Monitoring the Biological Activity of the Composting Process: Oxygen Uptake Rate (OUR), Respirometric Index (RI) and Respiratory Quotient (RQ)

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Abstract

Composting of several organic wastes of different chemical composition (Source-separated Organic Fraction of Municipal Solid Waste, dewatered Raw Sludge, dewatered Anaerobically Digested Sludge and Paper Sludge) has been carried out under controlled conditions to study the suitability of different biological indexes (Oxygen Uptake Rate, Respirometric Index and Respiratory Quotient) to monitor the biological activity of the composting process.

Among the indexes tested, Oxygen Uptake Rate (also referred to as Dynamic Respirometric Index) provided the most reliable values of microbial activity in a compost environment. On the other hand, values of Static Respirometric Index measured at process temperature, especially in the early stages of the composting process, were significantly lower than those of the Dynamic Index, which was probably due to oxygen diffusion limitations present in static systems. Both Static and Dynamic indexes were similar during the maturation phase. Static Respirometric Index measured at 37ºC should not be used with samples obtained during the thermophilic phase, since it resulted in an underestimation of the respiration values. Respiratory Quotient presented only slight variations when changing the process temperature or the waste considered, and its use should be restricted to ensure aerobic conditions in the composting matrix.

Key words: Biological Activity, Composting, Organic Wastes, Oxygen Uptake Rate (OUR), Respiratory Quotient (RQ), Respirometric Index (RI).

Introduction

In recent years, the increasing amounts of organic solid wastes generated by municipalities, industries or agricultural activities have become a world-wide problem. Among the available technologies to treat and recycle organic wastes, composting is presented as one of the most promising options to recycle organic materials into a valuable organic fertilizer popularly known as compost.

Composting is a biotechnological process by which different microbial communities decompose organic matter into simpler nutrients. Composting is an aerobic process, which requires oxygen to stabilize the organic wastes, optimal moisture and porosity (Haug, 1993). Temperature is often selected as the control variable in the composting process, because is an indicator of the biological activity of the material. Also, as the composting process is usually carried out within the thermophilic range of temperature, it permits the hygienization of the final product (Salter and Cuyler, 2003).

There is abundant literature related to different aspects of composting, such as microbiological studies (Gamo and Shoji, 1999; Tiquia et al., 2002), changes of chemical composition (Pichler et al., 2000), technical and operational considerations (Qiao and Ho, 1997; Wong and Fang, 2000), emission of pollutants (Eitzer, 1995; He et al., 2001) or process modeling (López-Zavala et al., 2004). However, there is scarce information about the monitoring of biological activity of composting processes in comparison with other biotechnology fields, such as fermentation technology or wastewater treatment.

Oxygen Uptake Rate (OUR) has been traditionally used in aerobic processes to estimate on-line the biological activity, especially in the wastewater treatment. In the composting field, OUR is often referred as Dynamic Respiration Index (DRI). OUR or DRI can also be estimated off-line and without continuous aeration by using respirometric techniques known as Static Respiration Index (SRI, or simply RI), which is commonly used to determine compost stability (Ianotti et al., 1993; Chica et al., 2003). Both parameters are indicators of the biological activity of a composting process. Ideally, DRI and SRI would be identical in an aerobic environment but significant differences have been found between both indexes in composting experiments. Concretely, the use of SRI results in an underestimation of the biological activity of a compost sample, which is usually attributed to oxygen diffusion problems in the determination of the respirometric index in solid static samples (Scaglia et al., 2000; Adani et al., 2003).

The respiration quotient (RQ), representing the relationship between CO_2 produced and O_2 consumed, is approximately equal to 1 under aerobic conditions (Atkinson and Mavituna, 1983), although it depends on the biochemical composition of the organic material. This parameter is, to our knowledge, rarely measured in composting processes. Since it is a characteristic value directly referred to organic waste composition and active microbial communities, RQ can be used in the monitoring and control of the composting process (Atkinson et al., 1997) and to predict air requirements and CO_2 production (Smars et al., 2001). Given a defined waste, the value of RQ in a composting process can be considered steady under different conditions of aeration rate or moisture (Klauss and Papadimitriou, 2002; Mönning et al., 2002). In other works, some authors have found some differences in RQ when composting wastes amended with fats (Weppen, 2001), or when composting the same waste under different temperature regimes (Nakasaki et al., 1985). Both facts have been correlated to metabolic effects associated to the growth of different microbial communities using different organic substrates under different conditions.

In the present work, different wastes were composted under controlled conditions with the following objectives: i) to determine the values of OUR-DRI, SRI and RQ related to the composting of different wastes of different biochemical composition; ii) to study the suitability of these indexes to monitor the biological activity of the composting process; iii) to compare the values of DRI and SRI; and iv) to study the factors affecting the RQ value.

Materials and Methods

Composted Materials

Four wastes were used in the composting experiments: Source-separated Organic Fraction of Municipal Solid Waste (OFMSW) amended with vegetal wastes from the municipal composting plant of Sant Cugat del Vallès (Barcelona, Spain); dewatered Raw Sludge (RS) composed of primary and activated sludge from the urban wastewater treatment plant of La Garriga (Barcelona, Spain); dewatered Anaerobically Digested Sludge (ADS) from the urban wastewater treatment plant of Granollers (Barcelona, Spain) and Paper Sludge (PS) from a recycled paper manufacturing industry (Zaragoza, Spain). Table I presents the main characteristics of composted materials. In the case of wastewater sludge (RS and ADS) wood chips from a local carpentry were used as bulking agent in a volumetric ratio 1:1, which was optimal for sludge composting (Gea et al., 2003).

Composting Experiments

Composting experiments were undertaken in a 100-L static composter (Figure 1). A plastic mesh was fitted at the bottom of the recipient to support the material and separate it from possible leachates. Several holes were perforated through the walls of the vessel to permit air movement, leachates removal and the insertion of different probes. The composter was placed on a scale (BACSA mod. I200) for on-line waste weight monitoring.

Four Pt-100 sensors (Desin mod. SR-NOH) inserted at different points inside the 100-L tank were used for monitoring temperature in the composting experiments. Temperature average values are presented. After aspiration from the sample, oxygen and CO_2 concentration in interstitial air were monitored with an oxygen sensor (Sensox, Sensotran, Spain) and an infrared detector (Sensontran I.R., Sensotran, Spain), respectively. All sensors were connected to a self-made data acquisition system. Oxygen was controlled by means of a feedback oxygen control which automatically supplied fresh air (room temperature) to the reactor by means of a flow meter (Sensotran mod. MR3A18SVVT) to maintain an oxygen concentration over 10%.

Moisture content was initially adjusted and maintained between 40-60% during all the experiences (adding tap water when necessary), since it is considered optimal for composting (Haug, 1993).

Monitored Parameters

Oxygen Uptake Rate (OUR) or **Dynamic Respirometric Index** (DRI) was on-line determined using Equation (1):

$$OUR = \frac{F\left(20.9 - O_{2,out}\right)}{M \cdot 100} \cdot \frac{P \cdot 32 \cdot 60}{R \cdot T \cdot DM \cdot TOM} \qquad (1)$$

where: OUR, oxygen uptake rate (g $O_2 \cdot$ Kg $TOM^{-1} \cdot h^{-1}$); F, air flow into the reactor ($L \cdot min^{-1}$); $O_{2,out}$, oxygen concentration in the exhaust gases (%, mol $O_2 \cdot mol^{-1}$); M, total mass of waste in the reactor (kg); P, atmospheric pressure at the elevation of measurement (atm); 32, oxygen molecular weight (g $O_2 \cdot$ mol O_2^{-1}); 60, conversion factor from minutes to hours; 20.9, percentage of oxygen in inlet air; R, ideal gas constant (0.08206 $L \cdot atm \cdot mol^{-1} \cdot K^{-1}$); T, temperature (K); DM, fraction of dry matter of a parallel sample aliquot (kg $DM \cdot kg^{-1}$); TOM, fraction of total organic matter of a parallel sample aliquot in dry basis (kg $TOM \cdot$ kg DM^{-1}).

Static Respirometric Index (SRI) was off-line determined using a static respirometer based on the model previously described by Ianotti *et al.* (1993) and Ianotti *et al.* (1994) and following the modifications and recommendations given by the U.S. Department of Agriculture and U.S. Composting Council (2001). Briefly, the drop of oxygen content in a flask containing a compost sample was monitored with an oxygen meter (Lutron 5510, Lutron Co. Ltd., Taiwan) connected to a personal computer (RS232 communication protocol) with a proper software to register the oxygen values. The setup included two water baths for carrying out experiments at two different temperatures simultaneously. Temperatures assayed were a fixed value of 37 ºC (U.S. Department of Agriculture and U.S. Composting Council, 2001) and the *in situ* temperature of the composter at the moment of sampling. Prior to the assays, samples for experiments at 37 ºC were incubated for 18 hours at this temperature, while samples for experiments at *in situ* temperatures where incubated for 4 hours at such temperature. During all the incubation period samples were aerated with previously humidified air at the sample temperature. Once the incubation period was finished, O_2 level was then recorded every 15 seconds for 90 minutes. In all experiments three replicates were used. After oxygen measurement, the total volume of free air space in each sample flask was determined. The Static Respirometric Index (SRI) of the compost sample referred to total organic matter content was calculated from the slope in a linear segment on the chart O_2 (%) versus time using Equation (2).

$$SRI = \frac{V \cdot P \cdot 32 \cdot s \cdot 60}{R \cdot T \cdot X \cdot DM \cdot TOM} \qquad (2)$$

where: SRI, Static Respirometric Index (g $O_2 \cdot$ kg $TOM^{-1} \cdot h^{-1}$); V, volume of air in the flask (L); s, slope of change in O_2 percentage per minute divided by 100 (%, mol $O_2 \cdot mol^{-1} \cdot min^{-1}$); X, wet weight of compost test aliquot (kg).

Respiratory quotient (RQ) was on-line determined using equation (3):

$$RQ = \frac{CO_{2,out}}{20.9 - O_{2,out}} \qquad (3)$$

where: RQ, respiratory quotient (dimensionless); $CO_{2,out}$, carbon dioxide concentration in the exhaust gases (%); $O_{2,out}$, oxygen concentration in the exhaust gases (%). CO_2 percentage in inlet air was considered negligible.

Analytical Methods

Moisture, Dry Matter (DM), Total Organic Matter (TOM), N-Kjeldhal and pH were determined according to the standard procedures (U.S. Department of Agriculture and U.S. Composting Council, 2001). The composter material was manually homogenized prior to sampling and the volume of sample was 1 L to ensure a representative portion of the material.

Results and Discussion

Composting experiments

Composting of different wastes was performed under controlled conditions. Relevant parameters of the composting experiments are presented in Figs. 2, 3, 4 and 5 for OFMSW, ADS, RS and PS, respectively. In the case of OFMSW, ADS and RS the thermophilic range of temperatures was quickly achieved and maintained for 3-5 days (Figs. 2a, 3a, 4a). This period was followed by a longer mesophilic maturation phase, which corresponded to a typical composting temperature profile at laboratory scale. In the case of PS, the thermophilic phase was longer and the air requirements were higher (Fig. 5a). This was probably due to the combination of organic compounds found in paper sludge, which consists of an easily biodegradable cellulose fraction and a more recalcitrant fraction of lignin responsible for the elongation of the composting process and the possible presence of a specialized microbial community (Charest et al., 2004).

An oxygen based control was used in the composting experiments. Using this control, oxygen in the material was maintained under strictly aerobic conditions (no oxygen limitation) by adjusting the air flow. As can be seen in Figs. 2b, 3b, 4b and 5b, oxygen content in interstitial air was over 10%, except in some sporadic occasions that corresponded to compressor failures or sampling. On the other hand, temperature profiles for all the wastes permitted the hygienization of the material.

Static Respirometric index (SRI)

Respirometric index has been proposed both as biological activity indicator and stability index (Ianotti et al., 1993; Adani et al., 2000). Among the different strategies used for the determination of the respirometric index, one of the most popular, simple and low-cost technique is the Static Respirometric Index (SRI, or simply RI), which is carried out off-line by incubating a compost sample and calculating the oxygen consumption. Respirometric index is often determined at temperatures ranging from 30 to 37ºC (Ianotti et al., 1993; U.S. Department of Agriculture and U.S. Composting Council, 2001; Lasaridi and Stentiford, 1998), which are adequate to predict compost stability. However, if the objective is to estimate the biological activity of the composting process in the initial thermophilic phase, the respirometric index should be determined at the process temperature (Liang et al., 2003; Mari et al., 2003).

In Figs. 2c, 3c, 4c and 5c, the profiles obtained in the determination of SRI for several samples both at 37ºC and process temperature are shown. Table II presents a summary of some of the results obtained for the SRI and other biological parameters. As can be seen, SRI determined at process temperature was higher than that of 37ºC. As expected, differences between both indexes were more significant in the thermophilic phase (Table II, maximum values of SRI) than in the final compost, when the temperature was close to 37ºC (mesophilic phase, Table II, minimum values of SRI). It is likely that in the determination of SRI at 37ºC, the thermophilic microorganisms only exhibit a limited growth, whereas the mesophilic population is scarce. At process temperature, SRI is determined at the *in situ* composting conditions and the microbial populations present in the material are fully active. It was also found that changes in the SRI determined at 37ºC during the composting process were minimal, whereas SRI profiles determined at process temperature correlated well with process temperature. On the other hand, the values of SRI at process temperature were initially higher for OFMSW and RS than for ADS and PS (Table II), which was in accordance with the biodegradability of the wastes and the presence of more labile organic compounds in "fresh" wastes such as OFMSW and RS.

In conclusion, it can be stated that SRI can be used for monitoring the biological activity of the composting process; however, it should be determined at the same conditions of the process material, especially temperature. Although the SRI determination is usually conducted at mesophilic temperatures, these values should be exclusively used for compost material in the maturation stage.

Oxygen Uptake Rate (OUR)

Microbial respiration is typically expressed as Oxygen Uptake Rate in the biotechnological field. Although OUR is a general term which does not presuppose any specific conditions in its determination, in the composting field it is usually reserved for on-line measurements of oxygen consumption. Indeed, OUR is often referred as Dynamic Respirometric Index (DRI) and it is determined in pilot scale composters with high levels of instrumentation (Adani et al., 2000; Adani et al., 2001).

In the present study, OUR was on-line determined for the different wastes studied in several stages of the composting process. Some representative values of OUR are shown in Figs. 2c, 3c, 4c and 5c. In general, evolution of OUR was well correlated with the composting activity (temperature) and an important decrease in OUR values was observed during the composting process. Additionally, when the different wastes were compared in terms of initial OUR, values for RS were largely higher (41.38 g $O_2 \cdot Kg\ TOM^{-1} \cdot h^{-1}$) than that of ADS (16.45 g $O_2 \cdot Kg\ TOM^{-1} \cdot h^{-1}$), according to the high biodegradability of RS. Both aspects confirmed that OUR can be very useful in the monitoring of the biological activity of the process. However, as OUR determination requires a closed reactor and a level of instrumentation that is not found in most of the composting plants (*e.g.* windrow composting), the values of OUR were compared to those of SRI at process temperature as OUR is inherently determined at process temperature. As can be seen in Figs. 2c, 3c, 4c and 5c and Table II, values of OUR were much higher than those of SRI, especially in the initial stages of the process. These important differences may be caused by the insufficient oxygen diffusion in static samples, which limited biological activity. In dynamic systems, forced aeration may contribute significantly to the oxygen supply in all the biologically active areas of the material. These results had been previously observed in the measurement of the biological activity of compost samples by static and dynamic approaches and the discrepancies between the static and dynamic index had been quantified (Scaglia et al., 2000; Adani et al., 2003). Concretely, some authors propose that the dynamic index can be estimated by multiplying the static index by a factor of 2 (Scaglia et al., 2000). The differences between the dynamic and the static index found in our work were, however, more important, especially at the initial stages of the process. For instance, in the case of ADS, RS and PS, the dynamic index was approximately 4-5 times higher than the static index, which could be due to a more efficient air supply in the composting reactor or the fact that the majority of referred respirometric indexes are obtained from samples of mature compost. OFMSW was the only waste where dynamic and static indexes were similar, which was probably due to the high level of porosity of this material, and the consequent absence of diffusional problems.

At the final maturation phase, values of OUR and SRI determined at process temperature and 37ºC were relatively similar (Figs. 2c, 3c, 4c and 5c). In this case, it was probable that a reduced biological activity had become the limiting step in the oxygen consumption instead of oxygen diffusion, which tended to equilibrate static and dynamic indexes. From this point of view, OUR (DRI) is the best biological activity correlating parameter in the composting process, since the SRI at process temperature provides an underestimated value of the biological activity in the early stages of the composting process. Nevertheless, the predicted patterns of biological activity seem correct when using both indexes (Figs. 2c, 3c, 4c and 5c).

Finally, it is worthwhile noticing that although temperature values are similar for all the wastes considered, biological activity indexes for each waste studied are significantly different according to its organic matter composition. Additionally, temperature is not always useful for monitoring the biological activity, for instance, large amounts of material with high thermal inertia may exhibit high temperatures when biological activity has ceased (Haug, 1993). This confirms the suitability of these indexes to monitor the biological activity in the composting process.

Although some of these results had been previously observed in the measurement of the biological activity of compost samples, this is, to our acknowledge, the first work where the different approximations to OUR used in the composting field, namely DRI, SRI at process temperature and 37ºC, are compared as biological activity monitors in the whole process of composting of wastes of different composition.

Respiratory Quotient (RQ)

The microbial respiratory quotient (RQ, moles of carbon dioxide produced per mol of oxygen consumed) is known to be different when wastes of different organic composition are degraded under aerobic conditions (Atkinson and Mavituna, 1983). In general, the values of RQ increases as the material becomes more oxidized. For instance, it is reported that the value of RQ decreases from 0.95 to 0.87 when some fats, a low-oxidized organic material, are mixed with OFMSW (Weppen, 2001). In Figs. 2b, 3b, 4b and 5b, values of oxygen and carbon dioxide contents, and the calculated value of RQ for the considered wastes are shown. Table II presents the average values of RQ for the studied wastes.

Although RQ is commonly used in the biotechnological field usually using pure cultures, it is rarely determined in composting process. From our results, it can be seen that only slight differences were observed when changing a waste. As expected, values of RQ for RS (Table II, 1.00) were lower than that of ADS (Table II, 1.09) because it is likely that RS contained more labile non-oxidized organic compounds. However, the value obtained for OFMSW (Table II, 1.24) is probably higher than expected, since it is a fresh material. Other authors have reported values of RQ for different wastes under composting conditions. For instance, values of RQ for MSW were between the range of 1.02 (Smars et al., 2001) to 0.95 (Weppen, 2001), whereas values for paper sludge were 0.92 (Atkinson et al., 1997). Other studies observed slight differences of RQ when temperature was changed, which was attributed to the dominance of catabolism or anabolism at different temperatures (Nakasaki et al., 1985). All these values are quite similar to our results. However, the comparison with these values may not be possible, since the presence of anaerobic conditions is not routinely quantified in the composting experiments. The production of methane and several nitrogen oxides emissions during composting has been extensively studied (He et al., 2001; Beck-Friis et al., 2003). Thus, since part of the material can obviously be anaerobically degraded the resulting RQ will undergo a dramatic change.

More interesting is the fact that RQ values are quite stable during composting of different wastes, even though when there is a transition between a thermophilic and a mesophilic phase (Figs. 2b, 3b, 4b and 5b) and the waste composition is changing. This fact has been confirmed by other studies, when deviations found in RQ during a composting process are usually below 10% even when aeration strategies and oxygen control were changed (Klauss and Papadimitriou, 2002).

This seems to indicate that biodegradation of organic matter in a composting environment may not be a sequential process, including different steps with different microbial communities involved in a complex structure of organic matter degradation, similarly to the anaerobic degradation of organic matter. It can be hypothesized that organic matter degradation in composting is a more straightforward process, in which communities of microorganisms able to degrade some substrates coexist and are sustained and the changes in microbial communities are more gradual. This fact could have important implications in the future modeling of the composting process.

Another possible explanation might be, nevertheless, a lack of sensibility in the determination of the RQ, or the presence of not-considered anaerobic or anoxic zones (He et al., 2001). The determination of the role of RQ in the composting field will be of course subject of future studies; however, from the scope of the present work, it is obvious that it cannot be used for monitoring the microbial activity of the process.

Conclusions

From the results obtained, it can be concluded that:

1) Oxygen Uptake Rate (Dynamic Respirometric Index) provided the most suitable values of microbial activity in a compost environment.

2) Static Respirometric Index measured at process temperature, especially in the early stages of the composting process, was significantly lower than Dynamic Index, which was probably due to oxygen diffusion limitations in static systems. Both values of Static and Dynamic indexes were similar during the maturation phase.

3) Static Respirometric Index measured at 37ºC should not be used with samples obtained during the thermophilic phase, since it resulted in an underestimation of the respiration values.

4) Respiratory Quotient presented only slight variations when changing the process temperature or the waste considered, and its utility should be restricted to ensure aerobic conditions in the composting matrix or future modeling studies.

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Tables

Table I: Main characteristics of the composted materials.

Parameter	OFMSW	ADS	RS	PS
Moisture (%)	36.1	67.7	72.7	36.7
Dry Matter (%)	63.9	32.3	27.3	63.3
Total Organic Matter (% dry basis)	52.3	52.8	60.4	33.7
N-Kjeldhal (% dry basis)	2.2	2.6	2.5	0.43
C/N ratio	20	8	12	34
pH	6.1	7.6	7.1	7.5

Table II: Summary of the results obtained in the monitoring of composted wastes.

Parameter	OFMSW	ADS	RS	PS
RQ (average and standard deviation)	1.24 ± 0.09	1.09 ± 0.08	1.00 ± 0.08	1.17 ± 0.09
Maximum OUR (g $O_2 \cdot$ Kg $TOM^{-1} \cdot h^{-1}$)	4.73	16.45	41.38	35.98
Minimum OUR (g $O_2 \cdot$ Kg $TOM^{-1} \cdot h^{-1}$)	0.11	0.79	0.27	1.80
Maximum SRI (T)* (g $O_2 \cdot$ Kg $TOM^{-1} \cdot h^{-1}$)	7.64	5.02	11.96	5.61
Minimum SRI (T)* (g $O_2 \cdot$ Kg $TOM^{-1} \cdot h^{-1}$)	1.77	1.95	0.23	2.40
Maximum SRI (37ºC) (g $O_2 \cdot$ Kg $TOM^{-1} \cdot h^{-1}$)	2.48	3.74	6.68	2.88
Minimum SRI (37ºC) (g $O_2 \cdot$ Kg $TOM^{-1} \cdot h^{-1}$)	1.05	1.48	1.46	1.11

* determined at composting process temperature

Figure Legends

Figure 1: Scheme of the composting vessel.

Figure 2: Composting of OFMSW: a) Temperature (continuous line) and Air Flow (dotted line); b) Oxygen content (continuous line), Carbon dioxide content (dotted line) and Respiratory Quotient (circles); c) Oxygen Uptake Rate (circles), Static Respirometric Index at process temperature (triangles) and Static Respirometric Index at 37ºC (squares).

Figure 3: Composting of ADS. Same legend as Figure 2.

Figure 4: Composting of RS. Same legend as Figure 2.

Figure 5: Composting of PS. Same legend as Figure 2.

Fig.1: Gea *et al*

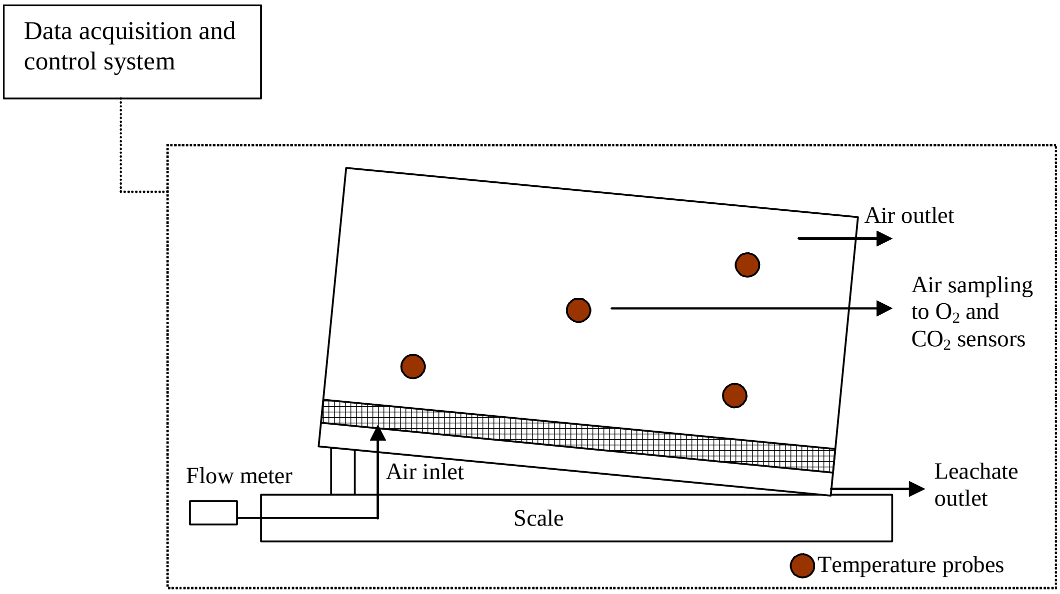

Fig.2: Gea *et al*.

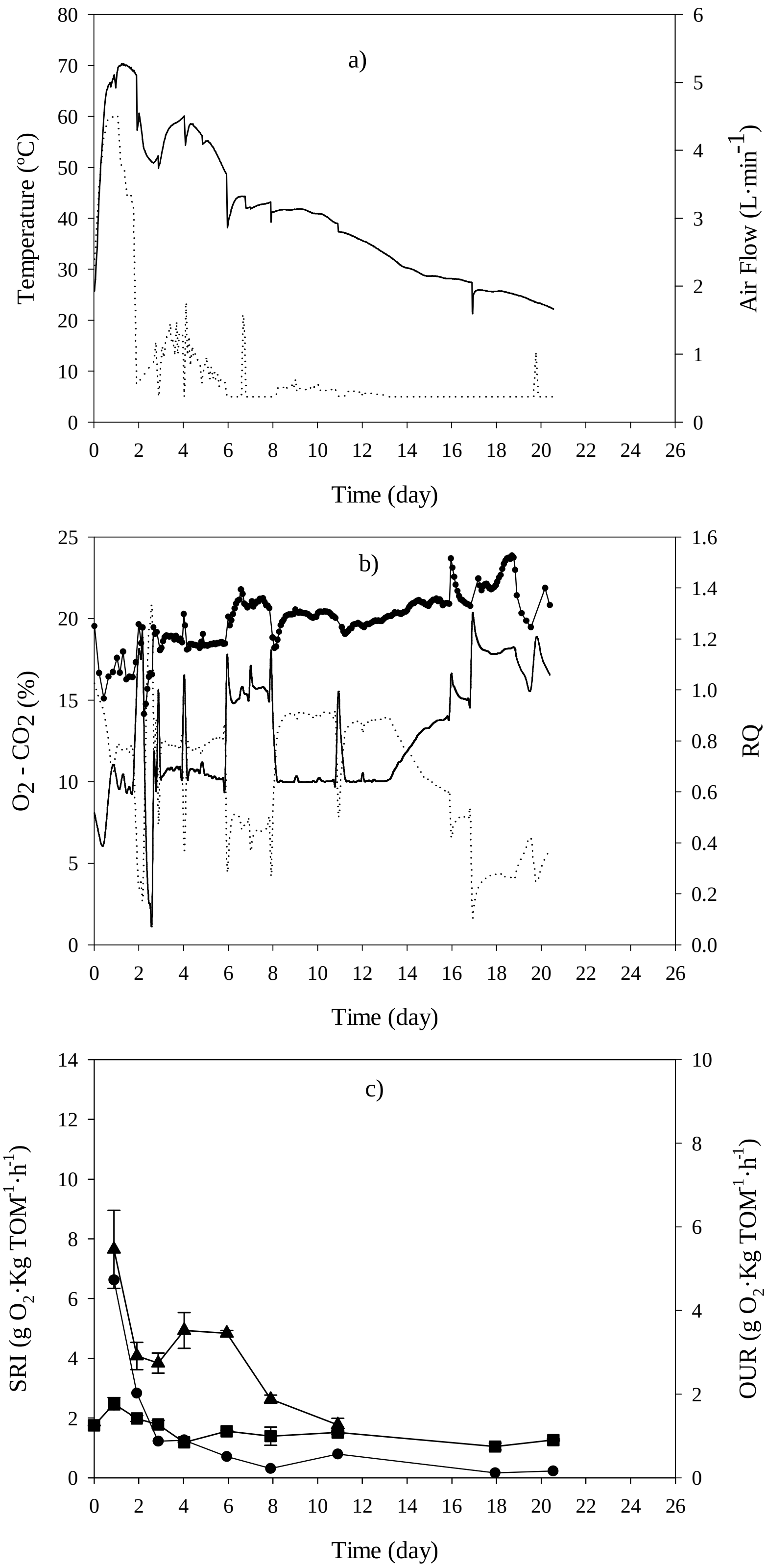

Fig.3: Gea *et al*.

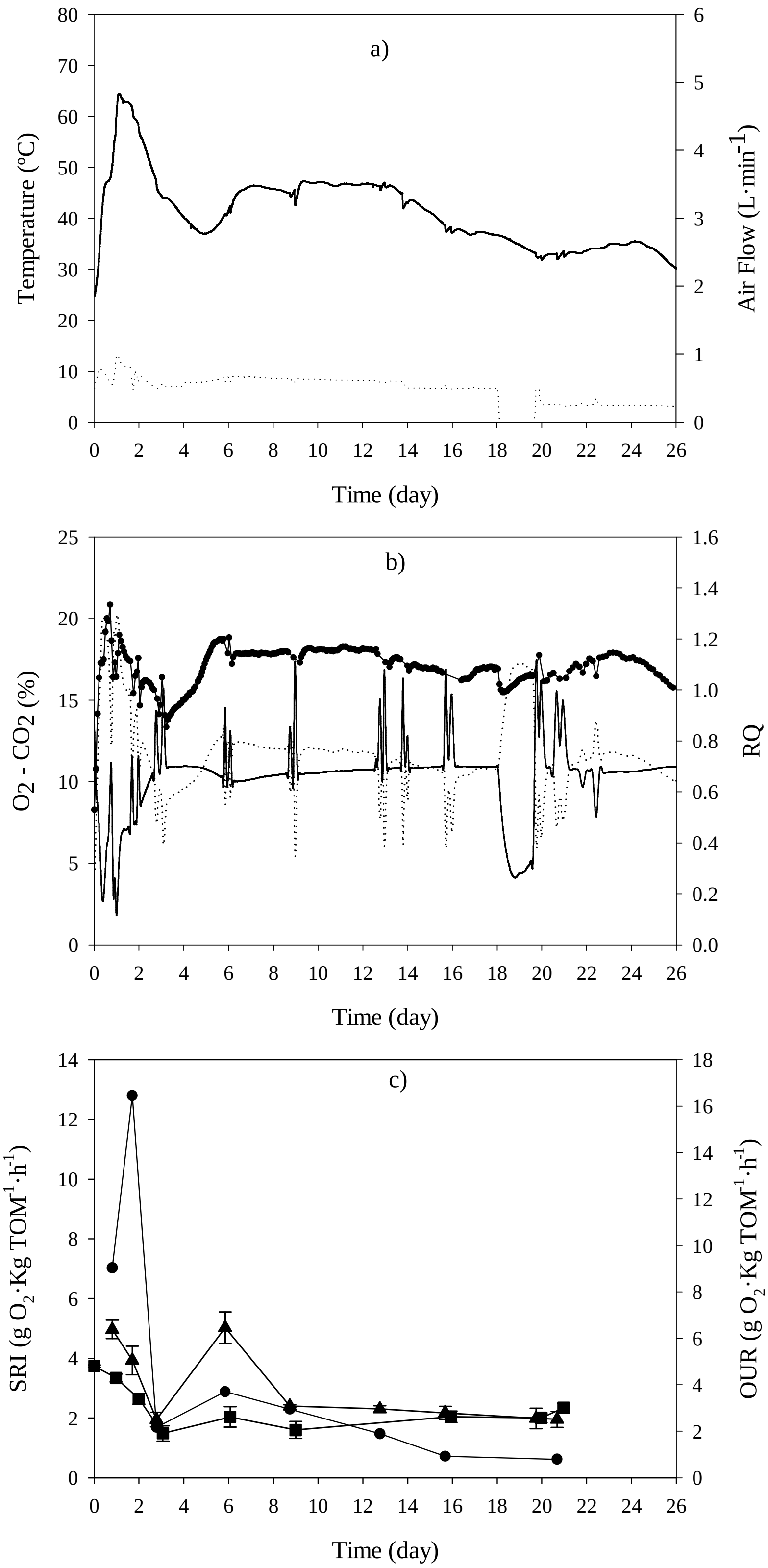

Fig.4: Gea *et al*.

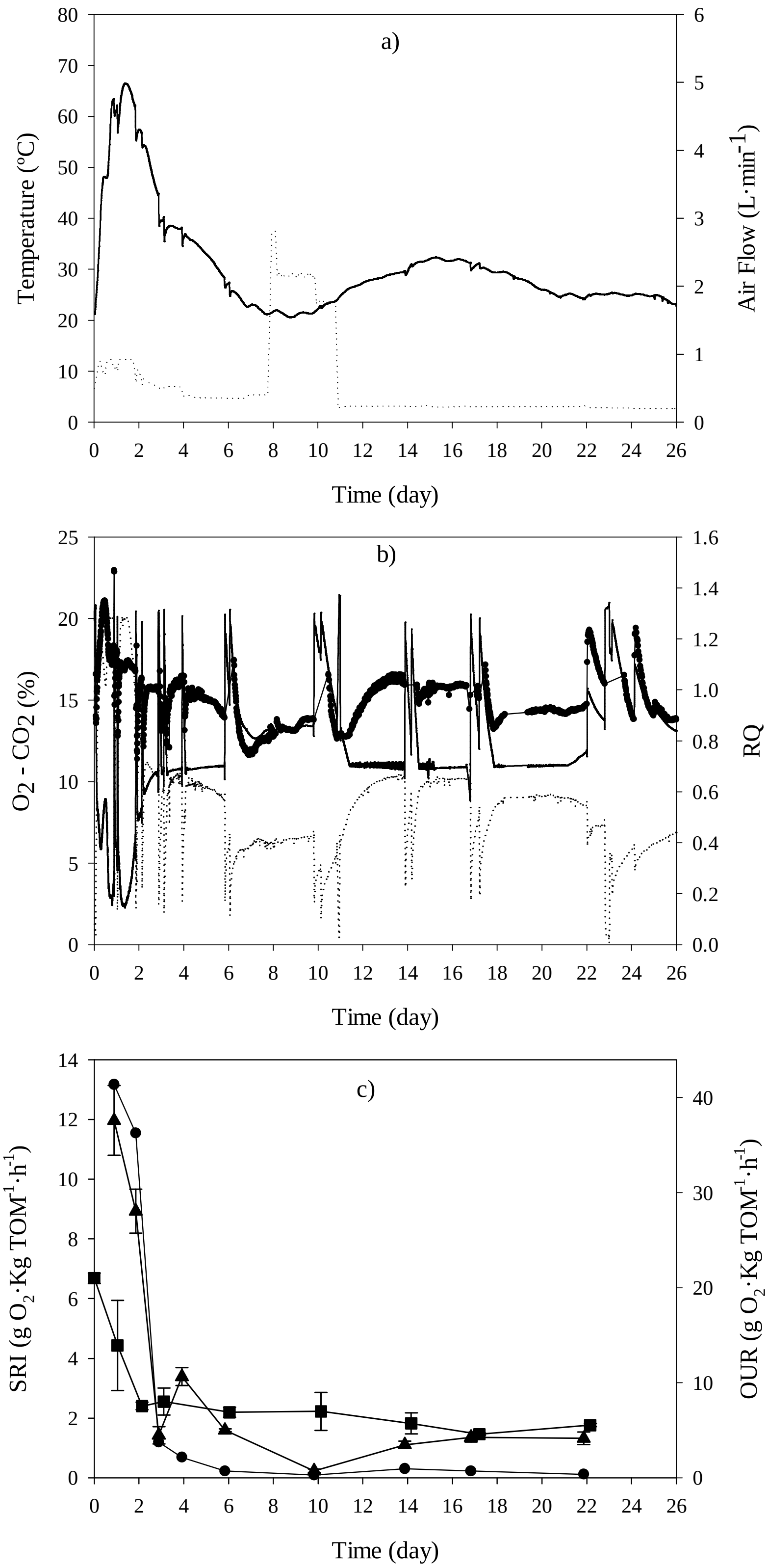

Fig.5: Gea *et al*.