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Mathematical modeling for monitoring and controlling aerobic degradation conditions of the organic fraction of urban solid waste

Modelamiento matemático para el monitoreo y control de las condiciones de degradación aerobia de la fracción orgánica de los residuos sólidos urbanos

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Abstract

Compost has applications in agriculture and environmental restoration. Therefore, it is important to evaluate control parameters that help accelerate and improve the aerobic degradation and stabilization processes of organic waste. A mixture of pruning waste, organic fraction of municipal solid waste, paper, and sawdust was subjected to an aerobic degradation process using mature and stabilized compost from the Bordo Poniente composting plant in Mexico City at different aeration rates (0.064, 0.125, 0.201 and 0.392 L air min^{-1} kg^{-1} dry matter) in laboratory-scale bioreactors for 140 h. On-line monitoring of CO_2 production and O_2 consumption and their setting to mathematical models allowed to select the conditions to obtain a stable compost, as well as to analyze the concentration of trehalose, citric acid, glucose, xylose, erythritol, acetic acid, fructose, and the production of oxalic acid during the degradation process. Germination rates higher than 80% were obtained in the growth of *Lactuca sativa* seeds in organic waste extracts after aerobic degradation. A vkgm of 0.392 L air kg^{-1} min^{-1} DM is suggested as a strategy to obtain a compost free of phytotoxic compounds for the application of compost in agriculture or environmental restoration and a null maintenance coefficient.

Keywords: Organic fraction of municipal solid waste, aerobic degradation, compost, solid-state fermentation, phytotoxicity.

Resumen

La composta tiene aplicaciones en la agricultura y la restauración ambiental. Es por ello, importante evaluar parámetros de control, que ayuden a acelerar y mejorar los procesos aerobios de degradación y estabilización de residuos orgánicos. Una mezcla de residuos de poda, fracción orgánica de los residuos sólidos urbanos, papel y aserrín fue sometida a un proceso de degradación aerobia usando composta madura y estabilizada proveniente de la planta de compostaje de Bordo Poniente de la Ciudad de México a diferentes tasas de aireación (0.064, 0.125, 0.201 y 0.392 L aire min^{-1} kg^{-1} materia seca) durante 140 h. La monitorización en línea de la producción de CO_2, consumo de O_2 y su ajuste a modelos matemáticos permitió seleccionar las condiciones para obtener un compost estable, así como analizar la concentración de trehalosa, ácido cítrico, glucosa, xilosa, eritritol, ácido acético, fructosa y la producción de ácido oxálico durante el proceso. Logrando índices de germinación superiores al 80% en semillas de *Lactuca sativa*. Se sugiere un vkgm de 0.392 L aire kg^{-1} min^{-1} ms como una estrategia para obtener una composta libre de compuestos fitotóxicos para la aplicación de la composta en la agricultura o restauración ambiental y un nulo coeficiente de mantenimiento.

Palabras clave: Fracción orgánica de los residuos sólidos urbanos, degradación aeróbica, compost, fermentación en medio sólido, fitotoxicidad.

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1 Introduction

In Mexico, according to the most recent statistic published in 2020, the generation of municipal solid waste (MSW) was 109 145.75 tons per day, which represents a generation of 0.87 kg per inhabitant per day, higher than the reported world average of 0.74 kg per inhabitant (Escamilla-García *et al*., 2020). In Mexico City, much of the MSW is organic (~47%), consisting mainly of food and yard waste, and is usually processed through composting. Currently, Mexico City has eight composting plants with a collective capacity to process 923.42 tons of organic waste per year (Romero De León *et al*., 2021). To achieve environmental sustainability, it is of utmost importance to consider further developing efficient aerobic degradation processes to reduce the volume of organic waste deposited in landfills, minimize the impacts generated by the production of leachates and greenhouse gases, and favor the reuse of waste. In composting processes, aeration is one of the essential parameters to accelerate and improve the degradation and stabilization process of the organic fraction of municipal solid waste (OFMSW) (Ma *et al*., 2021). Oxygen is essential for microbial activity. The main aeration methods in biological processes are: mixing, natural convection, and forced aeration (Rasapoor *et al*., 2016). In the composting process, oxygen consumption and growth rate are associated because oxygen is a substrate in organic matter degradation reactions. Additionally, the increase in growth rate will generate an increase in metabolic heat (DeLong *et al*., 2017). Therefore, the aeration rate in the bioreactor is one of the main factors to consider. In solid-state fermentation, the aeration rate can be expressed as the airflow rate per unit mass of substrate, obtaining a scale-independent variable, i.e., volumes of air per kilogram of substrate per minute (vkgm) (Rodriguez-Fernandez *et al*., 2012). The use of vkgm in the composting process has been proposed as a uniform unit to quantify aeration rates (Ma *et al*., 2021). A minimum oxygen concentration of 5% within the compost pile pore space is necessary for aerobic conditions (Rasapoor *et al*., 2009). Guo *et al*. (2012) noted that the aeration rate is the main factor influencing compost stability; when aeration rates do not provide an oxygen content above 10 % (v/v) the product is not adequately biologically stabilized. Jiang *et al*. (2011) observed that aeration rate is an important parameter in nitrogen metabolism during aerobic degradation, participating in ammonification, ammonia emission, and denitrification processes. Ammonification increases when the aeration rate increases, denitrification occurs when oxygen is higher than 15% and biodegradable carbon is still available. On the other hand, Cooperband *et al*. (2003) have highlighted the importance of phytotoxicity tests as one of the criteria to evaluate the quality of compost for agricultural purposes and to avoid environmental risks. It has been reported that the presence of short-chain aliphatic acids such as acetic acid and various phenolic compounds produced during the degradation process of organic compounds inhibit seed germination, root growth, and crop yield (Manios *et al*., 1987). OFMSW is made up of several carbon sources, which makes it difficult to degrade on a large scale. Therefore, mathematical models are essential tools in the development of design and optimization strategies for the operation of large-scale bioreactors. OFMSW is metabolized by different microorganisms with varying growth rates (Liwarska-Bizukojc *et al*., 2001). Therefore, mathematical models are efficient to describe and compare the behavior of microorganisms under different process conditions such as aeration, temperature, and pH. Carrizalez *et al*. (1981); Saucedo-Castañeda *et al*. (1994); Ponsá *et al*. (2011); Martínez-Valdez *et al*. (2015) have proposed the analysis of CO_2 generation and O_2 consumption as an indirect method to monitor the FORSU degradation process. The research objective was to evaluate the effect of aeration rate on the aerobic degradation of OFMSW in laboratory-scale batch bioreactors, monitoring online CO_2 production and O_2 consumption to obtain a stable compost for agricultural use. Determining the most suitable operating conditions for compost stability based on the mineralization constant, maintenance coefficient, O_2 consumption performance with respect to CO_2 production by applying mathematical models.

2 Material and methods

2.1 Biological material

In the study of aerobic degradation of organic wastes (OFMSW) from food establishments (restaurants and juice bar) of the Iztapalapa municipality in Mexico City were used according to Estrada-Martínez *et al*. (2019). A solid organic mixture (SOM) reported by Martínez-Valdez *et al*. (2015) was used as a substrate, which contained: pruning waste (2 % w w^{-1}), OFMSW (83 % w w^{-1}), paper (3 % w w^{-1}), and sawdust (4 % w w^{-1}); with a carbon/nitrogen (C N^{-1}) ratio of 30. Mature and stabilized compost from the Bordo Poniente composting plant in Mexico City was used as inoculum (8 % w w^{-1}).

2.2 Aerobic degradation test conditions

A 2^2 factorial design was used to determine the effect of aeration rate on the aerobic degradation of SOM. Aeration flow rate and bioreactor volume were used as independent variables. The analysis of variance (ANOVA) was achieved using k_{CO_2}, $CO_{2\,max}$, $O_{2\,max}$, m_{O_2} and $Y_{CO_2O_2{}^{-1}}$ as response variables. Glass bioreactors with airtight lids with a capacity of 0.98 and 1.9 L were used; they were packed with the SOM and mature compost up to 60% of their volumetric capacity and were supplied with saturated air (Table 1). The airflow intensity was required to maintain the temperature and cool

Table 1. Experimental treatments in the aerobic degradation process.

Treatments	Aeration flow rate (mL min^{-1})	Bioreactor volume (mL)	Mass (g)	Aeration rate (vkgm) (L air kg^{-1} DM min^{-1})
T1	40	980	319.14 ± 0.19	0.125
T2	40	1900	600.39 ± 0.15	0.064
T3	125	980	319.25 ± 0.42	0.392
T4	125	1900	600.12 ± 0.04	0.201

the bioreactor; it also provides oxygen for microbial growth. Airflow intensity is a key factor that must be considered in the scaling up of the process. The use of vkgm (L air kg^{-1} h^{-1}) has been proposed to have a uniform unit of aeration rates quantification (Arslan *et al*. 2011). The experimental units were incubated horizontally at 30 °C. The evolution of the bioprocess at the lab scale was directly monitored through CO_2 and O_2 concentrations.

2.3 Respirometric analysis

The concentration of O_2 and CO_2 in the gaseous stream at the bioreactor outlet was determined in three experimental replicates, as reported by Martínez-Valdez *et al*. (2015). A respirometry system was used, which, allows online analysis of the gaseous composition at the bioreactor outlet without disturbing the process (Saucedo-Castañeda *et al*., 1994; Jiménez-Rodríguez *et al*., 2020). The parameters associated with O_2 consumption and CO_2 production were estimated from the experimental data. CO_2 production and O_2 consumption rates were expressed in mmol/grams initial dry matter *h (mmol g^{-1} h^{-1} IDM). The respiratory coefficient was calculated as the molar ratio of O_2 consumed per CO_2 produced (O_2 CO_2^{-1}). The kinetic parameters associated with the CO_2 production mineralization constant (k_{CO_2}) was expressed as (h^{-1}), overall CO_2 production ($CO_{2\max}$) were obtained from the Logistic model (Eq. 1) (Martínez-Valdez *et al*. 2015):

$$CO_2 = \frac{CO_{2\max}}{1+\left(\frac{CO_{2\max}-CO_{2(0)}}{CO_{2(0)}}\right)\exp\left(k_{CO_2} * t\right)} \quad (1)$$

$CO_{2\max}$: Maximum carbon dioxide concentration (mmol g^{-1} IDM).

$CO_{2(0)}$: Carbon dioxide concentration at t = 0 (mmol g^{-1} IDM).

k_{CO_2} : Mineralization constant (h^{-1}).

t = Process time (h).

In this study, a modification to the substrate consumption model reported by Soto-Cruz *et al*. (2002) is proposed (Eq. 2), where O_2 is considered as a substrate. With the model, the following parameters were estimated: maintenance coefficient of O_2 consumption not associated with growth (m_{O_2}), global oxygen consumption ($O_{2\max}$), and the CO_2 production yield with respect to O_2 consumption ($Y_{CO_2O_2^{-1}}$):

$$O_2 = O_{2(0)} - \frac{1}{Y_{\frac{CO_2}{O_2}}}(CO_2 - CO_{20}) - \frac{m_{O2}CO_{2\max}}{k_{CO_2}}\ln\left(\frac{CO_{2\max}-CO_{2(0)}}{CO_{2\max}-CO_2}\right) \quad (2)$$

where:

O_2: Oxygen concentration (mmol g^{-1} IDM).

$O_{2(0)}$: Oxygen concentration at t = 0 (mmol g^{-1} IDM).

Y_{CO_2/O_2}: Yield CO_2 O_2^{-1}.

CO_2: Carbon dioxide concentration (mmol g^{-1} IDM).

$CO_{2(0)}$: Initial carbon dioxide concentration (mmol g^{-1} IDM).

$CO_{2\max}$: Maximum carbon dioxide concentration (mmol g^{-1} IDM).

mO_2: Maintenance coefficient of oxygen consumption not associated with growth (mmol O_2 mmol CO_2^{-1} h^{-1}).

k_{CO_2}: Mineralization constant (h^{-1}).

2.4 Analytical methods

The moisture content was determined by gravimetric analysis by dehydrating them at 105 °C for 24 h. The pH of the samples from aerobic degradation was measured utilizing a Conductronic pH 120 potentiometer, properly calibrated. The determination of carbon and nitrogen was performed on a Series II 2400 CHNS/O elemental analyzer (Perkin Elmer, Boston, USA). This analysis consists of the oxidation of the sample in an atmosphere of pure oxygen, where CO_2, H_2O, and N_2 are produced, which are identified through a thermal conductivity detector, using helium as a carrier. Calibration was performed with an acetanilide standard (C_8H_9NO). The fresh sample was placed on an aluminum tray and dried in an oven at 60 °C. Once dried, it was ground to reduce the particle size. Finally, it was sieved at 100 mesh (0.149 mm) and weighed between 2 and 3 mg in tin capsules on a high precision microbalance. The results were expressed as a percentage referred to as the dry matter of the sample.

2.5 *Determination of metabolites*

For the analysis of carbohydrates and organic compounds, 10 g wet mass (Wm) were placed in a 250 mL Erlenmeyer flask and extracted with 90 mL of distilled water. The samples were shaken in an orbital shaker at 100 rpm, centrifuged at 2120 g, and filtered using a nylon membrane with a pore size of 0.45 μm. Trehalose, citric acid, glucose, xylose, erythritol, acetic acid, fructose, and oxalic acid were quantified using a Shimadzu Prominence HPLC equipment (Shimadzu Corp., Kyoto, Japan) equipped with an LC-20 pump, DGU-20AS degasser, HT SIL-20A autosampler, RID-20A refractive index detector. Compounds were quantified from retention times and standardization curves for each compound. The results were expressed as mg kg^{-1} DM. All analytical techniques described in this section were performed in triplicate.

2.6 *Phytotoxicity test on compost*

The phytotoxicity test was performed as proposed by Kebrom *et al*. (2019) with slight modifications. 5g of the sample after each treatment (Table 1) were dried at ambient temperature by aeration and sieved on a 2 mm mesh. Subsequently, the samples were rehydrated with 25 mL of deionized water (1:5), shaken at 20 rpm for 1 h, centrifuged at 5000 g for 15 min, and filtered (0.8 μm). The supernatant of each sample was used to wet (5 mL) 2 filter paper discs (Whatman #1) in Petri dishes of 100 mm diameter and 25 mm height (Fisher Scientific). Twenty *Lactuca sativa* seeds were placed equidistant in each Petri dish. The Petri dishes were incubated for 5 days in a chamber at 25 ± 2 °C. At the end of the incubation period, the effect on germination and radicle and hypocotyl elongation was quantified (Kebrom *et al*. 2019). In each case, the effect generated in the seeds exposed to the supernatant from the four treatments was compared with the response of the seeds of the negative control exposed only to reconstituted hard water. A seed with a radicle length >2 mm was considered to have germinated. The analysis technique described in this section was performed in triplicate. The results were analyzed by determining seed germination (SG, Eq. 3), root elongation (RE, Eq. 4), and germination index (GI, Eq.5), as shown in the following equations:

$$SG = \frac{\text{Number of seeds germinated in aqueous extract}}{\text{Number of seeds germinated in desionized water (control)}} \times 100\% \tag{3}$$

$$RE = \frac{\text{Mean root length of germinated seeds in aqueous extracts}}{\text{Mean root length of germinated seeds in deionized water (control)}} \times 100\% \tag{4}$$

$$GI = SG \times RE \times 100\% \tag{5}$$

2.7 *Statistical analysis*

The kinetic parameters and the quantifications for the different parameters were analyzed using the Shapiro-Wilk goodness-of-fit test. Data with normal distribution were analyzed with ANOVA (α = 0.05). Data that did not correspond to a normal distribution were analyzed with the Kruskal-Wallis test. In cases where significant differences were recorded, Tukey's test (α = 0.05) was performed for comparison among treatments.

3 Results and discussion

3.1 *Effect of aeration rate on aerobic degradation*

CO_2 production rate and O_2 consumption were similar in all treatments (T1, T2, T3, and T4); which, contrasts with the O_2 consumption rate, whose profile decreases in the treatments with lower aeration (T1 and T3) (Fig. 1a, 1b, 1c and 1d). It could suggest an insufficient oxygen supply in treatments with an aeration flow rate of 40 mL min^{-1}. CO_2 production is usually a sensitive indicator of compost stability, as it is closely related to aerobic microbial activity (Interiano-López *et al*. 2019). In all treatments, maximum CO_2 production rates were above 0.1 mmol h^{-1} g^{-1} IDM and were obtained at approximately 18 h of culture. Similar values were reached for maximum CO_2 production rate and maximum O_2 consumption rate in the essays carried out at an aeration flow of 125 mL min^{-1}. Decreasing the aeration flow rate from 125 to 40 mL min^{-1} represented an 18 and 27 % decrease in the maximum O_2 consumption rate in the 0.98 and 1.9 L bioreactors, respectively. The respiratory coefficient (CO_2 O_2^{-1}) was determined from O_2 consumption and CO_2 production presenting values ≥ 0.8 in the different treatments. However, the highest profiles of the respiratory coefficient were obtained in the bioreactors with lower aeration flow (40 mL min^{-1}); in which, values higher than 1.2 were observed between 10 and 25 h of culture (Fig. 1e and 1f). Evangelou *et al*. (2017) reported a maximum respiration coefficient of 0.5 to 1 when increasing the airflow rate from 6.1 to 29.7 L air kg^{-1} h^{-1}. Gea *et al*. (2004) indicate that the microbial respiration coefficient (RC) is related to the type of waste to be degraded; in general, the RC values increase as the material is more oxidized. Additionally, respiration coefficients greater than 1 could be indicative of a lack of dissipation of the CO_2 produced due to a low airflow rate.

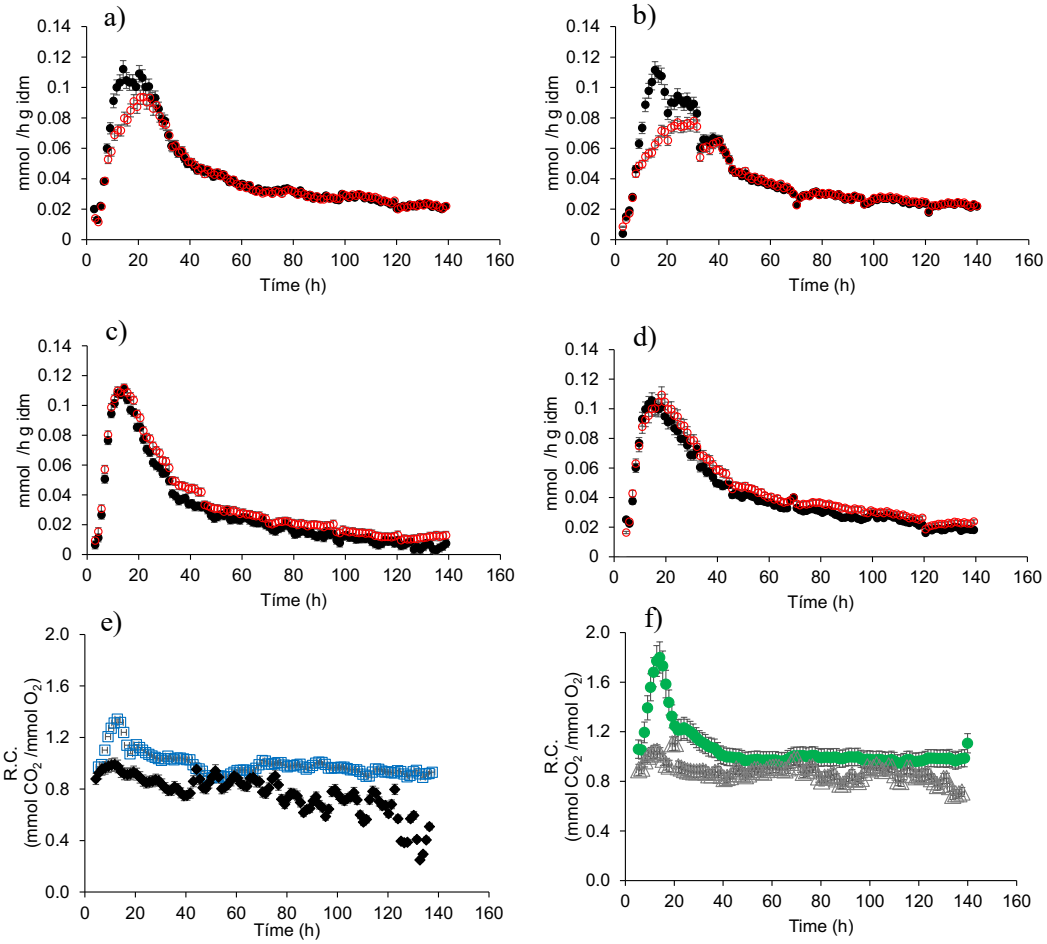

Fig. 1. Rates of oxygen consumption (○) and carbon dioxide production (●) in treatments T1(a), T2 (b), T3 (c), and T4 (d). The respiratory coefficient in the different treatments, e) 980 mL bioreactor 40 mL min^{-1} (□), 125 mL min^{-1} (♦) and f) 1900 mL bioreactor 40 mL min^{-1} (●), 125mL min^{-1} (Δ).

Noting that the RC was obtained with an aeration flow rate of 40 mL min^{-1} were greater than 1, which could indicate an accumulation of the CO_2 produced.

Oxygen consumption during the aerobic degradation of SOM was successfully fitted to the modified model of Soto-Cruz *et al*. (2002). The goodness of fit was evaluated by the correlation coefficient between experimental and calculated oxygen concentration data. For treatments 1 (Fig. 2a), 2 (Fig. 2b), 3 (Fig 2c) and 4 (Fig 2d) the following correlation coefficients 0.992, 0.995, 0.999 and 0.989, respectively, were obtained.

With the experimental data fit to the logistic model, the mineralization constant (kCO_2), global CO_2 production ($CO_{2\,max}$), and global O_2 consumption ($O_{2\,max}$) were calculated, as well as the maintenance coefficient of oxygen consumption not associated with growth (mO_2) and the YCO_2 O_2^{-1} yield (Table 2), using the modified model proposed by Soto-Cruz *et al*. (2002).

The k_{CO_2} presented significant differences in the analyzed treatments, presenting a maximum of 0.062 h^{-1} in T3, the global production of CO_2 and global consumption of O_2 ($O_{2\,max}$) presented the lowest values of 3.71± 0.02 mmol g^{-1} IDM and 4.34 ± 0.20 mmol g^{-1} IDM in T3, which was lower than their counterparts, possibly due to the increase in the airflow rate. On the other hand, the highest overall O_2 consumption ($O_{2\,max}$) was presented in T4 with an aeration flow rate of 125 mL min^{-1} but with a higher amount of organic matter.

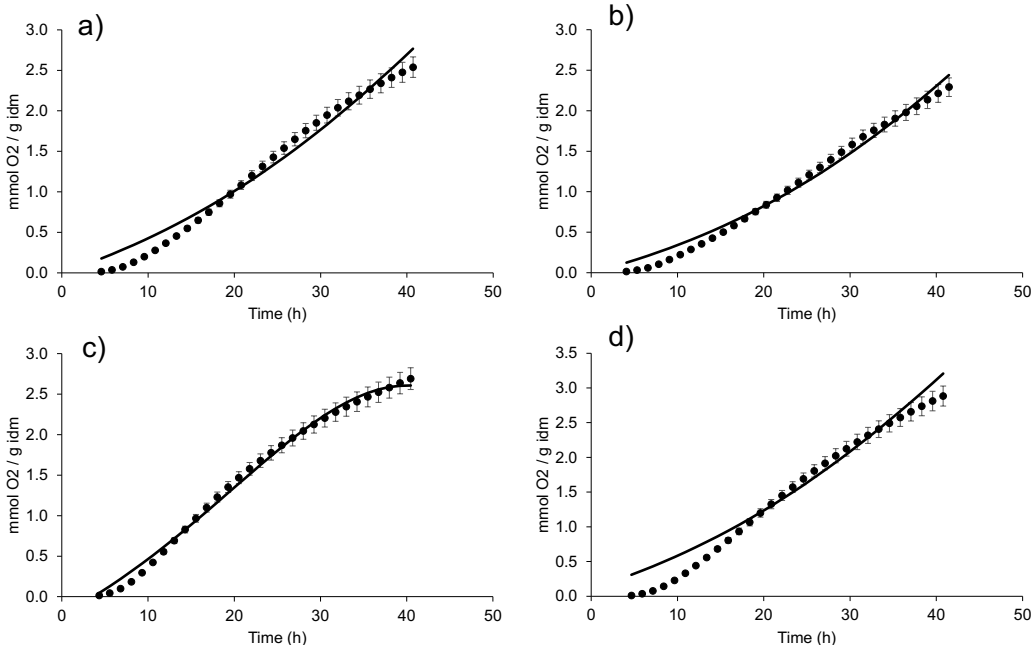

Fig. 2. Oxygen consumption (-) during aerobic degradation of SOM adjusted to the modified model by Soto-Cruz *et al*., (2002) in a continuous line for T1 (a), T2 (b), T3 (c), and T4 (d).

Table 2. Parameters obtained during the fitting of the experimental data to the Logistic and oxygen consumption models.

Treatments	k_{CO_2} (h^{-1})	$CO_{2\,max}$ (mmol g^{-1} IDM)	$O_{2\,max}$ (mmol g^{-1} IDM)	m_{O_2} (mmol O_2 mmol CO_2^{-1} h^{-1})	$Y_{CO_2O_2^{-1}}$
T1	0.045 ± 0.001bc	5.56 ± 0.02a	5.25 ± 0.05b	0.014 ± 0.001ab	0.8 ± 0.02b
T2	0.047 ± 0.002b	5.43± 0.02b	4.97 ± 0.43b	0.023 ± 0.008a	1.08 ± 0.01a
T3	0.062 ± 0.002a	3.71± 0.02d	4.34 ± 0.20c	-0.116 ± 0.005c	0.22 ± 0.04c
T4	0.044 ± 0.001c	5.35± 0.02c	5.89 ± 0.21a	0.012 ± 0.002b	0.83 ± 0.01b

Different letters represent significant differences (Tukey, $\alpha = 0.95$).

The maximum value of maintenance coefficient (m_{O_2}) was recorded at T2 (0.023 mmol O_2 mmol CO_2^{-1} h^{-1}) at the same aeration flow rate as T1 and higher organic matter content, which decreased significantly in the bioreactors with higher aeration supply. Similar behavior was presented when evaluating $Y_{CO_2O_2^{-1}}$ where the highest value (1.08 ± 0.01) was presented at T2. The term mO_2 is associated with maintenance. Pirt, (1965) defines the concept of maintenance as the amount of substrate energy consumed per unit amount of organism per unit of time to maintain the organism in a healthy state. T3 presented a negative coefficient, which means that no substrate energy was consumed to maintain the organism. On the other hand, in the lower vkgm treatments (0.064 and 0.125 L air kg^{-1} h^{-1}), a higher maintenance coefficient was observed due to the conditions of decreased O_2 supply, which impacted the metabolism of the microorganisms present. M'Bou *et al*. (2010) reported an increase in the maintenance coefficient with increasing stress due to a decrease in nitrogen concentration in *Eucalyptus cuttings*. This is consistent with the maintenance coefficient reported considering oxygen as a substrate, since the lower the oxygen supply, the higher the maintenance coefficient.

3.2 Characterization during aerobic degradation

The characterization of SOM during aerobic degradation at different vkgm is shown in Tables 3 and 4. Moisture SOM decreased significantly in the treatments with a higher level of aeration. In the treatment with a vkgm of 0.392 L air min^{-1} kg^{-1} DM, lower CO_2 production was observed; this might be related to the significantly higher moisture loss that could affect the nutrient transport mechanisms between the cells and the substrate. Therefore, the result suggests using vkgm close to 0.201 L air min^{-1} kg^{-1} DM to obtain high yields of mineralization of organic residues. The final pH values in T1 and T2 were like the initial ones (7.0 ± 0.2) and in the treatments with an aeration flow rate of 40 mL min^{-1} with 7.1 ± 0.05;

Table 3. Conditions in the different treatments of aerobic degradation.

Treatments	Aeration rate (vkgm) (L air min^{-1} kg^{-1} DM)	Moisture (%)	pH	C N^{-1}
Initial		70 ± 0.5	7.0 ± 0.2	30 ± 0.5
T1	0.125	66.3 ± 0.03a	6.8 ± 0.02c	11.4 ± 0.2a
T2	0.064	67.4 ± 0.03a	7.1 ± 0.05b,c	11.3 ± 0.2a
T3	0.392	52.0 ± 0.52c	7.8 ± 0.18a,b	10.8 ± 0.1b
T4	0.201	62.4 ± 0.60b	7.7 ± 0.15a,b	10.9 ± 0.1b

Different letters represent significant differences (Tukey, $\alpha = 0.95$).

Table 4. Comparison of carbohydrates and organic compounds in the different aerobic degradation treatments.

Compounds	**Concentration (mg g^{-1} DM)**				
	INITIAL	T1	T2	T3	T4
Trehalose	1.04 ± 0.9	n.d.	n. d.	n. d.	n. d.
Xylose	35.73 ± 0.25	5.44 ± 0.21	1.33 ± 0.2	n. d.	n. d.
Fructose	24.81 ± 0.24	1.47 ± 0.29	n. d.	n. d.	n. d.
Glucose	34.16 ± 0.28	7.23 ± 0.3	1.48 ± 0.2	1.04 ± 0.2	0.13 ± 0.1
Citric acid	4.27 ± 0.24	3.97 ± 0.3	3.76 ± 0.3	8.58 ± 0.1	0.37 ± 0.2
Oxalic Ac.	n. d.	n. d.	n. d.	0.19 ± 0.9	n. d.
Erythritol	n. d.	n. d.	2.61 ± 0.4	n. d.	n. d.
Acetic acid	n. d.	94.52 ± 0.2	153.81 ± 0.35	5.35 ± 0.2	30.85 ± 0.2
Total	100.01 ± 0.4	112.63 ± 0.3	163.0 ± 0.3	15.16 ± 0.35	31.35 ± 0.3

n. d. = not determined

however, in the aerated treatments with 125 mL min^{-1}, it increased significantly reaching values of 7.8 ± 0.18. Said-Pullicino *et al*. (2007) and Yu *et al*. (2018) mention that the decrease in pH is usually due to the anaerobic conditions that are established in the degraded materials, resulting in the formation of organic acids. When aerobic conditions are established, an increase in pH is observed as organic acids are degraded. The final C N-1 ratio was lower than 11.4 in all treatments and presented significant differences with 6% lower in the treatments with a lower aeration rate. This is possibly related to CO_2 production. Bernal *et al*. (2009) stated that when the C N^{-1} ratio decreased below 15, the compost had met an acceptable standard of maturation. Therefore, it could be assumed that all compost treatments with an initial C N^{-1} ratio of 30 can be defined as mature.

In contrast, when analyzing some metabolites such as the content of trehalose, xylose, fructose, and glucose in the samples of aerobic degradation of SOM, high consumption of these carbohydrates was observed (Table 4). In the treatments with higher aeration flow (T3 and T4, 125 mL min^{-1}) the presence of trehalose, xylose, fructose and erythritol were not detected. In the treatments with lower aeration flow (T1 and T2, 40 mL min^{-1}) the highest production of acetic acid (94.52 ± 0.2 and 153.81 ± 0.35 mg g^{-1} DM, respectively) was detected. Only in T2, the production of erythritol was recorded. The highest concentrations of citric acid and oxalic acid were recorded at T3 (8.58 ± 0.1and 0.19 ± 0.9 mg g^{-1} DM, respectively). Rashwan *et al*. (2020) mention that glucose and xylose are the two most abundant carbohydrates derived from the decomposition of lignocellulosic biomass. González *et al*. (2017) analyzed the metabolites produced during glucose and xylose consumption under aerobic and anaerobic conditions by *E. coli*, detecting a higher production of acetic acid and erythritol in anaerobic conditions; and low consumption of xylose, as observed in the assays analyzed. In addition, Veiga-da-Cunha *et al*. (1993) reported in *Leuconostoc oenos* GM the production of erythritol under anaerobic conditions from glucose and the minimum production of the organic compound in the presence of oxygen. Comparable what was observed, with a concentration of 2.61 ± 0.4 mg g^{-1} DM of erythritol at T2. In contrast, in the treatments with higher aeration flow (125 mL min^{-1}), the lowest generation of products from anaerobic degradation (erythritol and acetic acid) and a higher presence of products associated with aerobic degradation (oxalic acid and acetic acid) were observed. The concentration of acetic acid decreased as the aeration rate increased.

3.3 Phytotoxicity test

The parameters in the percentage of seed germination (SG), root elongation (RE), and germination index (GI) in the growth of *Lactuca sativa* seeds in the supernatants obtained after aerobic digestion of the SOM at different aeration rates (Fig. 3), considering as germination a radicle length >2 mm.

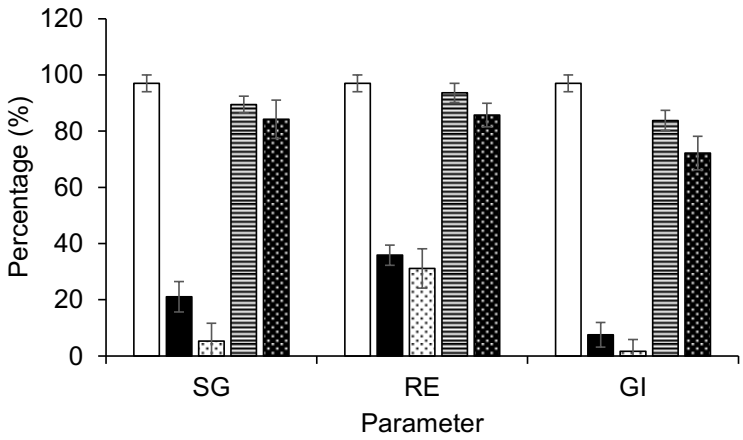

Fig. 3 Parameters obtained from the phototoxicity test of *Lactuca sativa*, seed germination (SG), root elongation (RE), and germination index (GI), in the different treatments. Control (□), T1(■), T2 (⚀), T3(▤) and T4(⚅).

It could be seen that the treatments with lower aeration flow rate presented germination parameters with values below 40%. The best germination parameters were observed in T3, with an aeration rate of 0.392 vkgm with a germination index (GI) of 83.8 ± 3.6 %. Kebrom *et al*. (2019) indicate that the germination index is commonly used to determine the phytotoxicity of compost; a GI above 80% indicates that the compost is free of phytotoxicity, while a GI below 80% indicates moderate phytotoxicity of the compost to crops and a GI below 50% indicates high phytotoxicity. However, the GI test being a quantifiable value does not convey the intensity of the toxic effect. Lee *et al*. (2002), evaluated the use of food waste composted with sawdust, dry sludge from a paper mill, and wood dust stabilized for 80 days at a temperature of 50°C, reporting a germination rate of 59.1%, using seeds of *Lepidium sativum*. Gao *et al*. (2021) studied the effect of heat treatment on the release of nutrients from food waste and the subsequent evaluation of the viability of the hydrolyzed liquor as a liquid organic fertilizer. Using wheat seed, they report a germination rate >80% with good root and shoot lengths. Cobos *et al*. (2020) indicated that the germination index value is related to the inhibitory effect of short-chain organic acids, phenols, alkaloids, aldehydes, ketones, amino acids, lipids, ammonia, heavy metals, phenolic compounds especially tannins, and the values of initial pH. With vkgm values of 0.392 and 0.201, the stability of the organic residues was accelerated. In this study, a higher aeration flow rate stimulates the compost to degrade more of the SOM nutrients and reduces the presence of inhibitory compounds was demonstrated. Based on these criteria, the use of T3 (0.392 L air min^{-1} kg^{-1} DM) is suggested as a strategy for obtaining a compost free of phytotoxic compounds, low in organic compounds, and with a zero-maintenance coefficient. Further studies are expected to optimize the process.

Conclusions

Oxygen consumption during aerobic degradation of SOM was successfully fitted to the modified model. Modification of the model allowed obtaining the maintenance coefficient and $Y_{CO_2O_2^{-1}}$, which decrease with increasing aeration rate. The maintenance coefficient could be a reliable indicator to ensure that the compost is ready for use, presenting the lowest coefficient with 0.392 vkgm. The characterization of the compost obtained and the phytotoxicity test confirmed the results obtained by the mathematical models, showing that a germination percentage higher than 80% was obtained in the growth of *Lactuca sativa* seeds in organic waste extracts after aerobic degradation with the highest aeration rate. Therefore, the use of an aeration rate of 0.392 L air min^{-1} kg^{-1} DM is suggested as a strategy to obtain a compost free of phytotoxic compounds (low content of acetic acid, considered as a phytotoxic compound), zero maintenance coefficient, and cost savings in the production of compost for agricultural use.

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