OM is the mass in kg of biodegradable volatile solids in a composting process, t is the time in days and k_T is the rate constant of reaction in d^{-1}.

$$\frac{d(OM)}{dt} = -k_T \cdot OM \tag{1}$$

In order to calculate the decomposition rate constant k_T, seven reported equations shown in Table 1 were applied to the experimental data. Where T is the process temperature (°C); M_c is the daily moisture content (% w.b.); C is the daily concentration of CO_2 in composting reactor (%), EC ($dS\ m^{-1}$), O_2 is the oxygen concentration (%), and a, b, c, d, f, g are constants.

Table 1: Selected equations of kinetic models

Model No.	Kinetics Model	Eq.	References
1	$k_T = a \cdot exp\left\{\left[(b \cdot T) + \left(c \cdot \frac{M_c}{T}\right)\right]\right\}$	2	Külcu and Yaldiz (2004)
2	$k_T = a \cdot exp\left\{b \cdot \left[\left(\frac{M_i - c}{d}\right) + \left(\frac{T - f}{g}\right)\right]\right\}$	3	Ekinci et al. (2001)
3	$k_T = \frac{\frac{a}{M_c}}{T - (C \cdot b)} \cdot exp\left\{\left[(T \cdot c) + \left(d \cdot \frac{M_c}{T}\right)\right]\right\}$	4	Külcu and Yaldiz (2004)
4	$k_T = a \cdot b^c \cdot exp\left\{\left[(c \cdot T) - \left(d \cdot \frac{M_c}{T}\right)\right]\right\}$	5	Külcu and Yaldiz (2004)
5	$k_T = a \cdot b^{O_2} \cdot exp\left\{\left[(c \cdot T) + \left(d \cdot \frac{M_c}{T}\right)\right]\right\}$	6	Petric et al. (2012)
6	$k_T = a \cdot exp\left\{\left[(b \cdot T) + \left(c \cdot \frac{O_2}{T}\right) - \left(d \cdot \frac{EC}{T}\right)\right]\right\}$	7	Petric et al. (2012)
7	$k_T = O_2^{(1-a)} \cdot b^{(T-23)} \cdot pH^c \cdot \left(\frac{M_c}{T}\right)^d$	8	Petric et al. (2012)

2.4 Kinetic parameters fitting

Equations shown in Table 1 were fitted to each composting site data through an algorithm developed in Scilab 6.0.1 software. The optimization subroutine fminsearch (based on the Nelder-Mead algorithm) was used to fit the kinetic models selected. The procedure is based on the stepwise non-linear regression by minimizing the average square relative error (ASRE). It is closely related to the regression or determination coefficient and it is defined by Eq(9). Where n is the number of experimental data, k_T^{exp} is the experimental constant kinetic value and k_T^{calc} is the value predicted by the Eq(9).

$$ASRE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{k_T^{calc} - k_T^{exp}}{k_T^{exp}}\right)^2 \qquad (9)$$

3. Results

3.1 Compost analysis

Compost quality is influenced by the composting procedure, climate and composting materials (Faverial et al., 2016). After seven weeks of evaluation of composting processes, it was found that the two final products comply with Standard legislation (NTC-5167). All the parameters values were in the optimum range of quality suggested for the agricultural use of compost (Gómez-Brandón et al., 2008) which guarantees a correct development of the composting process. The final product fulfilled NTC-5167 Standard and was packaged for commercialization. Table 2 shows the principal properties of the final composts.

The temperature ranged from 40 to 80 °C with a rapid activation of the degradation process. Site 1 and site 2 composting systems showed a similar trend in the temperature profile, with two noticeable thermophilic phases, produced by biological successions that occur throughout the composting processes, which allows material sanitization (Gómez-Brandón et al., 2008). The microbial analysis showed the absence of pathogenic microorganisms.

The Mc is related to a proper aeration during the composting process. In this study, Mc ranged from 35 to 60 wt.% which is consistent with the values published (Som et al., 2009). Water retention capacity (WRC) indicated that the material is suitable for use as solid organic amendment. Cationic exchange capacity (CEC) reached values greater than 30 cmol/kg, which indicated that both processes have significant values that guarantees the formation of highly oxidized compounds (Amir et al., 2008). C/N ratio in both, site 1 and site 2 showed a decrease to 10.7 and 9.71, which suggested an advanced stabilization of the composting material. There were insignificant differences between the two evaluated sites.

Table 2: Characteristics of the final composts

	Site 1	Site 2	NTC-5167
Density (kg/m^3)	0.16±0.00	0.15±0.00	< 0.6 g/cm^3
M$_c$ (wt. %)	34.7±0.06	31.2±0.06	< 35%
WRC (wt. %)	154.3±14.6	158.7±6.34	>100%
Ash (wt. %)	42.8±0.00	44.5±0.00	< 60%
EC (mS/cm)	5.28±0.29	5.56±0.00	-
pH	8.88±0.18	8.56±0.03	4 – 9
Total nitrogen (wt. %)	1.52±0.03	1.78±0.00	Report if >1%
TOC (wt. %)	16.2±0.24	17.3±0.04	>15%
CEC (cmol/kg)	44.2±1.74	47.1±0.14	> 30 cmol/kg
Phosphorus (wt. %)	0.53±0.01	0.55±0.01	Report if >1%
C/N ratio	10.7	9.71	-
Temperature (°C)	30	27	-
Respirometry (mg/CO$_2$)	0.14±0.04	0.11±0.09	-
Enterobacteriaceae (CFU/g)	30±0.04	12±0.00	< 1,000
O$_2$ (%)	0.47	0.37	-

3.2 Selected models and fitting of kinetic parameters

Experimental data from composting process in site 1 and site 2 were used to test the selected equations as a representative of first-order models shown in Table 1. The kinetic parameters were calculated with the procedure of minimizing the average square relative error (ASRE) described in the previous section. The fitted kinetic parameters are presented in Table 3, ASRE$_{orig}$ and ASRE$_{opt}$ represent the ASRE value calculated before and after fitting procedure respectively.

Table 3: Kinetic parameters fitted for the seven models in composting process

Model No.	Site	Kinetic parameters						ASRE$_{orig}$	ASRE$_{opt}$
		a	b	c	d	f	g		
1	1	1.18	0.05	-0.76				100.00	21.79
	2	0.20	-0.01	4.21				100.00	35.61
2	1	0.02	1.71	0.69	-0.38	0.81	0.57	98.86	75.01
	2	0.02	0.87	1.03	-0.37	-0.86	0.55	98.11	87.50
3	1	115.29	-7.63	0.09	-0.90			97.34	20.16
	2	2.51	-7.37	0.04	-7.59			96.91	32.39
4	1	0.31	0.89	0.07	0.38			99.95	21.47
	2	0.00243	0.84	0.00205	-8.54			99.89	33.88
5	1	0.19	0.65	0.08	0.26			99.89	21.50
	2	0.00243	0.60	0.00205	-8.54			99.86	33.88
6	1	0.00065	0.11	46.78	-43.05			98.68	1.21
	2	0.00009	0.14	55.75	-4.72			5.49×10^{23}	9.34
7	1	1.27	1.07	0.01	-0.15			99.52	21.23
	2	-0.39	1.01	0.89	-3.34			98.76	21.84

The algorithm implemented in Scilab (version 6.0.1) showed a good fit for all equations, notably improving all ASRE from the original, except for the Eq(2) proposed by Külku and Yaldiz (2004), which after the fitting still has high ASRE values, it was put aside from the analysis. The best-fit equation was the Model No. 6, which was proposed by Petric et al. (2012) and takes into account key parameters in composting processes such as temperature, O$_2$ availability for microbial activity and EC. Other studies have shown that these parameters are suitable in the degradation of MSW (Gómez-Brandón et al., 2008). Eq(1) to Eq(5) only consider the M$_c$ and temperature, although Eq(3) also considers the O_2 concentration. It is suggested to apply Eq(5) to Eq(7) because they considered EC, O_2 and pH variables which have been proven necessary for an adequate process and good final product (Saldarriaga et al., 2018). In a closed reactor when controlling all the variables, only the temperature and M_c end up affecting the process (Petric et al., 2012).

3.3 Application of the kinetic models to experimental data

The composting process and OFMSW degradation rate under tropical conditions need clearer understanding to improve the management of composting (Faverial, et al. 2016). In this study, real-scale composting data were analyzed and compared with the Eq(5) to Eq(7) raised by Petric et al. (2012) to obtain new values of kinetic parameters. Eq(10) and Eq(11) show the best-fit parameters for Eq(6) in both site 1 and site 2.

$$\mathrm{k}_T = 0.00065 \cdot exp\left[(0.11 \cdot T) + \left(46.78 \cdot \frac{O_2}{T}\right) - \left(-43.05 \cdot \frac{EC}{T}\right)\right] \tag{10}$$

$$\mathrm{k}_T = 0.00009 \cdot exp\left[(0.14 \cdot T) + \left(55.75 \cdot \frac{O_2}{T}\right) - \left(-4.72 \cdot \frac{EC}{T}\right)\right] \tag{11}$$

The new equations Eq(10) and Eq(11) showed a good fitting to selected data of OM degradation (Figure 2a and Figure 2c). Figures 2b and 2d shows the good fit between the experimental results and those of the model for the k_T in Eq(6).

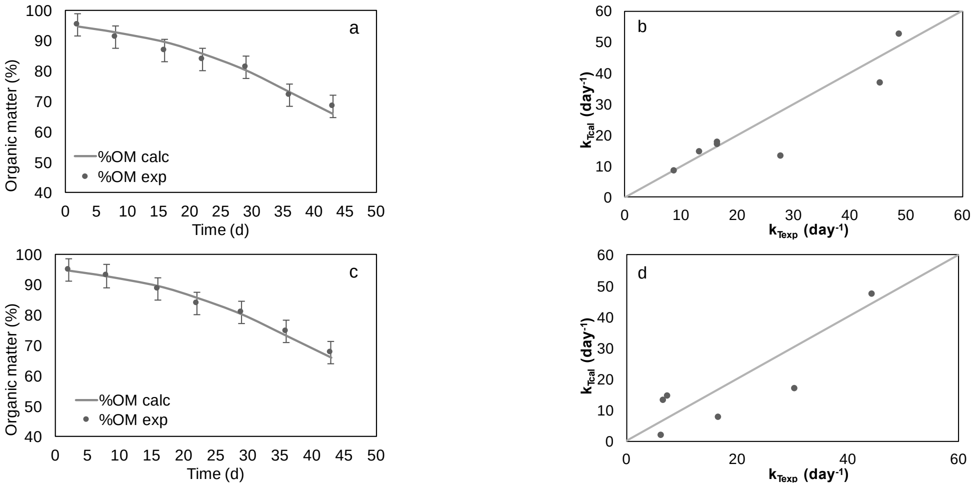

Figure 2. Kinetic parameters fitting, a.OM degradation during the process for site 1. b. Comparison between experimental and calculated k_T *for site 1. c. OM degradation during the process for site 2. d. Comparison between experimental and calculated* k_T *for site 2 process.*

From these results, it can be observed that the Eq(10) and Eq(11) that best represented the real conditions were those that took into account the oxygen, EC and temperature, which are considered as important parameters to carry out a good composting process. However, the differences between coefficients of Eq(10) and Eq(11) suggested that the process not only depends on the temperature, oxygen and EC. Other variables, like the amount of waste at the beginning of the process and the ambient conditions regarded to the location of composting facilities, should be added to the development of future kinetic models, in order to consider diffusional or physical limitations (Faverial, et al. 2016).

4. Conclusions

Existing kinetic models were tested to calculate the rate of OM degradation at two sites in a city with a tropical climate. The kinetic parameters were adjusted by a nonlinear fitting procedure. The developed model has been adjusted with experimental data and the selected model showed very good agreement during the composting process. The Eq(10) and Eq(11) show the good behavior of the composting process and give an approximation to the kinetic degradation that occurred during the seven weeks of processes, which shows the good management of the system and a final product, suitable to be applied to the soil. According to the kinetic parameters it could be suggested that it is necessary to include new factors such as pH, M_c and TOC for a better fitting of kinetic equations in order to take into account external variables that could be crucial to generalize coefficients as those of Eq(10) and Eq(11). The final adjusted models for the experimental data in each site allowed a good prediction of the degradation of OM through time for its specific environmental conditions. The selected models could be used as a tool for composting simulation and optimization of process parameters.

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