Rapid mineralisation of the Organic Fraction of Municipal Solid Waste

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Rapid mineralisation of the Organic Fraction of Municipal Solid Waste

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HIGHLIGHTS

- Rapid mineralisation of OFMSW is an alternative for ecological processes.
- Respirometry analysis allowed to determine rapid and slow phases of mineralisation.
- Rapid mineralisation allows up to 432.9 mg of CO_2 g^{-1} IDM after 50 h.
- Highest CO_2 rate constant found (5.28 d^{-1}) is 3.5 times higher than that reported.
- Highest CO_2 formation rate (22 CO_2 mg g^{-1} IDM h^{-1}) is 73% higher than that reported.

GRAPHICAL ABSTRACT
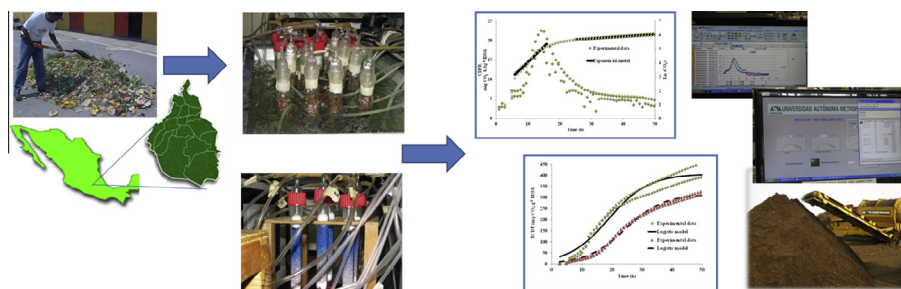
ABSTRACT

The effect of pH, C/N ratio, addition of a microbial consortium (MC) and temperature upon mineralisation of Organic Fraction of Municipal Solid Waste (OFMSW) was studied; mineralisation was measured through the CO_2 production rate and total CO_2 formation. Through this process up to 432.9 mg of CO_2 g^{-1} initial dry matter (IDM) after 2 days of treatment was obtained. It was found that under a slightly acidic pH (5–6) and C/N of 30, the mineralisation process was accelerated. Moreover, temperature (27–50 °C) had no effect on the total CO_2 produced. The highest CO_2 production rate (5.28 d^{-1}) was observed at 27 °C, C/N ratio of 30 and 8% of microbial consortium; it is at least 3.52 times higher than that reported (1.5 d^{-1}). The highest release of reducing sugars was determined at 50 °C, possibly due to an increase in hydrolytic enzymes. Results suggest the potential use of rapid mineralisation of OFMSW for further friendly environmental processes.

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1. Introduction

The generation of municipal waste is increasing day by day with the increase in population. Improper processing of the Organic Fraction of Municipal Solid Waste (OFMSW) represents a high risk of environmental pollution. Waste generation in Mexico was 40,000 million tons in 2011, with 12% of these wastes generated in Mexico City area, and which were approximately 53% organic matter (http://www.sedesol.gob.mx/). Composting is an aerobic

mineralisation process, whereby microorganisms degrade organic matter into CO_2, H_2O and the final product is known as compost. Aeration is one of the most important factors in composting systems. A minimum oxygen concentration of 5% in the void fraction of the composting pile is necessary to maintain aerobic conditions (Kulcu and Yaldiz, 2004).

Temperature, humidity, pH, aeration and C/N (carbon to nitrogen ratio) are important in the process of aerobic degradation. Heat and mass gradients appear in this process due to the heterogeneity of the solid substrate. Particularly, the temperature and humidity gradients in the solid mass must be controlled to achieve a satisfactory process (Martins et al., 2011). Continuous measurement of

oxygen consumption and carbon dioxide production during the composting process is an important indicator of the metabolic state in microorganisms; this can be carried out through online analysis of the air coming from the culture. Online analysis allows quantification of the concentrations of oxygen and carbon dioxide online, in real-time, without disturbing the system (Iannotti et al., 1993; Saucedo-Castañeda et al., 1994). The metabolic changes of microorganisms involved in the bioprocess are manifested through changes in respiration rate. Respirometry is frequently used in the evaluation of aerobic processes as solid-state culture (SSC); it provides direct measurements of biological activity in the bioprocess and indicates the degree of mineralisation or degradability of the material (Guo et al., 2012). When the rate of mineralisation is greater, the microbial activity and the respiration rate are greater. Otherwise, with the lack of microbial activity, the respiration rate is low; consequently the material is more stable (Barrena et al., 2011a). Aerobic respiration represents an appropriate measurement of biodegradability of waste. The information obtained from this measurement can classify solid wastes into easy, moderate or difficult mineralisation (Ponsá et al., 2010).

Mathematical description of the mineralisation of solid wastes is difficult because of the heterogeneity of substrates and microbial diversity. The OFMSW consists of various carbon sources. These are metabolised during mineralisation by different microorganisms with variable growth rates. Although this has been studied with different mathematical models, there remains a need to study mathematical description of the mineralisation rate of the OFMSW; it could be used to compare processes and improve the design and operation of biological reactors. Mathematical models are used to describe and compare microorganisms' behaviour under different physical or chemical conditions such as temperature and pH. These models describe the three phases of the growth curve (Zwietering et al., 1990). Several authors have proposed the use of the formation of CO_2 and O_2 consumption as an indirect method for the determination of biomass in SSC (Carrizalez et al., 1981). In this regard, the exponential, logistic Gompertz models are frequently used in SSC (Table 1).

In the OFMSW, soluble molecules of low molecular weight are readily biodegradable and are used primarily as a source of nutrients for microbial growth. However, most of the nutrients in the municipal solid waste are high molecular weight biopolymers and in some cases, are in solid form. These polymers, consisting principally of cellulose, hemicellulose, pectin, starch, lignin and proteins, are hydrolysed by extracellular microbial enzymes that release and solubilise monomers which are subsequently metabolised. The final product of the degradation is a stable material with a C/N ratio lower than the initial one because of carbon mineralisation. During aerobic degradation, it is important to have C/N ratio, pH and temperature conditions, enabling the development of appropriate microbial activity (Barrena et al., 2011a). Carbon/nitrogen ratio (C/N) is one of the most important factors influencing aerobic degradation. Generally, the initial C/N ratio (25–30) is considered ideal for aerobic degradation (Guo et al., 2012). Also, pH is

an important variable, as it can inhibit microbiological activity and inhibit the composting in the initial phase, because of the presence of organic acids. The presence of short-chain fatty acids in acidic conditions can alter microbial activity in aerobic degradation. Another disadvantage may be the increase in emissions of ammonia in an alkaline medium (Yu and Huang, 2009). Temperature influences the population dynamics and the efficiency of aerobic degradation. It has been observed that at temperatures below 20 °C, microbial activity decreases and aerobic degradation is very slow. On the other hand, temperatures above 60 °C also decrease the microbial activity; some researchers suggest that the optimal temperature for aerobic degradation is in the range from 52 to 60 °C. However, some researchers have found that a higher microbial activity can be observed at lower temperatures (Liang et al., 2003).

The aim of this study was to evaluate the effect of pH, C/N ratio, adding a microbial consortium (MC) and incubation temperature upon the rate and total CO_2 formation from the carbon present in the Organic Fraction of Municipal Solid Waste. These variables were analysed through different mathematical models (logistic, Gompertz and exponential). The initial and final concentration of reducing sugars and the xylanase and pectinase activities were also assessed at the beginning and end of each assay.

2. Methods

2.1. Biological material

The Organic Fraction of Municipal Solid Waste was obtained from local food sale in Iztapalapa sector in Mexico City. As a source of microbial consortium (MC), compost from the Bordo Poniente composting plant in Mexico City was used.

2.2. Assay conditions

The effect of pH, C/N ratio, microbial consortium level and temperature upon mineralisation of OFMSW was determined through the rate and total CO_2 formation. The mineralisation of OFMSW was performed in tubular bioreactors (TBRs) of 5 cm diameter and 15 cm height. TBRs were packaged with mix 1 or 2, as indicated in Table 2. Once packed, TBRs were incubated at constant temperature for about 50 h with an air flow of 0.5 mL/min g of wet matter at an initial moisture content of 70% (Liang et al., 2003). The initial pH was adjusted to 5, 6, 7 or 8, adding citric acid or sodium citrate directly to residues; assays were realised at a C/N ratio of 20. Two C/N ratios (20 and 30) of the initial solid matter was modified, changing the proportion of components of the material to be treated. To study the effect of C/N ratio (20 and 30) and the addition (5% and 8% w/w, wet base) of microbial consortium (MC), TBRs were packed with the 2 types of mix (1 and 2, Table 2) and incubated under the previously described conditions. Moreover, the effect of incubation temperature (27, 31, 35, 42, 47 and

Table 1
Models for microbial growth (Mazaheri and Shojaosadati, 2013; Zwietering et al., 1990).

Models	Differential equations[1] where $CO_2(0) = CO_2$ at $t = 0$	Integral equations[1]
Gompertz	$\frac{dCO_2}{dt} = k_{CO2} \cdot CO_2 Ln\left(\frac{CO_{2max}}{CO_2}\right)$ $\frac{dCO_2}{dt} = 0$, when $CO_2 = 0$, or $CO_2 = CO_{2max}$	$CO_2 = CO_{2max} \exp\left(-b \exp\left(-k_{CO2}t\right)\right)$ If $t-> 0$, $CO_2-> CO_{2(0)} = CO_{2max} \exp(-b)$
Logistic	$\frac{dCO_2}{dt} = k_{CO2} \cdot CO_2\left(1 - \left(\frac{CO_2}{CO_{2max}}\right)\right)$ $\frac{dCO_2}{dt} = 0$, when $CO_2 = 0$, or $CO_2 = CO_{2max}$	$CO_2 = \frac{CO_{2max}}{1+\left(\frac{CO_{2max}-CO_{2(0)}}{CO_{2(0)}}\right)\exp\left(-k_{CO2}t\right)}$
Exponential	$\frac{dCO_2}{dt} = CO_2 k_{CO2}$	$CO_2 = CO_{2(0)} \exp\left(k_{CO2}t\right)$

[1] $CO_{2(0)}$ refers to the initial concentration of CO_2; and CO_{2max} refers to the maximum formation of CO_2, while k_{CO2} is the first order constant of mineralisation.

Table 2
Components in mixtures (% ww, wet basis) for mineralisation.

Component	Mixture 1	Mixture 2
Pruning	2	8
OFMSW	83	84
Paper	3	3
Sawdust	4	–
Microbial consortium	8	5
Relation (carbon/nitrogen)	30	20

50 °C, precision used was 0.1 °C) on the mineralisation of the OFMSW was studied at initial pH of 6 and C/N = 20.

The CO_2 (%), O_2 (%) and flow of gas (mL/min) coming from the TBRs were measured (Saucedo-Castañeda et al., 2013) using a respirometry system which enables online analysis of O_2 and CO_2 concentrations and flow measurement in the exhausted dry gases coming from fermenters. Gas flow was analysed using a micro-bridge mass airflow sensor (Honeywell, USA) operated on the theory of heat transfer. Mass airflow is directed across the surface of the sensing elements; air flow can be analysed from 0 to 300 ml/min. The system used an infrared sensor for analysis of CO_2 (0–30% v/v, United Phosphorus, Ltd., India) and an electrochemical detector for analysis of O_2 (0–25% v/v, United Phospshorus Ltd, India). The system is coupled with a data acquisition system (Comet System, model MS6D, Czech Republic) and the platform LabView (National Instruments, USA). The calibration of respirometry equipment for measuring gases was performed using CO_2 and O_2 of known concentrations.

2.3. Sampling and analytical techniques

After respirometry analysis (ca 50 h), the contents of each TBR was unpacked and weighed on an analytical balance (Ohaus Galaxy 200); then, 5 g of sample was used for moisture determination and 10 g of sample was used to determine pH, enzyme activity and reducing sugars. This fraction of sample (10 g) was placed in 250 mL flasks; 90 mL of cold water was added, stirred in a shaker at 300 rpm for 10 min, and allowed to stand for 30 min. Once this time elapsed, the pH in the supernatant was determined by

a previously calibrated potentiometer (Conductronic, model pH 120), moisture content of the samples was determined gravimetrically (Saucedo-Castañeda et al., 1994).

The supernatant was separated by centrifugation at 10,000 rpm for 5 min, which was used for the determination of reducing sugars by the Miller method (Miller et al., 1960). Reducing sugars and enzyme activities were measured at the beginning and end of the assay. Xylanase and pectinase activity was quantified by the release of reducing sugars using xylan (0.5%) and pectin (0.5%) as a substrate in 50 mM citrate buffer. Following the reported method for pectinase and for xylanase, enzyme activities were determined at the beginning and at end of the trials (Zhang et al., 2000). The results of reducing sugars were expressed as mg per g of dry matter (DM), and the specific enzyme activity was expressed as U/g DM. One unit (U) is defined as the enzyme amount that catalyses the conversion of 1 μmol of product per minute. All analyses were performed at least in duplicate. Mineralisation rate is expressed in terms of the rate of formation of CO_2 as mg h^{-1} g IDM^{-1} and the total mineralisation was expressed in terms of the total CO_2 production in mg g IDM^{-1}. Total formation of CO_2 was estimated by assessing the area under the curve of CO_2 formation rate by the trapezoid method (Chapra and Canale, 1998).

2.4. Statistical analysis

All extractions and analysis were carried out at least in duplicate and the results are expressed as means ± standard deviation. Tukey's HSD test was used to compare the means and to reveal significant differences between samples (α = 0.05). Statistical analysis was performed using the package Sigma Plot (Systat Software Inc., San Jose, Cal).

3. Results and discussion

3.1. Kinetic analysis of mineralisation of the OFMSW

Fig. 1 presents the data of mineralisation in terms of total CO_2 formation (TCDF) and CO_2 formation rate (CDFR) of the OFMSW with a C/N ratio of 20 and a MC of 5%. The TCDF was adjusted to
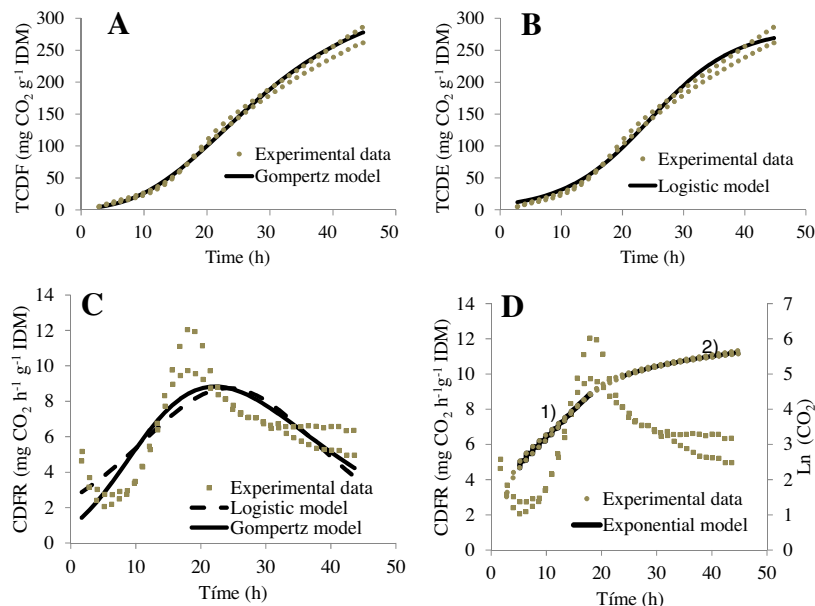
Fig. 1. Total CO_2 formation, TCDF, (A and B) and CO_2 formation rate, CDFR, (C and D), during aerobic mineralisation of the Organic Fraction of Municipal Solid Wastes (OFMSW) at initial pH of 6 and C/N = 20. (1) Adjusted to rapid (5–18 h) mineralisation phase; (2) adjusted to slow (25–45 h) mineralisation phase.

Gompertz and Logistic models (Fig. 1A and B); the goodness of fit for both models is high, showing correlation coefficient higher than 0.99. Integral forms of the models were used to simulate the overall process. The CDFR at the beginning was 5.2–4.9 mg CO_2 h^{-1} g^{-1} IDM, which quickly decreased to a value of 2.05–2.74 mg CO_2 h^{-1} g^{-1} IDM at 5 h of the process. It might be explained due to the respiration of fresh vegetable residues (Rahman et al., 2013). Subsequently, CDFR rose rapidly to reach a maximum of 9.72–12.03 mg CO_2 h^{-1} g^{-1} IDM at 18 h. Then, CDFR decreased to values close to 6 mg CO_2 h^{-1} g^{-1} IDM at 49 h.

The models used cannot accurately describe the behaviour of the CDFR, showing low correlation coefficients (R^2) close to 0.70 (Fig. 1C). Accurate kinetic models are required for designing of bioreactor and modelling of bioprocesses. Mazaheri and Shojaosadati (2013) indicated that models like Gompertz and Logistic cannot accurately describe CDFR. They proposed estimating reaction rate constants using the exponential model in the proper time intervals, using the plot of Ln CO_2 vs. time.

In accordance with other authors (Ponsá et al., 2011; Mazaheri and Shojaosadati, 2013) and the analysis of CDFR, it was possible to identify two phases of aerobic mineralisation of the OFMSW. The first one of rapid mineralisation (5–18 h) on the left side of the plot before the maximum attained, and the second one of slow mineralisation (25–45 h) on the right side of the plot. Differences of at least 5 times were used to distinguish rapid from slow mineralisation rates (Table 5).

Respirometry has been used in solid state culture as indirect method to estimate microbial growth in axenic cultures (Carrizalez et al., 1981). In order to compare our respirometry results with the classical exponential approach, the respiratory activity (μ_r) was estimated using the plot of Ln CO_2 vs. time (Fig. 1D) as described before (Saucedo-Castañeda et al., 1994). The rapid mineralisation phase corresponds to the exponential growth of the mixed culture, which can be explained because of the presence of compounds which are easily metabolised. On the other hand, the slow phase of mineralisation can be associated to the utilisation of biopolymers that are not easily metabolised.

This methodology is suitable when culture conditions are well known in axenic cultures and yields are kept constants throughout the fermentation process. Nevertheless, in mixed non-axenic cultures, these conditions cannot be ensured, especially concerning the values of these yields, nevertheless results presented indicate that gas analysis can help for monitoring different growth phases in non-axenic cultures. In axenic cultures specific growth rate could be estimated precisely through respiratory activity (μ_r) by continuous measurements of CO_2 (Saucedo-Castañeda et al., 1994). The experimental evidence presented indicate that this approach can be extended to non-axenic cultures and the respiratory activity (μ_r) can be understood as an global specific growth rate of the non-axenic culture. All further assays presented similar behaviour, and a similar approach was used for the analysis of results. The comparison between parameters is presented and discussed in next sections.

3.2. Effect of initial pH

The effect of initial pH (5, 6, 7 and 8) at 35 °C with a C/N ratio of 20 on the mineralisation of the OFMSW was studied. In this type of aerobic process, pH is closely related to the mineralisation of organic matter, but it has not been studied enough. Municipal wastes often have a pH ranging from 4 to 6. Acidic conditions can be explained because of the presence of short-chain organic acids. These acids are found in wastes, and their concentrations increased during the initial phase of aerobic processes due to the consumption of sugars in the medium (Miller, 1996; Sundberg et al., 2004).

Parameters obtained fitting the data to integral forms of the logistic and exponential models are shown in Tables 3 and 4, respectively. The parameters were estimated by the use of Solver Excel subroutine.

Mineralisation constants (k_{CO_2}) of Logistic model presented higher values (3.53–3.46 d^{-1}) at an initial of pH of 5 and 6, as indicated in Table 3. Mineralisation constants (k_{CO_2}) of the exponential model in the period areas of rapid and slow degradation were calculated by estimating the slope of the plot of Ln CO_2 vs. time (Fig. 1D); these values (Table 4) are almost 8–11% higher than those estimated by the logistic model, which describes the entire process successfully (Table 3). The mineralisation constants of the Gompertz model were lower (50%) than the data obtained for the Logistic model; for this reason, it was not considered any further in this work (data not shown). Therefore, it was decided to use the exponential model to analyse the rapid and slow mineralisation phases and the Logistic model to describe the entire process. Total mineralisation (Table 3) estimated by the Logistic model was 197.99 mg and 283.66 mg of CO_2/g IDM for the initial pH of 5 and 6, respectively. Mineralisation first order constants obtained for the OFMSW at phases of rapid and slow mineralisation were 3.94 d^{-1} and 3.73 d^{-1}, which were at least 3.52 times higher (Table 5) than those reported in the literature (Sundberg et al., 2004; Yu and Huang, 2009). Therefore, a slightly acidic pH 5 and 6 enhances the mineralisation of organic matter.

Barrena et al. (2011b) indicated the relevance of respiration activity to determine biodegradability, waste management and their appropriate treatment. Using different wastes they showed that the highest value of the maximum respiration oxygen con-

Table 3
Estimated parameters of the integrated Logistic model at different initial pH, incubated at 35 °C with a ratio C/N of 30.

pH	Integral logistic model		
	Parameter[1]	Value	R^2
5	k_{CO_2}	3.53[a]	0.993
	CO_{2max}	197.99	
	$CO_{2(0)}$	5.192	
6	k_{CO_2}	3.46[a]	0.991
	CO_{2max}	283.66	
	$CO_{2(0)}$	8.095	
7	k_{CO_2}	2.95[b]	0.885
	CO_{2max}	174.06	
	$CO_{2(0)}$	7.732	
8	k_{CO_2}	3.12[b]	0.955
	CO_{2max}	182.72	
	$CO_{2(0)}$	7.050	

Same letter by column means no significant differences (Tukey HDS test, $\alpha = 0.05$) between samples.
[1] Where k_{CO_2} is the first order constant of mineralisation (d^{-1}), CO_{2max} is the maximum formation of CO_2 and $CO_{2(0)}$ is the initial value of CO_2. Units for CO_2 are mg g^{-1} IDM.

Table 4
First order constant of mineralisation estimated using the exponential model for the slow and rapid phase mineralisation at different initial pH values.

pH	Rapid mineralisation		Slow mineralisation	
	k_{CO_2} (d^{-1})	R^2	k_{CO_2} (d^{-1})	R^2
5	3.94 ± 0.144[a]	0.991	0.672 ± 0.024[a]	0.985
6	3.74 ± 0.168[ab]	0.989	0.744 ± 0.048[a]	0.955
7	3.07 ± 0.168[b]	0.986	0.648 ± 0.048[a]	0.963
8	3.19 ± 0.384[b]	0.926	0.744 ± 0.072[a]	0.913

Same letter by column means no significant differences (Tukey HDS test, $\alpha = 0.05$) between samples.

Table 5
Comparison of first order constant of mineralisation during aerobic treatment of the Organic Fraction of Municipal Solid Waste reported in literature and estimated in this work.

Reference	Mineralisation constants (k_{CO_2})	
	Rapid (d^{-1})	Slow (d^{-1})
Beck-Friis et al. (2001)	0.550	
Saviozzi et al. (1993)	0.011–0.200	
Zhang et al. (2012)	0.001–0.075	
Rodríguez-Fernández et al. (2011)	0.014–0.069	
Bernal et al. (1998)	0.795–0.060	0.0319–0.0010
Tosun et al. (2008)	0.254–0.087	0.0050–0.0021
Ponsá et al. (2011)	0.240–1.500	0.024–0.120
Pascual et al. (1998)	0.030–0.180	0.030–0.150
Komilis (2006)	0.060–0.100	0.005–0.060
This work	2.16–5.28	0.36–0.744

sumption rate is close to 9.22 mg O_2 g^{-1} of organic matter h^{-1}, corresponding to 12.67 mg CO_2 g^{-1} of organic matter h^{-1}, for the case of source – selected OFMSW, like those residues used in our study. Our higher result of carbon dioxide formation rate was close to 22 mg CO_2 mg O_2 g^{-1} of dry matter h^{-1}, which to 73% higher than that reported. This result suggests the potential use of rapid mineralisation of OFMSW for CO_2 capture and biofuels productions using microalgae, to increase efficiency in aerobic treatment of OFMSW reducing time process or increasing capacity of facilities and mitigation of greenhouse gases production.

3.3. Effect of C/N ratio and addition of microbial consortium

The C/N ratio is one of the most important variables influencing processes in the aerobic treatment of organic waste. The recommended initial C/N ratio in composting is close to 25–30 (Kumar et al., 2010; Zhu, 2007); this criterion can be applied to our process. Four treatments were applied in the mineralisation of the OFMSW: two values of C/N (20 and 30) and two levels of addition of microbial consortium (5% and 8% w/w, wet basis). OFMSW mineralisation to C/N of 20 and 30, respectively, is presented in Fig. 2A and B, using two levels of MC assayed. Mineralisation constants of the process are shown in Table 6. Higher TCDF was obtained with C/N of 30 and MC of 8% (432.9 mg CO_2/g IDM); this value is higher than any condition analysed after 50 h. This can be explained because a lower concentration of nitrogen in conjunction with an increase of CM favours the process, where a productivity of 8 mg CO_2 g^{-1} IDM per hour was also observed. The CDFR is shown in Fig. 2C, a maximum CDFR was observed at 15 h (ca. 22 mg CO_2 h^{-1} g^{-1} IDM). The two phases of rapid and slow mineralisation can be easily identified from which mineralisation constants were obtained. In the case of a C/N ratio of 30 and in the period of rapid mineralisation, a higher mineralisation constant was observed at a microbial consortium of 8% (5.28 d^{-1}) in comparison with that of a microbial consortium of 5% (3.67 d^{-1}). In the case of a C/N ratio of 20, the higher mineralisation rate constant was observed at an MC of 5% (4.92 d^{-1}); this can be explained because the higher proportion of nitrogen may favour microbial growth under these
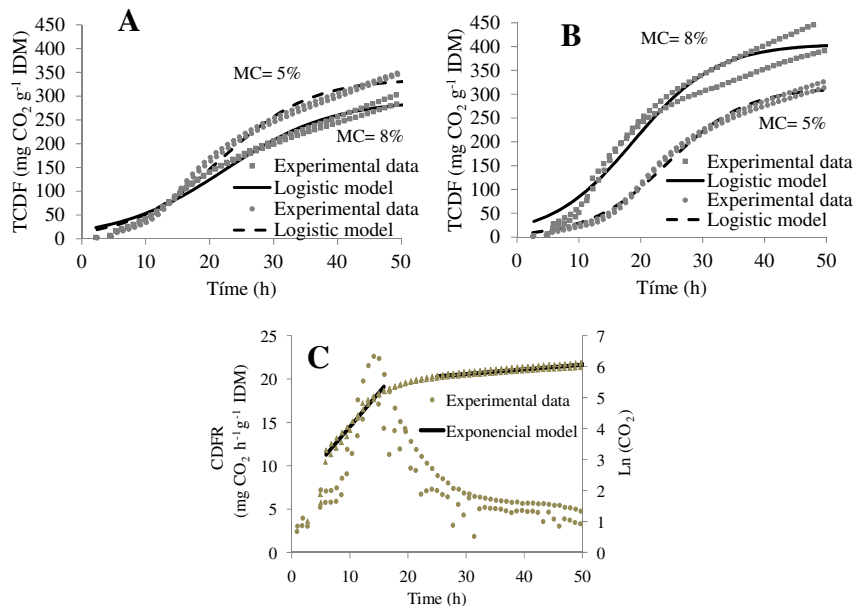

Fig. 2. Total CO_2 formation, TCDF, ((A) C/N = 20; and (B) C/N = 30) during mineralisation of the OFMSW at two levels of C/N ratio (20 and 30) and two levels of addition of the microbial consortium (5% and 8%, w/w wet basis). Dashed lines correspond to MC 5% and solid lines to MC 8%. (C) CO_2 formation rate, CDFR and estimation of mineralisation constant of the exponential model at a C/N of 30 and MC 8%, (1) rapid and (2) slow mineralisation phase.

Table 6
First order constant of mineralisation estimated using the exponential model for the rapid and slow phase of mineralisation a different C/N ratio and percentage of microbial consortium.

C/N	MC (%)	Rapid mineralisation		Slow mineralisation		Total Mineralisation
		k_{CO_2} (d^{-1})	R^2	k_{CO_2} (d^{-1})	R^2	(mg CO_2 g^{-1} IDM)
20	5	4.92 ± 0.072[a]	0.998	0.48 ± 0.024[a]	0.958	360.1[b]
20	8	4.30 ± 0.144[a]	0.993	0.504 ± 0.024[a]	0.965	305.3[d]
30	5	3.67 ± 0.192[a]	0.978	0.576 ± 0.048[a]	0.906	330.2[c]
30	8	5.28 ± 0.504[a]	0.957	0.36 ± 0.048[a]	0.810	432.9[a]

Same letter by column means no significant differences (Tukey HDS test, $\alpha = 0.05$) between samples.
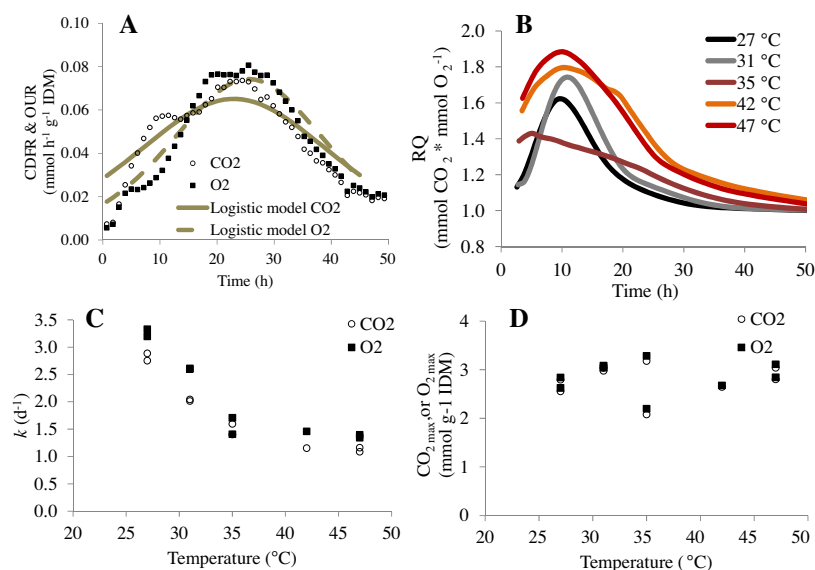
Fig. 3. Effect of temperature incubation (27, 31, 35, 42 and 47 °C) on the mineralisation of OFMSW. Symbols represent the experimental data and the lines the calculated data using the logistic model (A) CO_2 formation rate (CDFR) and O_2 Uptake rate (OUR) patterns at 27 °C; (B) the respiratory quotient (RQ) at different temperatures; (C) mineralisation constants using the logistic model and the total formation of CO_2 (k_{CO2}) and total consumption of O_2 (k_{O2}) data; (D) estimation of total formation of carbon dioxide (CO_{2max}) and total consumption of oxygen (O_{2max}) during treatment of OFMSW at different temperatures, using the logistic model.

conditions. However, the same consideration cannot be applied to an MC of 8%. For the case of mineralisation constant (k_{CO2}), values in the slow mineralisation phase represent only 6.8–15.7% of the k_{CO2} values in the rapid mineralisation phase. This may be because in this period, the higher mineralisation occurred at an earlier stage and the available materials are of slower degradation. Apparently, the addition of 5% favours the slow mineralisation phase (Ponsá et al., 2011). Therefore, it was observed that an increase in the C/N ratio (30) and the percentage of microbial consortium (8%) favours mineralisation of the OFMSW. A complete conclusion cannot be addressed about these two variables studied; an apparent inconsistency could be observed in the results in Table 6, which may be explained by the heterogeneity of the OFMSW.

3.4. Temperature effect on the process of aerobic mineralisation of OFMSW

Aerobic mineralisation of the OFMSW was conducted at six temperatures (27, 31, 35, 42, 47 and 50 °C). Low temperatures were used in order to favour the development of mesophilic microorganisms, whereas higher temperatures enhance the development of thermophilic microorganisms and a possible highest enzyme activity is favoured (Beck-Friis et al., 2001; Miller, 1996). The CDFR and O_2 uptake rate (OUR) at 27 °C expressed in mmol h^{-1} g^{-1} IDM is shown in Fig. 3A. The adjustment of CDFR and OUR was fitted to the logistic model in period where the greatest changes in respiratory quotient were observed (0–40 h). Correlation coefficients were satisfactory ($R^2 > 0.91$). These results were integrated in order to estimate the respiratory quotient (RQ) defined as the ratio of mmol CO_2 produced per mmol of O_2 consumed. RQ were estimated at 5 temperatures tested (Fig. 3B). In all cases, RQ was increased to a maximum value in the first 10–15 h of the process. The maximum value of RQ was 1.9 and corresponded to the test at 47 °C. This increase may be because of the waste vegetable respiration, such as the oxidation of short-chain organic acids (malic acid and citric acid), which are present in some fruits and vegetables. Subsequently, RQ values decrease to values close to unity. These results suggest that the processes are similar to the stoichiometry of the oxidation of hexoses. Moreover, Fig. 3C shows the values of mineralisation constant at different

temperatures studied; it was observed that (k_{CO2}) decreases from 3.33 to 1.08 d^{-1} as the temperature increases, and the same trend was observed for k_{O2}. Fig. 3D shows that the TCDF and total O_2 consumption (TOC), expressed in mmol g^{-1} IDM of OFMSW, was not affected by the increase in temperature in the range studied. These results contrast with those reported in the literature, where the temperature has an effect on organic matter mineralisation (Beck-Friis et al., 2001; Ekinci et al., 2004). This result could be explained because the process could be developed by the activity of mesophilic microorganisms; in this case, it is worth indicating the importance of aeration in order to avoid heat accumulation with the consequent increase of temperature.

The analysis and characterisation of soluble compounds during OFMSW mineralisation improve the understanding of the process. Enzymes released by microorganisms during the process also play a key role in biological and biochemical transformations (Raut et al., 2008). The peel of fruit and vegetables is the major solid sub-products that are generated, constituting approximately 50% of the organic solid waste generated (http://www.sedesol.gob.mx/). The waste composition of some fruits and vegetables can mainly promote the induction of pectinases and xylanases (Rodríguez-Fernández et al., 2011).

TCDF, loss of dry weight, reducing sugars and pectinases and xylanases and final pH at two temperatures, 35 and 50 °C, after of 44 h of the process were analysed. TCDF can be correlated (332.1 and 70.1 mg CO_2 mg g^{-1} IDM at 35 and 50 °C) to the loss of dry weight (34.8 and 9. at 35 and 50 °C) due to the carbon present in the OFMSW, which is release like CO_2. Also, the increase in total mineralisation of OFMSW is 3.6 higher at 35 than at 50 °C. Reducing sugars content is almost 10 times higher at 50 °C (118.4 mg g^{-1} DM) than at 35 °C (12.2 mg g^{-1} DM); it can be explained because the higher enzyme activities (at least 3 times higher) were found at 50 °C, 18.3 ± 2.8 14.17 ± 2.6 U g^{-1} DM, for pectinases and xylanases, respectively. Regarding the final pH, an acidic pH (4.7) was determined at 50 °C in contrast to the neutral final pH (7.4) found at 35 °C. The results at 35 °C are in agreement with that reported in the literature where low enzyme activities, basic pH and a low CO_2 formation rate indicate that the organic matter is in the process of stabilization and microbial activity gradually ceases (Beck-Friis et al., 2001; Tejada et al., 2009).

4. Conclusion

Controlled conditions in aerobic mineralisation of the OFMSW allowed high rates of mineralisation, yielding up to 432.9 mg CO_2 g^{-1} IDM after 2 days of treatment. The maximum CO_2 constant rate obtained ($5.28\ d^{-1}$) is 3.52 times higher than that reported in literature ($1.5\ d^{-1}$). Respirometry analysis clearly allowed to determine rapid and slow mineralisation phases of the OFMSW. Aerobic mineralisation of the OFMSW is favoured in a slightly acidic pH (5–6) at 35 °C with the addition of CM of 8% and a C/N ratio of 30. The experimental evidence suggests the potential use of this process for further friendly environmental processes.

Acknowledgements

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