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PREDICTION OF TEMPERATURE AND THERMAL INERTIA EFFECT IN THE MATURATION STAGE AND STOCKPILING OF A LARGE COMPOSTING MASS

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Abstract

A macroscopic non-steady state energy balance was developed and solved for a composting pile of source-selected organic fraction of municipal solid waste during the maturation stage (13500 kg of compost). Simulated temperature profiles correlated well with temperature experimental data (ranging from 50 to 70ºC) obtained during the maturation process for more than 50 days at full scale. Thermal inertia effect usually found in composting plants and associated to the stockpiling of large composting masses could be predicted by means of this simplified energy balance, which takes into account terms of convective, conductive and radiation heat dissipation. Heat losses in a large composting mass are not significant due to the similar temperatures found at the surroundings and at the surface of the pile (ranging from 15 to 40ºC). In contrast, thermophilic temperature in the core of the pile was maintained during the whole maturation process. Heat generation was estimated with the static respiration index, a parameter which is typically used to monitor the biological activity and stability of composting processes. In this study, the static respiration index is presented as a parameter to estimate the metabolic heat that can be generated according to the biodegradable organic matter content of a compost sample, which can be useful in predicting the temperature of the composting process.

Keywords: Composting, Energy balance, Maturation, Respiration index, Temperature profile, Thermal inertia.

1. Introduction

At present, composting is becoming an attractive and environmentally friendly technology to treat and recycle organic solid wastes, and its use is increasing in developed countries. From the technical and scientific point of view, composting is an extraordinarily complex process, in which mass and energy transfer phenomena and microbiological degradation and non-steady state conditions coexist. Composting is an aerobic process, which requires oxygen to stabilize the organic wastes, optimal moisture and porosity. Temperature, oxygen and moisture are often selected as the control variables in the composting process, because they can be simply determined and they are the most significant parameters in controlling the process (Haug, 1993).

There is abundant literature related to different aspects of composting, such as microbiological studies (Tiquia et al., 2002), changes of chemical composition (Pichler et al., 2000), technical and operational considerations (Wong and Fang, 2000) or even some aspects of process modeling such as kinetics (López-Zavala et al., 2004). However, there is scarce information about the prediction of temperature profiles in composting processes, especially at full-scale. Under these conditions, metabolic heat generation is combined with the thermal inertia effect found in compost materials due to their self-insulating properties (Haug, 1993), in consequence, high thermophilic temperatures are usually maintained during the maturation or stockpiling of compost (Liao et al., 1995; Avnimelech et al., 2004). This phenomenon is not observed in laboratory or pilot scale studies, in which temperature decreases rapidly when the easily biodegradable organic matter is consumed (Gea et al., 2003; Petiot and de Guardia, 2004). In general, the set-up of an industrial-scale facility is not directly transferable to laboratory-scale (Körner et al., 2003). Since temperature is a crucial parameter in composting because it determines the pathogen kill of the compost prior to its application to soil, the evolution of this parameter requires a full scale study. In general, international requirements on compost sanitation are based on a combination of time-temperature conditions that must be guaranteed (European Commission, 2001; U.S. Environmental Protection Agency, 1995). According to these conditions, the prediction of temperature evolution both in active composting and in maturation phases is of especial interest for composting plant managers and for the commercialisation and safe application of compost.

From the few works conducted on the thermal properties of the composting process, the studies conducted by Weppen (2001; 2002) are particularly remarkable. In these works, energy balances for composting materials are fully developed and solved, and all the terms responsible for heat dissipation (convective, conductive and water evaporation) are quantified. However, the results are limited to laboratory scale (Weppen, 2002) or full-scale closed reactors (Weppen, 2001), which is not the common operation mode at composting plants, especially for the maturation stage, which is usually carried out by means of the open windrow process. This process consists of non-aerated piles of compost stored outdoors, which are typically turned on a monthly basis (Haug, 1993).

In other few works, other relevant studies for the prediction of temperature in composting process have been carried out. Recent studies have focused of the study of surface compost temperatures of composting heaps and its relation to core temperatures (Turner et al., 2005) in an aerated active composting pile, with the aim of inferring pathogen deactivation, since important temperature gradients have been observed in large composting masses (Sommer et al., 2004). Other related works have studied the temperature effect on the biodegradation kinetics (Tremier et al., 2005) or the effect of turning on the temperature and oxygen profiles in composting (Avnimelech et al., 2004).

One of the main problems which hinders a reliable energy balance performance is the difficulty to obtain accurate measures of heat generation, especially when complex microbial communities interact (Daverio et al., 2003). Respiration indices have been routinely used in the monitoring of composting process to quantify the global biological activity or to determine the stability of compost (Ianotti et al., 1993; Scaglia et al., 2000; Adani et al., 2003; Gea et al., 2004). However, the use of these indices as a measure of heat generation is, to our knowledge, very limited (Cronje et al., 2003). RI is the amount of oxygen consumed by a compost sample per gram of organic matter, and it is well known that during aerobic oxidation, 4 moles of electrons must be transferred for each mole of oxygen reduced. Therefore, it can be estimated that oxygen consumption by aerobic microorganisms releases 440 kJ per mol O_2 (Haug, 1993; Weppen, 2001).

The main objective of this work is to develop a simplified energy balance for the prediction of temperature profiles during the maturation or stockpiling of a large compost mass. The energy balance is presented as a combination of typical heat dissipation terms and an approach to the metabolic heat generation based on the respiration index of the material, a parameter usually determined for the evaluation of the stability of compost samples. The balance is validated with experimental data from a composting plant.

2. Materials and methods

2.1. Maturation experiments

Source-selected organic fraction of municipal solid wastes (OFMSW), consisting of food and shredded yard wastes, and previously composted for 50 days was used as the main substrate for maturation experiments. OFMSW was composted at the composting plant of Jorba (Barcelona, Spain) and piles of composted OFMSW were investigated in the maturation stage (after 50 days of active composting). Four piles were built on a sloped concrete floor and stored outdoors, nonetheless, they were covered and protected from rainfall according to the normal operation of the plant (Figure 1). Trapezoidal piles (base: 2 m; height: 1.5 m; length: 10 m) of approximately 13500 kg of compost were monitored for 50 days. Table 1 shows the main initial (before maturation) and final (after maturation) parameters of the pile. No forced aeration or turning was provided to the maturation piles as this is the normal operation of the plant. No leachates were detected during the maturation process. During the maturation period, average outside temperature was 15ºC.

The pile core temperature and oxygen content were measured at 100 cm depth (centre of the pile) in 4 points of the pile. Pile surface temperature was measured at 5 cm depth in different points of the pile. Temperature and oxygen values have been presented as average values. Variability of temperature and oxygen values measured at different points of the pile was in the range of 10-20%. Temperature was measured with a portable Pt-100 sensor (Delta Ohm HD9214) and oxygen concentration was measured with a portable O_2 detector (Oxy-ToxiRAE, RAE) connected to a portable aspiration pump. The results shown in this paper are referred to one of the piles studied, since the temperature profiles obtained with the other three piles were very similar (less than 10% of variation).

2.2. Respiration tests

A static respirometer was built according to an original model previously described (Ianotti et al., 1993) and following the modifications and recommendations given by the U.S. Department of Agriculture and U.S. Composting Council (U.S. Department of Agriculture and U.S. Composting Council, 2001). A detailed description of the respirometer can be found elsewhere (Barrena et al., 2005).

Approximately 250 ml of a compost sample (between 100 and 150 g) were placed in 500 ml Erlenmeyer flasks on a nylon mesh screen that allowed air movement through the compost samples. In the experiments presented, respirometric measures were obtained at the same temperature of the pile in the moment of sampling to ensure the same conditions of the pile (Gea et al., 2004). Prior to the assays, samples were incubated for 4 hours. During all the incubation period, samples were aerated with previously humidified air at the sample temperature. The drop of oxygen content in a flask containing a compost sample was monitored with a dissolved oxygen meter (Lutron 5510, Lutron Co. Ltd., Taiwan) connected to a data logger. The rate of respiration of the compost sample based on organic matter content was then calculated from the drop of oxygen level. Results of the static respiration index (RI) are presented as an average of three replicates. A detailed description of the RI calculation can be found elsewhere (Barrena et al., 2005). Samples for respiration index were periodically obtained at day 0, 14, 28, 42 and 50. The standard deviation among respirometric replications was in the range of 5-10%.

2.3. Analytical Methods

Moisture content, organic matter content, pH, electrical conductivity, nitrogen content (N-Kjeldhal) and bulk density were determined according to the standard procedures (U.S. Department of Agriculture and U.S. Composting Council, 2001). These parameters were analyzed in the laboratory after extracting a representative solid sample of the pile. For this, four equidistant points of the pile (two for each side of the pile at a medium height of the pile) were sampled extracting about 5 l of compost. The total volume of sample (about 20 l) was manually mixed and a final volume of 2 l (1 kg) was used to carry out the analytical procedures. An aliquot of this solid sample (250 ml, 100-150 g) was also used for the determination of respirometric index. All measurements are presented in weight basis, unless specified.

2.4. Numerical procedures

Resolution of differential equations was carried out by means of Matlab 4 software (1994), using a 4th and 5th order Runge-Kutta method.

3. Results and discussion

3.1. Respiration index as a measure of heat generation

As it has been pointed before, the respiration index provides a metabolically generated heat estimation. Evolution of RI during the maturation stage is presented in Figure 2. As expected, an exponential decay fitted well the experimental values (R^2=0.997), since microbial degradation kinetics in composting processes are often described by firstorder kinetics (Haug, 1993; Nielsen and Berthelsen, 2002). According to the fit obtained and considering a total mass of 13500 kg of compost, an approximately constant moisture and organic matter content (40% and 46%, respectively, Table 1) and the equivalence between RI and heat generation mentioned previously, the metabolic heat generated during the maturation stage can be described by Equation (1):

$$Q_{gen} = 9193.7 \exp(-6.87t) \qquad (1)$$

where Q_{gen} is the heat metabolically generated (kJ h^{-1}) and t is time (h). The metabolic heat generated described by Equation (1) must be considered as a specific factor of the waste and conditions studied.

3.2. Development of the energy balance

Other important terms in the energy balance are those related to heat dissipation. Heat dissipation from a composting mass occurs through three basic mechanisms: convection (water evaporation and air movement), conduction and radiation. Surface temperature of the composting mass (T_{surf}) is required to estimate the terms of heat dissipation, with the exception of water evaporation. This term can be estimated by considering the loss of moisture of the composting mass (Table 1), assuming a linear pattern of water loss and a total weight constant, and considering the vaporization heat of water (Table 2). This pattern is typically observed in maturation piles presenting low biological activity determined by the respiration index or other methods (Larney et al., 2000; Richard et al., 2002). According to this, energy dissipated by water evaporation is approximately 1590 kJ h^{-1} (denominated as Q_{wev}). This value must be considered as specific to this waste, since water loss by evaporation is mainly depending on the compost temperature and porosity (Haug, 1993). Although water evaporation is the main contribution to maintain and control temperature in aerated active thermophilic composting processes (Haug, 1993), this term is comparable in order of magnitude to other heat dissipation terms in the energy balance when considering the maturation stage of piles presenting low biological activity according to the respiration index.

Convective heat dissipation is caused by the enthalpy differences between air entering and exiting the pile. It can be described by Equation (2):

$$Q_{conv} = n_2 C_{P2}(T_{surf} - T_0) - n_1 C_{P1}(T_{amb} - T_0) \qquad (2)$$

where: Q_{conv} is the convective heat dissipation (kJ h^{-1}), n_2 and n_1 are the air flows entering and exiting the composting mass respectively (mol h^{-1}), C_{P2} and C_{P1} are the average heat capacity of air entering and exiting the composting mass respectively (kJ mol^{-1} K^{-1}), T_{surf} is the surface temperature (K), T_0 is standard temperature (K) and T_{amb} is the ambient temperature (K).

T_0 was set to 298 K whereas the average ambient temperature during the maturation experiments was assumed to be 288 K (15ºC) according to local average temperature. Standard molar composition of air entering the pile was used (21% of O_2 and 79% of N_2), whereas the average molar composition of air exiting the pile was approximately 15% of O_2, 79% of N_2 and the rest (6%) is assumed to be CO_2. Values of C_{P1} and C_{P2} can be calculated according to the physical properties of these compounds (Table 2). On the other hand, air flow through the composting mass is mainly due to the convective airflow under passive aeration, because of the different temperatures and densities of air in a compost pile in a phenomenon known as "chimney effect" (Haug, 1993; Barrington et al., 2003). Air flows can be also estimated by performing a mass balance of air that takes into account the oxygen consumption predicted by RI and the average oxygen concentration in exiting gases (15%). The results obtained showed an average air flow of 180 mol h^{-1} and 193 mol h^{-1} for n_1 and n_2, respectively. Results provided by other authors on passive airflow are in the range of 1.5-0.7 mg dry air s^{-1} kg of dry material^{-1} for active composting materials (Barrington et al., 2003), whereas our results (expressed in these units) are approximately 0.3 mg dry air s^{-1} kg of dry material^{-1}, in accordance to the limited biological activity typically found in mature compost (Lasaridi and Stentiford, 1998).

Conductive and radiation heat dissipation terms can be calculated according to Equations (3) and (4) respectively (Haug, 1993):

$$Q_{cond} = UA(T_{surf} - T_{amb}) \quad (3)$$

$$Q_{rad} = sAF_aF_b(T^4_{surf} - T^4_{amb}) \quad (4)$$

where: Q_{cond} is the conductive heat dissipation (kJ h^{-1}), U is the overall heat transfer coefficient (kJ h^{-1} m^{-2} K^{-1}), A is the area of conduction and radiation heat transfer (m^2), T_{surf} is the surface temperature (K), T_{amb} is the average ambient temperature during the course of the experiment (288 K), Q_{rad} is the radiation heat dissipation (kJ h^{-1}), s is the Stefan-Boltzmann constant (kJ h^{-1} m^{-2} K^{-4}), F_a is the emissivity radiation factor and F_b is the configurational radiation factor. Values of U, σ, F_a, F_b can be obtained from literature

(Table 2) whereas A can be estimated from the pile geometry (Figure 1), resulting in a value of 46.1 m^2.

As can be observed in Equations (2), (3) and (4), T_{surf} is the only parameter necessary to solve the energy balance that can be described by Equation (5):

$$MC_P dT/dt = Q_{gen} - Q_{wev} - Q_{conv} - Q_{cond} - Q_{rad} \quad (5)$$

where: M is the total composting mass assumed constant (13500 kg), C_P is the heat capacity of compost (Table 2) and T is the core temperature of the pile (K), the parameter to be predicted.

Surface temperature (T_{surf}) is a crucial parameter for the simulation of temperature profiles since it determines the heat dissipation by convection, conduction and radiation mechanisms. To estimate T_{surf} a local calorific balance was carried out, taking into account that given a heat exchange area and under pseudo-steady state conditions, the heat internally transferred from the core to the surface of the pile must be equal to the heat dissipated in the surface (conduction and radiation terms) as shown in Equation (6):

$$Q_{icond} = Q_{rad} + Q_{cond} \quad (6)$$

with:

$$Q_{icond} = kA(T-T_{surf})/dx \quad (7)$$

where: Q_{icond}: heat internally conducted from the core to the surface of the pile (kJ h^{-1}), k is the average thermal conductivity of compost obtained from Haug (1993) and assuming a moisture content of 40% (Table 2) and dx is the average distance from the core to the surface which is assumed to 1 m.

Solving Equation (6) a relation between T and T_{surf} is obtained, which is presented in Figure 3. It can be observed that the relation between both temperatures is highly linear (T_{surf} = 0.0798T+13.809) and that the values of temperature surface are very different from those found in the core. This fact may be explained in terms of heat transfer processes. Thus, the important temperature gradient between the core and the surface represents a large heat transfer driving force and a large heat transfer rate. This fact has been experimentally confirmed by other works conducted during the active composting phase (Sommer et al., 2004; Turner et al., 2005) and it was also confirmed in the studied maturation pile. In Figure 1, experimental values of surface temperatures (determined at 5 cm depth) were measured at different locations in the maturation pile (after 15 days of maturation). Temperature values found in most of the surface were very low and near to the ambient temperature (15ºC), except for some points of the upper surface of the pile. This is probably due to the chimney effect that provokes the movement of hot air (low density) from the lower parts of the pile to the upper surface. Nevertheless, it is clear that heat dissipation terms must be low in comparison to other mechanisms of heat transfer, and this phenomenon will contribute to maintain high thermophilic temperatures in the core of the pile for a long time, provoking a thermal inertia effect.

3.3. Validation with experimental data

Equation (5) was numerically solved using the relationship found between T_{surf} and T (Figure 3) and taking into account all the hypotheses and simplifications discussed in the development of the energy balance. The core temperature profile obtained is presented in Figure 4. The curve starts with a slight temperature increase, which is typically observed when large masses of compost are stockpiled. The metabolic heat generated by relative stable compost piles (RI within 150-200 mg O_2 g organic matter^{-1}) is responsible for such effect. On the other hand, amounts of compost at laboratory scale (little mass and high area volume ratio) remain at mesophilic or ambient temperature. This phenomenon is observed in laboratory and pilot composting reactors, where the thermophilic temperature is only maintained for few weeks or even few days (Petiot and de Guardia, 2004). Afterwards, the simulated core temperature reaches a maximum value at day 15 (75ºC). After the temperature peak, a progressively decrease in temperature is observed, to reach a final value of 54ºC at day 50.

Figure 4 also shows the average experimental values found in the maturation of the pile. As it can be observed, dispersion of temperature values in different points of the pile was high (15-20%), which was probably due to the heterogeneity found in organic solid wastes, especially when large masses are considered. Nevertheless, the simplified energy balance correlated well with the experimental values during the maturation process. In general, heat losses in a large composting mass were not significant due to the similar temperatures found in the surroundings of the pile and on the surface temperature (Figure 1), since radiation term becomes the most important contribution to heat losses (Figure 5). In contrast, thermophilic temperature in the core of the pile was maintained during the whole maturation process. This is of special interest when the sanitation of a given waste is studied, since the industrial-scale temperature profiles are not directly transferable to laboratory-scale composting units.

4. Conclusions

From the results obtained, it can be concluded that:

1) A simplified energy balance developed and solved for a composting mass at the maturation stage predicted well the experimental temperature profile. It was observed that the heat generated by the biological activity is retained in the composting mass. This energy balance can be generalized to the study of the maturation phase of other composted materials and to predict sanitation of the material.
2) Heat dissipation in a compost pile occurred by convection, conduction and radiation mechanisms. The values of heat dissipation were not significant due to the similar temperature values of the surface of the compost pile and the surroundings. The most important heat loss was due to the radiation effect. On the other hand, thermophilic temperature was maintained during the maturation stage in the core of the pile, because of the self-insulating properties of compost.
3) Heat generation could be estimated with the static respiration index, a parameter which is typically used to monitor the biological activity and stability of composting processes. In this study, the static respiration index is used to calculate the metabolic heat that can be generated according to the biodegradable organic matter content of a compost sample.
4) The results found in this work can be useful in predicting the temperature profiles of the composting process, which is necessary to confirm the sanitation of the compost prior to soil application. Moreover, further developments in composting process

modeling should include the thermal effects described in this work. However, these developments should be accompanied by an important effort in the determination of the thermal properties of the compost at different phases of the composting process.

5. Appendix A. Nomenclature

A: area, m^2

C_P: heat capacity, kJ (kg^{-1} or mol^{-1}) K^{-1}

F_a: emissivity radiation factor

F_b: configurational radiation factor

k: thermal conductivity of compost, kJ m h^{-1} m^{-2} K^{-1}

n: air flow, mol h^{-1}

M: mass, kg

Q_{cond}: heat dissipation (conduction), kJ h^{-1}

Q_{conv}: heat dissipation (convection), kJ h^{-1}

Q_{rad}: heat dissipation (radiation), kJ h^{-1}

Q_{wev}: heat dissipation (water evaporation), kJ h^{-1}

Q_{gen}: heat generation, kJ h^{-1}

Q_{icond}: heat internally conducted in the pile, kJ h^{-1}

RI: respiration index, mg O_2 g organic matter^{-1}

t: time, h or d

T: core temperature, K or ºC

T_{amb}: ambient temperature, K or ºC

T_{surf}: surface temperature, K or ºC

T_0: standard temperature, K

U: overall heat transfer coefficient, kJ h^{-1} m^{-2} K^{-1}

dx: length of flow path, m

L: vaporization heat of water, kJ kg^{-1}

s: Stefan-Boltzmann constant, kJ h^{-1} m^{-2} K^{-4}

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Tables

Table 1: Initial (before maturation) and final (after maturation) characteristics of the maturation pile.

Parameter	**Initial**	**Final**
Moisture (%)	40.0	35.3
Organic matter (%, dry basis)	46.0	45.8
pH	8.3	8.6
Electrical conductivity (mS cm^{-1})	5.4	5.3
Respiration index (mg O_2 g organic $matter^{-1}$)	189.6	63.2
Bulk density (kg m^{-3}, wet basis)	600	620
Nitrogen content (N-Kjeldhal) (%, dry basis)	2.2	3.1

Table 2: Thermal and thermodynamic properties used in the energy balance.

Parameter	**Units**	**Value**	**Source**
C_P oxygen	kJ $kmol^{-1}$ K^{-1}	29.35	(Weppen, 2001)
C_P nitrogen	kJ $kmol^{-1}$ K^{-1}	29.12	(Weppen, 2001)
C_P carbon dioxide	kJ $kmol^{-1}$ K^{-1}	37.11	(Weppen, 2001)
C_P compost (40% moisture)	kJ kg^{-1} K^{-1}	2.01	(Haug, 1993)
T_0	K	298	(Haug, 1993)
F_a		0.9	(Haug, 1993)
F_b		1.0	(Haug, 1993)
L	kJ kg^{-1}	2260	(Weppen, 2001)
U	kJ h^{-1} m^{-2} K^{-1}	4.18	(Haug, 1993)
s	kJ h^{-1} m^{-2} K^{-4}	2.04 10^{-7}	(Haug, 1993)
k (40% moisture)	kJ m h^{-1} m^{-2} K^{-1}	1.436	(Haug, 1993)

Figure Legends

Figure 1: Experimental values of surface temperatures (ºC) at different locations in a composting pile (day 15 of maturation). Framed values correspond to measured core temperatures at the centre of the pile. Scheme is reproduced to approximate scale.

Figure 2: Evolution of respiratory index during the maturation stage. Exponential decay fit for respiration index is also included. Vertical bars in experimental values of respiratory index represent 95% probability of respiratory index value.

Figure 3: Simulation of surface temperature (T_{surf}) predicted from core temperature (T) according to the resolution of Equation (6): $Q_{icond} = Q_{rad} + Q_{cond}$. The curve is linear in the range considered. Equation of the linear fit is presented in Figure.

Figure 4: Simulated and experimental values of temperature and interstitial oxygen during the maturation stage. Simulation has been obtained by resolving the energy balance presented in Equation (5): $MC_P dT/dt = Q_{gen} - Q_{wev} – Q_{conv} – Q_{cond} – Q_{rad}$. Vertical bars in experimental values of temperature and interstitial oxygen represent 95% probability.

Figure 5: Quantification of heat losses by different mechanisms of heat transfer in the maturation pile (Convection: Equation (2): $Q_{conv} = n_2C_{P2}(T_{surf} - T_0) - n_1C_{P1}(T_{amb} - T_0)$, Conduction: Equation (3): $Q_{cond} = UA(T_{surf} - T_{amb})$, Radiation: Equation (4): $Q_{rad} = sAF_aF_b(T^4_{surf} – T^4_{amb})$ and Water Evaporation: Q_{wev} = 1590 kJ h^{-1}).

Figure 1: Barrena and Sánchez.

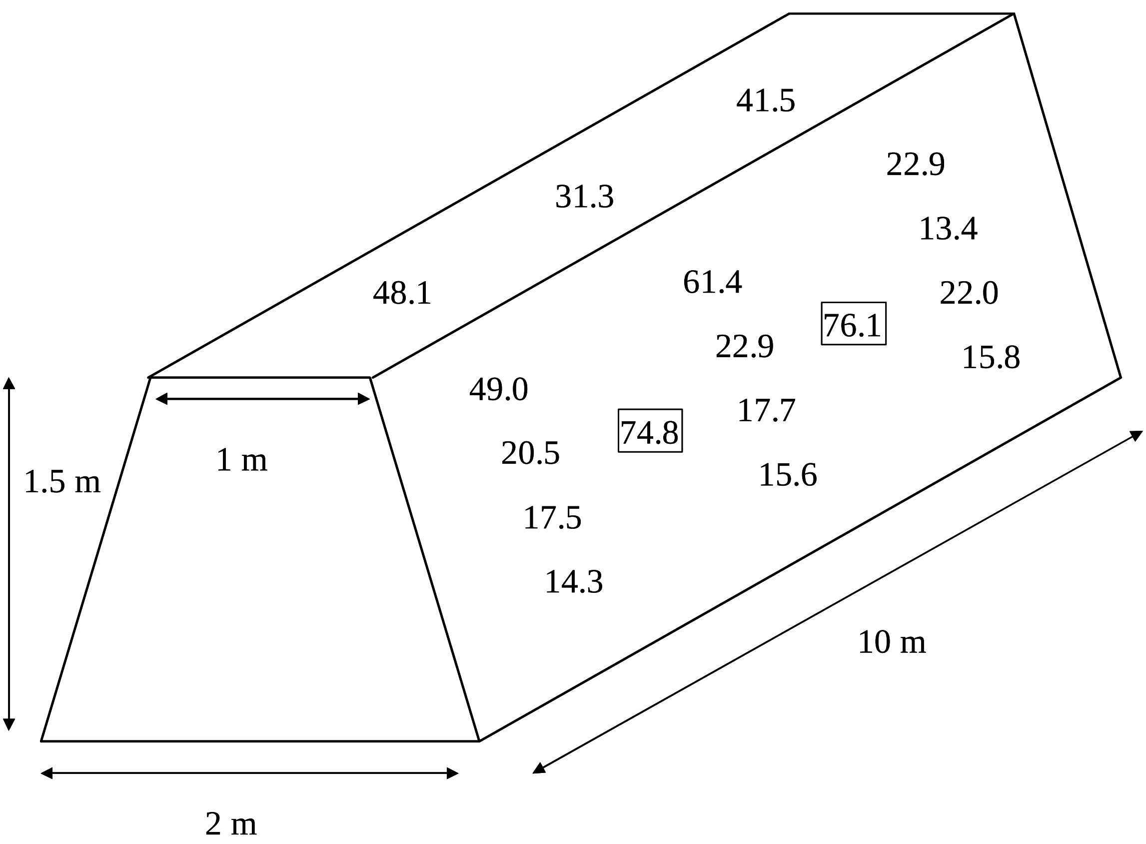

Figure 2: Barrena and Sánchez.

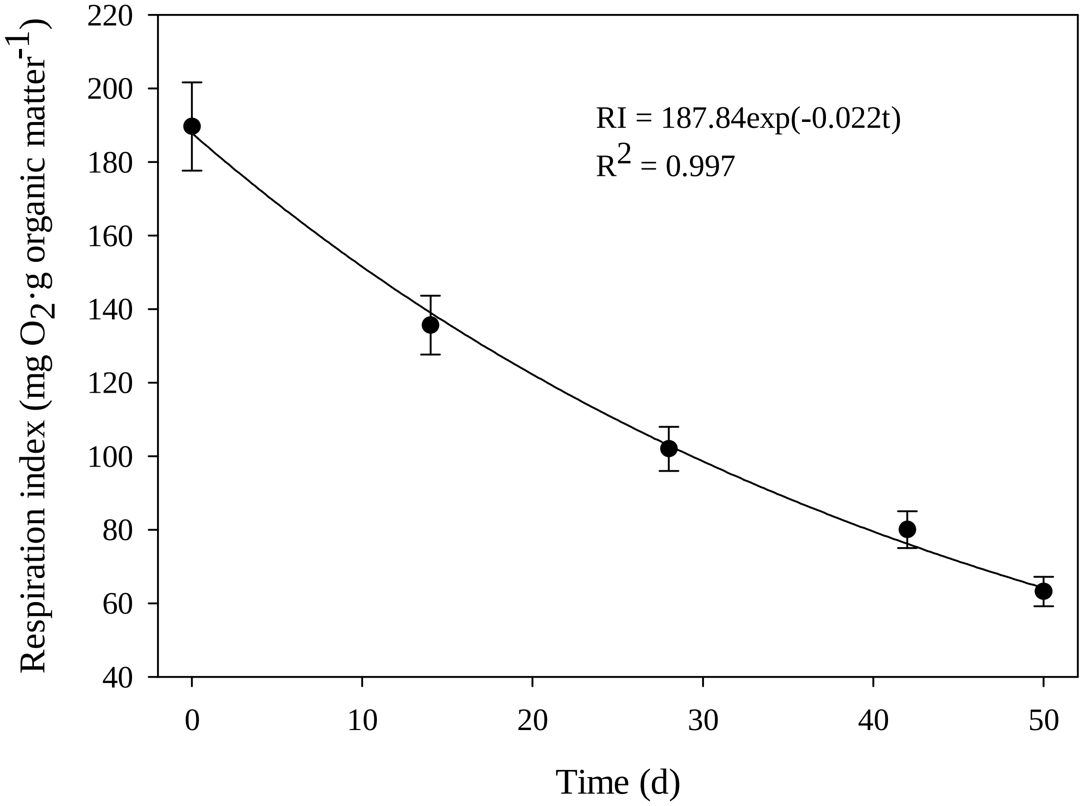

Figure 3: Barrena and Sánchez.

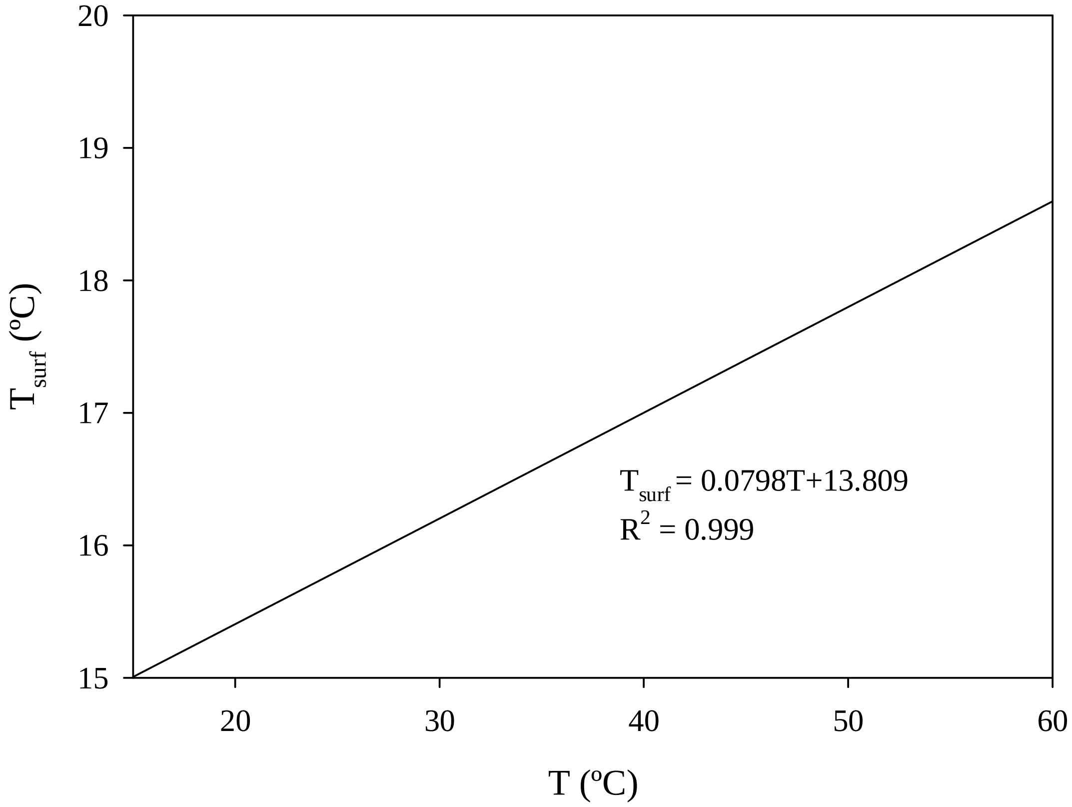

Figure 4: Barrena and Sánchez.

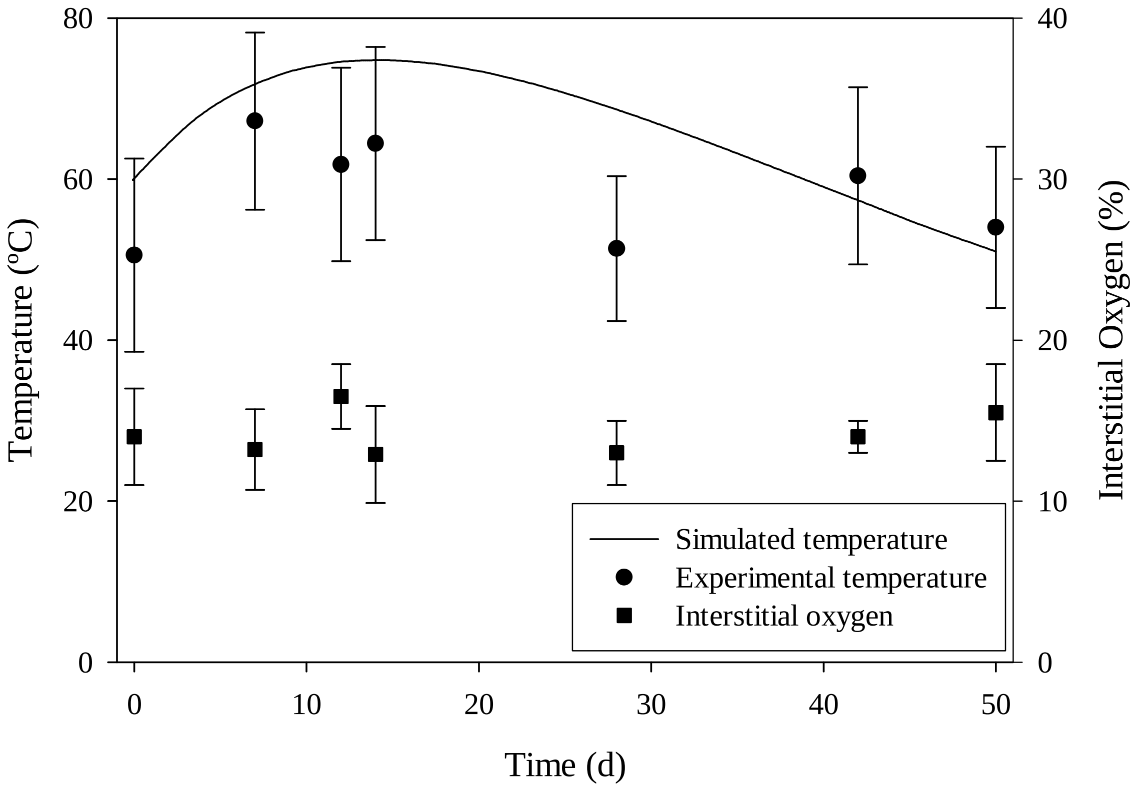

Figure 5: Barrena and Sánchez.