Bioresource Technology 117 (2012) 300–309

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

# A modified dynamic respiration test to assess compost stability: Effect of sample size and air flowrate

Dimitrios Komilis *, Dimitrios Kanellos

*Laboratory of Solid and Hazardous Waste Management, Department of Environmental Engineering, Democritus University of Thrace, Xanthi 671 00, Greece*

## HIGHLIGHTS

- ▶ We measured compost dynamic respiration indexes under different unit air flowrates.
- ▶ The unit air flowrates (UAF) ranged from 6 to 30 L air $kg^{-1}$ VS $h^{-1}$.
- ▶ The dynamic respiration index (DRI) increased as the UAF increased.
- ▶ A negative correlation existed between the $CO_2$ index and the UAF.
- ▶ The respiratory quotients (RQ) decreased from 0.5 to 0.05 as UAF increased.

## ARTICLE INFO

*Article history:*
Received 7 March 2012
Received in revised form 24 April 2012
Accepted 25 April 2012
Available online 2 May 2012

*Keywords:*
Compost stability
Dynamic respiration index
Air flowrate
Microbial respiration activity

## ABSTRACT

Goal of this work was to study the effect of the unit air flowrate on dynamic respiration activity indexes during the assessment of compost stability. A MSW compost was used and six experimental runs were performed with variable compost masses and variable air flowrates, so that to achieve six unit air flowrates (6, 9, 16, 17, 23 and 30 L air $kg^{-1}$ organic matter $h^{-1}$). Six respiration activity indexes were quantified, namely a dynamic respiration index ($DRI_{24}$), the cumulative $O_2$ consumption at 4 and 7 days ($DCRI_4$, $DCRI_7$), a $CO_2$ index, the cumulative $CO_2$ generation after 7 days (Total $CO_2$) and the respiratory quotient. Results indicate that the $CO_2$ related indexes and the respiratory quotients had a strong negative correlation with the unit air flowrate, whilst the $DRI_{24}$ and both DCRIs slightly increased with increasing unit air flowrates.



## 1. Introduction

The composting process has the primary goal to produce a stabilized end-product. The term "stability" is related to the microbial decomposition or the microbial respiration activity of the composted matter (Iannotti et al., 1993). There has been quite a significant effort among researchers to characterize stable composts using indexes that are mainly based on the quantification of microbial respiration activity. The most common microbial respiration activity indexes are the ones based on oxygen consumption (or uptake) and carbon dioxide generation (or evolution). Respiration activity tests are classified in two major groups, namely the static and dynamic ones. The static respiration tests (SRT) are performed at the absence of a continuous air flow; $O_2$ consumption is often measured via pressure differences or via direct measurements of the $O_2$ content usually in the gaseous phase (Adani et al., 2001, 2003, 2006; Binner and Zach, 1999; Gea et al., 2004; Iannotti et al., 1993; Komilis and Tziouvaras, 2009; Komilis et al., 2011a; Ponsá et al., 2009, 2010a,b; Ruggieri et al., 2008; Wagland et al., 2009). On the other hand, dynamic respiration tests (DRT) are using a continuous air flow regime with the goal to achieve an adequate oxygen supply to the microorganisms. These dynamic tests require the precise measurement of air flowrate throughout the process and the measurement of the $O_2$ and $CO_2$ contents at the inlet and outlet of the test devices (Adani et al., 2006; Barrena-Gómez et al., 2005, 2006; Barrena et al., 2009; Gea et al., 2004; Ponsá et al., 2010a,b; Scaglia et al., 2000; Tremier et al., 2005; Wagland et al., 2009).

There is a large variability in the sample sizes and the air flowrates adopted during DRT. Sample sizes vary from 100 g (Ponsá et al., 2009, 2010a,b), to 500 g (ASTM, 1996) to up to 10–13 kg (Adani et al., 2001, 2003, 2006; CEN, 2007; Scaglia et al., 2000). Air flowrates also seem to vary during DRT. Ponsá et al. (2010a,b) have used an initial air flowrate of 30 and 20 ml $min^{-1}$ for active and more stable samples, respectively to maintain $O_2$ content at the exhaust gases above 10% (v/v). The ASTM method suggests that the unit air flowrate (UAF) should not exceed 200 L $kg^{-1}$ waste $d^{-1}$

* Corresponding author. Tel./fax: +30 2541079391.
*E-mail address:* dkomilis@env.duth.gr (D. Komilis).

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http://dx.doi.org/10.1016/j.biortech.2012.04.095

and that $O_2$ content should be always maintained above 6% (v/v). An Italian research team suggests that the air flowrate should be continually adjusted to constantly maintain an $O_2$ content equal to 140 ml $L^{-1}$ air (14% v/v) at the reactor's exhaust gas (Adani et al., 2001, 2003, 2006; Scaglia et al., 2000).

From the above, it is apparent that there is a variability in the operating parameters of the dynamic respiration tests. The effect of air flowrate and sample size on the respiration activity indexes has not been thoroughly investigated. Particularly, the effect of the above two parameters on the $CO_2$ generation and the respiratory quotient (i.e., the ratio of the moles of $CO_2$ generated over the moles of $O_2$ consumed during the same time period) – which are both important, and sometimes undervalued, respiration activity indexes – has not been studied well. In the case of the respiratory quotient (RQ), for example, values ranging from 0.6 to 1.9 have been reported in the literature (de Guardia et al., 2010; Gea et al., 2004; Klauss and Papadimitriou, 2002; Komilis and Tziouvaras, 2009; Komilis et al., 2011a,b; Nakasaki et al., 1985).

Based on the above, goal of this work was to show how several $O_2$ consumption and $CO_2$ generation related respiration activity indexes are affected by the sample size, the air flowrate and, as a consequence, by the UAF during DRT. The main research question tackled in this work was, therefore: "How important is the sample size and the air flowrate during a dynamic respiration activity test?". To achieve the desired UAF, both the air flowrate and the mass of the material placed in the reactor (sample size) were changed during the experiments.

## 2. Methods

### 2.1. Compost

A municipal solid waste (MSW) compost was obtained from a large commingled MSW mechanical and biological aerobic pretreatment facility located in Athens, Greece. In that facility, MSW is first screened and the undersized fraction passes through an 18-h retention time precomposter (rotating bioreactor) that raises the internal temperature to up to 40–45 °C. The material, then, proceeds to a 6 week retention time negative aeration composting phase, which takes place in agitated channels. The end-product is, then, cured for 5–6 weeks in static windrows. The final compost produced after curing is screened and stored in plastics bags. The specific samples that were used in this experiment had remained in the plastic bags for more than 3 years. Approximately 20 kg of the compost was transferred to the university laboratory for use in the experiments. Organic matter (OM) or volatile solids (VS), moisture and dry mass (DM), total carbon and total nitrogen were measured according to USDA and USCC (2001) and Komilis et al. (2012). The as received (wet) compost sample sizes that were used in the experiments ranged from 300 to 900 g (100–301 g organic matter) and were chosen randomly from the initial compost, which was, anyway, very homogeneous.

Deionized water was added to the compost prior to the initiation of a run to achieve an initial moisture content of 55% on a wet weight basis (ww). Branches, collected from trees at the university campus, were cut to approximately 7 cm length and were mixed with the compost at a 4:1 wet weight ratio (wet compost prior to the addition of water: wet branches) to provide bulking.

### 2.2. Aerobic reactor

The reactor was custom made and is shown in Fig. 1. The reactor was air-tight and was constructed from plexi-glass. It had a total internal volume of 5.5 L and one bottom inlet and two outlets at the top. Gravel was placed at the bottom 7 cm to provide an air plenum. The substrate (compost + branches) had a variable height, which ranged from 7 to 23 cm during the runs. Therefore, the volume within the reactor that was occupied by the compost and the branches ranged from approximately 1–3.5 L. Air was distributed to the reactors by a small air compressor and via a plain manifold with plastic tubing. The flow to each reactor was adjusted with a glass float type flowmeter provided by Aalborg® (PMR1–016587) with a precision needle valve attached to the inlet; the flow range was 0 to 100 ml $min^{-1}$ and the resolution was 2.5 ml $min^{-1}$. Only the one top reactor outlet was kept constantly open during the experiments and was periodically connected to a portable gas analyzer. The flow was adjusted to the initial desired level for each experiment and was kept constant throughout the 7-day experimental period. No fluctuation of the flowmeter glass float was observed during the experiments.

Blank runs were performed in triplicates using (i) empty reactors and (ii) reactors that contained solely the (wetted) branches that were used during the main experiments to provide bulking. This was done in order to quantify the potential biodegradation of the branches and to calculate their likely contribution in the gross $O_2$ consumption and $CO_2$ generation rates of the main experiments.

Gas sampling was performed with a portable gas analyzer (GA 94, Geotechnical Instruments Ltd., U.K) equipped with infrared absorption sensors to measure $CH_4$ and $CO_2$ and with a galvanic cell type sensor to measure $O_2$. The gas analyzer had a measuring range from 0.0% (v/v) to 100.0% (v/v) with a resolution of 0.1% (v/v) and with a linear response throughout the above range for all gases. The gas analyzer was calibrated, and periodically checked, using standard gases provided by AEROSCOPIO Hellas S.A. (Athens, Greece). The standard gases comprised a mixture of $CH_4$:$CO_2$ at 49.9%:50.1% (v/v), respectively, and a mixture of $O_2$:$N_2$ containing $O_2$ at 8.06% (v/v). Atmospheric air was also used for calibration purposes assuming a 20.9% (v/v) $O_2$ content and a 0.0% content for $CO_2$. A new instrument calibration was performed when deviation from the standard concentrations exceeded 5%. The experiments took place in a temperature controlled room at a constant temperature of 35 ± 2 °C.

### 2.3. Gas sampling

Gas sampling was performed manually (i.e., off-line system). Since the compost used in this work was stable, preliminary runs showed that no abrupt changes of the respiration activity rates within a 24 h period existed. Therefore, the respiration activity rate curves could be adequately constructed using 3 sampling events per day. The measurements of the instantaneous $O_2$ and $CO_2$ contents at the reactors' exhaust gases were performed during the morning (8:00–11:00), afternoon (15:00:18:00) and evening (20:00–23:00), which coincided with the university operating hours. Acquisition time per measurement was approximately 5–7 min so that to achieve a constant reading by the gas analyzer. The $O_2$ and $CO_2$ contents of the ambient air within the incubation room were always measured prior to the initiation and after the termination of a series of measurements. Room temperature was measured with a common thermometer at the time of gas sampling. A moisture filter, which was provided by the gas analyzer's manufacturer, was always installed at the gas analyzer's inlet to remove the moisture of the exhaust gases. Therefore, all gas contents mentioned in this work are expressed on a dry air basis. The instantaneous $O_2$ consumption rates and instantaneous $CO_2$ generation rates were calculated at the incubator temperature based on Eqs. (1) and (2). Runs lasted 7 days.

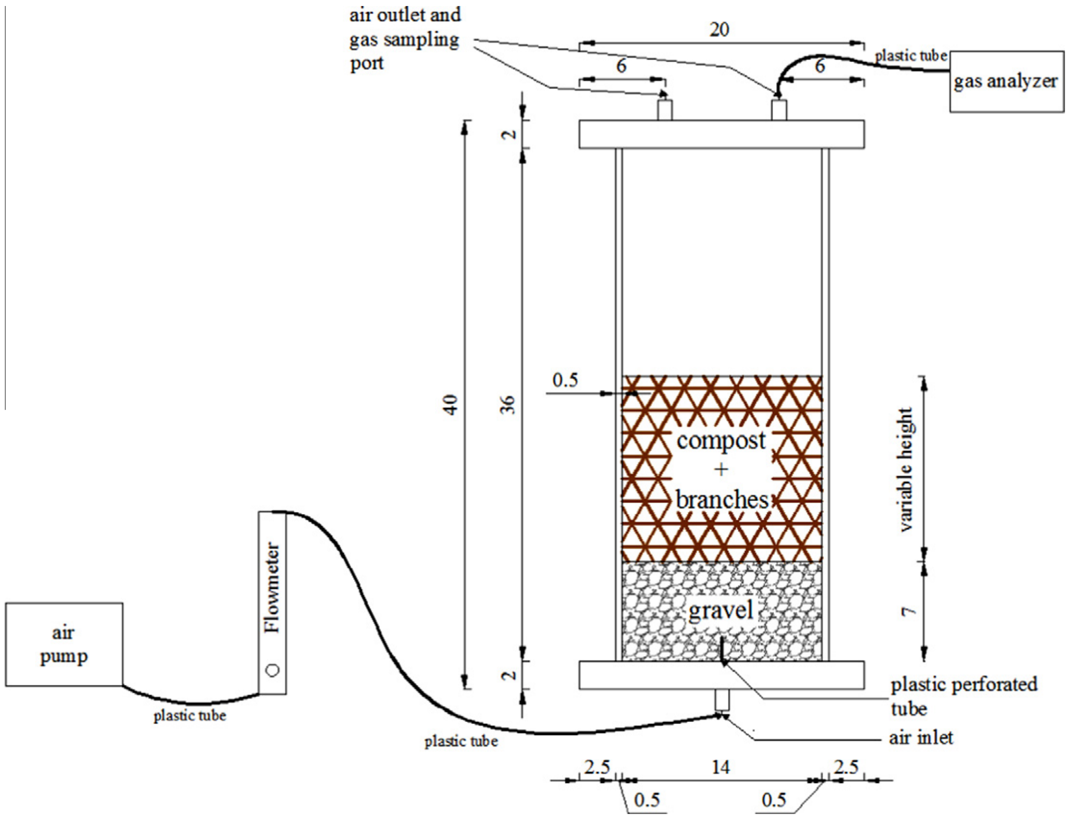


**Fig. 1.** Schematic of dynamic flow reactor. All dimensions are in cm (not to scale).

$$O_2\,\text{cons} = \frac{(O_2\text{in} - O_2\text{ out}) * Q * 60 * 31.98 * 1000^a}{22.4 * \frac{273+\text{TempRoom}}{273} * VS * 1000^b} \quad (1)$$

$$CO_2\,\text{gener} = \frac{(CO_2\text{out} - CO_2\text{in}) * Q * 60 * 12 * 1000^a}{22.4 * \frac{273+\text{TempRoom}}{273} * VS * 1000^b} \quad (2)$$

$O_2$ cons: instantaneous oxygen consumption rate in mg $O_2$ kg$^{-1}$ VS h$^{-1}$.

$O_2$ in: Percentage of $O_2$ at the inlet of the reactor (ambient air), % of dry air (v/v).

$O_2$ out: Percentage of $O_2$ at the outlet of the reactor, % of dry air (v/v).

*Q*: air flow into the reactor (ml min$^{-1}$) adjusted at the incubator's temperature.

60: conversion factor (min h$^{-1}$).

31.98: g of $O_2$ per mole.

22.4: L of gas per g-mole at standard conditions (0 °C, 1 atm).

12: g of C per $CO_2$ mole.

VS: organic matter (or volatile solids) placed in the reactor at time 0 (kg).

1000$^a$: conversion factor (mg g$^{-1}$).

1000$^b$: conversion factor (mL L$^{-1}$).

$CO_2$ gener: instantaneous carbon dioxide generation rate in mg C-$CO_2$ kg$^{-1}$ VS h$^{-1}$.

$CO_2$ in: Percentage of $CO_2$ at the inlet of the reactor, % v/v.

$CO_2$ out: Percentage of $CO_2$ at the outlet of the reactor, % v/v.

TempRoom: Incubation room temperature (°C).

The air flow read by the flowmeter was adjusted to the room's temperature using a formula provided by the flowmeter manufacturers. Barometric pressure in the room was very close to 1 atm (i.e., standard conditions) and a pressure correction is, thus, not included in Eqs. (1) and (2).

### 2.4. Experimental design

The initial conditions of the 6 experiments performed in this work are included in Table 1. According to Table 1, the sample sizes (dry weights of compost) that were used in this work were 231, 250, 462 and 693 g, which corresponded to organic matter weights that ranged from 100 to 301 g. The air flowrates that were adopted in this work were 29, 54 and 78 ml min$^{-1}$ (see Table 1). As a result, the UAFs that were achieved in this work were: 6.0, 9.0, 16, 17, 23 and 30 L air kg$^{-1}$ VS h$^{-1}$. The above range of UAFs has been also used in other studies (Adani et al., 2006). All experimental runs were performed in triplicates; the three replicate reactors were always run concurrently per experiment. Only run 2, which was performed chronologically last, had no replication. This was not considered necessary due to the establishment of a good precision of the replicate runs in the previous experiments. As a result, a total of 16 runs were performed (blank runs not included). Statistical analysis was performed with MINITAB® v.16 and STATISTICA® v.8.0.

It is noted that when UAF above 30 L kg$^{-1}$ VS h$^{-1}$ were attempted in this work, the resulting respiration rates could not be reliably computed. This was due to the fact that practically excess air was entering the reactor in those high UAFs, so that the $O_2$ content at the exhaust air was always close to the ambient air content (20.9%). In addition, significant $CO_2$ dilution was apparently occurring so that $CO_2$ in the exhaust gases was practically undetectable by the gas analyzer.

### 2.5. Respiration indexes

The respiration indexes that were calculated were the following: a 24 h dynamic respiration index ($DRI_{24}$), a C–$CO_2$ index, a dynamic cumulative $O_2$ consumption after 4 and 7 days (herein

**Table 1**
Initial experimental conditions.

| Experiment ID* | Wet mass in reactor (g) ** | Dry mass in reactor (g) | Organic matter weight in reactor (g) | Constant air flowrate (ml $min^{-1}$) *** | Unit air flowrate (L air $kg^{-1}$ VS $h^{-1}$) *** |
|---|---|---|---|---|---|
| 1 | 300 | 231 | 100 | 29 | 17 |
| 2 | 325 | 250 | 109 | 54 | 30 |
| 3 | 600 | 462 | 201 | 29 | 9 |
| 4 | 600 | 462 | 201 | 78 | 23 |
| 5 | 900 | 693 | 301 | 29 | 6 |
| 6 | 900 | 693 | 301 | 78 | 16 |

* All experiments were run in triplicate, except for experiment 2.
** Wet mass of compost as received from the storage bags.
*** Calculated at the incubator's temperature.

referred to as $DCRI_4$ and $DCRI_7$, respectively), a cumulative $CO_2$ generation (Total $CO_2$) after 7 days, an average respiratory quotient over the 7-day period ($RQ_{average}$) and a peak respiratory quotient ($RQ_{peak}$). The $DRI_{24}$ was calculated according to the suggestions of Scaglia et al. (2000), CEN (2007) and Ponsá et al. (2009, 2010a,b) and it was taken as the maximum of the averages of the instantaneous $O_2$ consumption rates that were recorded during a continuous 24-h period. In this work, a 24 h period included readings of instantaneous rates. The C–$CO_2$ index was calculated based on the same concept, and was taken as the maximum of the averages of the instantaneous $CO_2$ generation rates recorded during a continuous 24-h period. Fig. 2 shows an example of how these aforementioned two indexes were calculated. The momentary $O_2$ consumption and momentary $CO_2$ generation rates that are included in the boxes of Fig. 2 were averaged in order to calculate the $DRI_{24}$ and the C–$CO_2$ index, respectively.

The cumulative $O_2$ consumptions after 4 or 7 days ($DCRI_4$, $DCRI_7$) were calculated by integrating the area under the $O_2$ consumption rate versus time curve from day 0 to 4 or from day 0 to 7, respectively. This was done with simple numerical integration and DCRIs were expressed in mg $O_2$ $kg^{-1}$ VS. Similarly, the cumulative $CO_2$ generation (Total $CO_2$) after 7 days (expressed in mg C $kg^{-1}$ VS) was calculated by integrating the area under the C–$CO_2$ generation rate curve from day 0 to 7.

The momentary respiratory quotient (RQ) at each sampling event was calculated based on the following formula:

$$RQ = \frac{\text{moles}\, CO_2\, \text{generated}}{\text{moles}\, O_2\, \text{consumed}} = \frac{CO_2\text{gener} \div 12}{O_2\text{cons} \div 32} \quad (3)$$

with parameters as defined earlier.

The same approach to calculate the $DRI_{24}$ and the C–$CO_2$ index was used to calculate $RQ_{peak}$. $RQ_{average}$ was calculated as the fraction of the cumulative moles of $CO_2$ generated during the 7-day sampling period over the cumulative moles of $O_2$ consumed during the same sampling period.

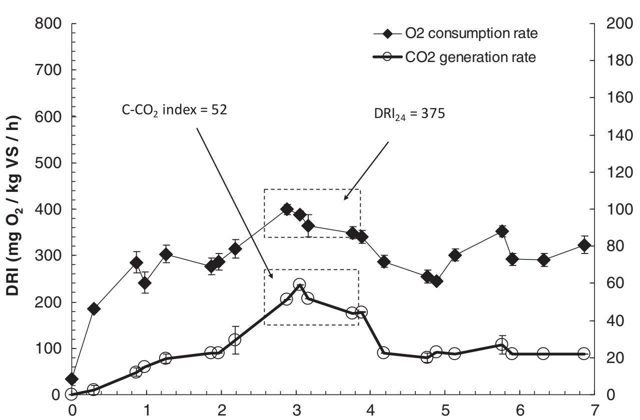


**Fig. 2.** Example of the calculation of $DRI_{24}$ and the C–$CO_2$ index.

## 3. Results and discussion

### 3.1. Compost characterization

The organic matter content of the compost was 43% on dry weight basis (dw), whilst the as-received moisture content was around 23% on a wet weight basis (ww). Total carbon and total nitrogen contents were 25.5% ± 12% (dw) and 2.3% ± 11% (dw), respectively (mean ± coefficient of variation based on $n = 9$). The average C/N ratio of the compost was 11.3 ± 8.2%.

### 3.2. Respiration indexes

The minimum $O_2$ and maximum $CO_2$ contents (on a v/v dry air basis) that were recorded in the exhaust gases of all runs are shown in Table 2. According to Table 2, the $O_2$ contents never dropped below 16% v/v in any of the runs, which ensured that aerobic environments were maintained within the reactor. The maximum $CO_2$ content recorded was 2.0% (v/v) (in experiments 3 and 5).

Table 3 includes all the respiration indexes that were measured in this work. $DRI_{24}$ ranged from 270 to 520 mg $O_2$ $kg^{-1}$ VS $h^{-1}$, whilst the C–$CO_2$ indexes ranged from less than 5 to 53 mg C $kg^{-1}$ VS $h^{-1}$. All $DRI_{24}$ were less than 500 mg $kg^{-1}$ DM $h^{-1}$, which, according to CEN (2007), is a stability limit for very stable composts. Therefore, using that limit, the compost can be considered stable. In addition, according to the limits of Ponsá et al. (2010a), the MSW compost used in this work can be also classified as a low degradability material, since it had a dynamic respiration activity less than 2000 mg $O_2$ $kg^{-1}$ DM $h^{-1}$. The $DRI_{24}$ values measured here are also within the range of values (150–1500 mg $O_2$ $kg^{-1}$ VS $h^{-1}$) reported by Scaglia and Adani (2008) for biostabilized

**Table 2**
Minimum $O_2$ and maximum $CO_2$ contents measured in the exhaust gases of all 6 experiments.*

| | Gas contents (% v/v on a dry air basis) | |
|---|---|---|
| | Minimum $O_2$ | Maximum $CO_2$ |
| Experiment 1 | 18.3 ± 0.25 | 0.53 ± 0.06 |
| Experiment 2 | 19.4 | 0.10 |
| Experiment 3 | 16.3 ± 0.25 | 2.0 ± 0.36 |
| Experiment 4 | 18.3 ± 0.30 | 0.57 ± 0.06 |
| Experiment 5 | 17.0 ± 0.26 | 2.0 ± 0.26 |
| Experiment 6 | 17.5 ± 0.20 | 0.80 ± 0.0 |

* Values shown are mean ± standard deviations, except for experiment 2 for which no replicate runs were performed.

**Table 3**
Dynamic respiration activity indexes.*

| Experiment | UAF (L air $kg^{-1}$ VS $h^{-1}$) | $DRI_{24}$ (mg $O_2$ $kg^{-1}$ VS $h^{-1}$) | C–$CO_2$ index (mg C $kg^{-1}$ VS $h^{-1}$) | $DCRI_4$ (mg $O_2$ $kg^{-1}$ VS) | $DCRI_7$ (mg $O_2$ $kg^{-1}$ VS) | Total $CO_2$ (mg C $kg^{-1}$ VS) | $RQ_{peak}$ | $RQ_{average}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 17 | 310 ± 6.5% (130) | 35 ± 7.4% (15) | 23000 ± 12.5% (10000) | 42000 ± 11.8% (18000) | 3800 ± 2.5% (1700) | 0.31 ± 7.3% | 0.25 ± 9.4% |
| 2 | 30 | 480 (210) | 3.5 (1.5) | 34000 (15000) | 57000 (25000) | 230 (99) | 0.031 | 0.011 |
| 3 | 9 | 400 ± 11% (180) | 79 ± 14% (34) | 33000 ± 9.2% (14000) | 49000 ± 9.1% (21000) | 9300 ± 9.3% (4000) | 0.54 ± 4.8% | 0.51 ± 1.8% |
| 4 | 23 | 520 ± 13% (230) | 46 ± 14% (20) | 36000 ± 18% (16000) | 63000 ± 16% (27000) | 4100 ± 19% (1800) | 0.25 ± 8.7% | 0.17 ± 6.9% |
| 5 | 6 | 270 ± 5.9% (120) | 53 ± 7.7% (23) | 19000 ± 11% (8400) | 36000 ± 4.5% (16000) | 6600 ± 5.5% (2900) | 0.53 ± 1.3% | 0.48 ± 1.1% |
| 6 | 16 | 380 ± 6.0% (160) | 52 ± 0.0% (22) | 28000 ± 8.7% (12000) | 49000 ± 7.4% (21000) | 4300 ± 3.5% (1900) | 0.37 ± 6.2% | 0.23 ± 4.2% |

* Mean ± coefficients of variation; values in parentheses are expressions on a per dry matter (DM) basis. VS: volatile solids or organic matter; UAF: unit air flowrate; $DRI_{24}$: 24-h based dynamic respiration index; $DCRI_4$: dynamic cumulative respiration index at 4 days; $DCRI_7$: dynamic cumulative respiration index at 7 days; $RQ_{peak}$: peak respiratory quotient; $RQ_{average}$: average respiratory quotient after 7 days.

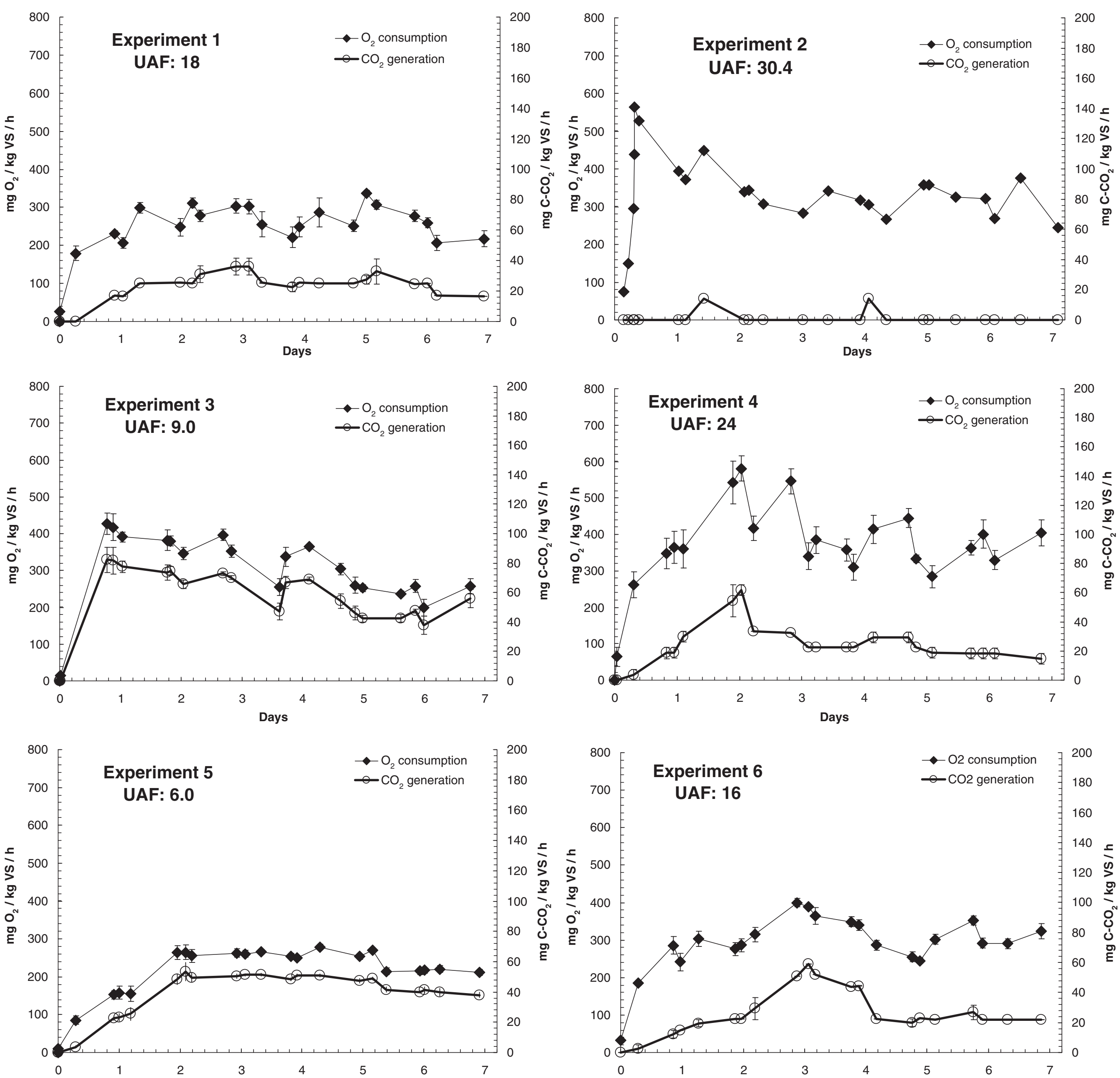


**Fig. 3.** Instantaneous oxygen consumption and carbon dioxide generation rates over the 7-day period (UAF: Unit air flowrate).

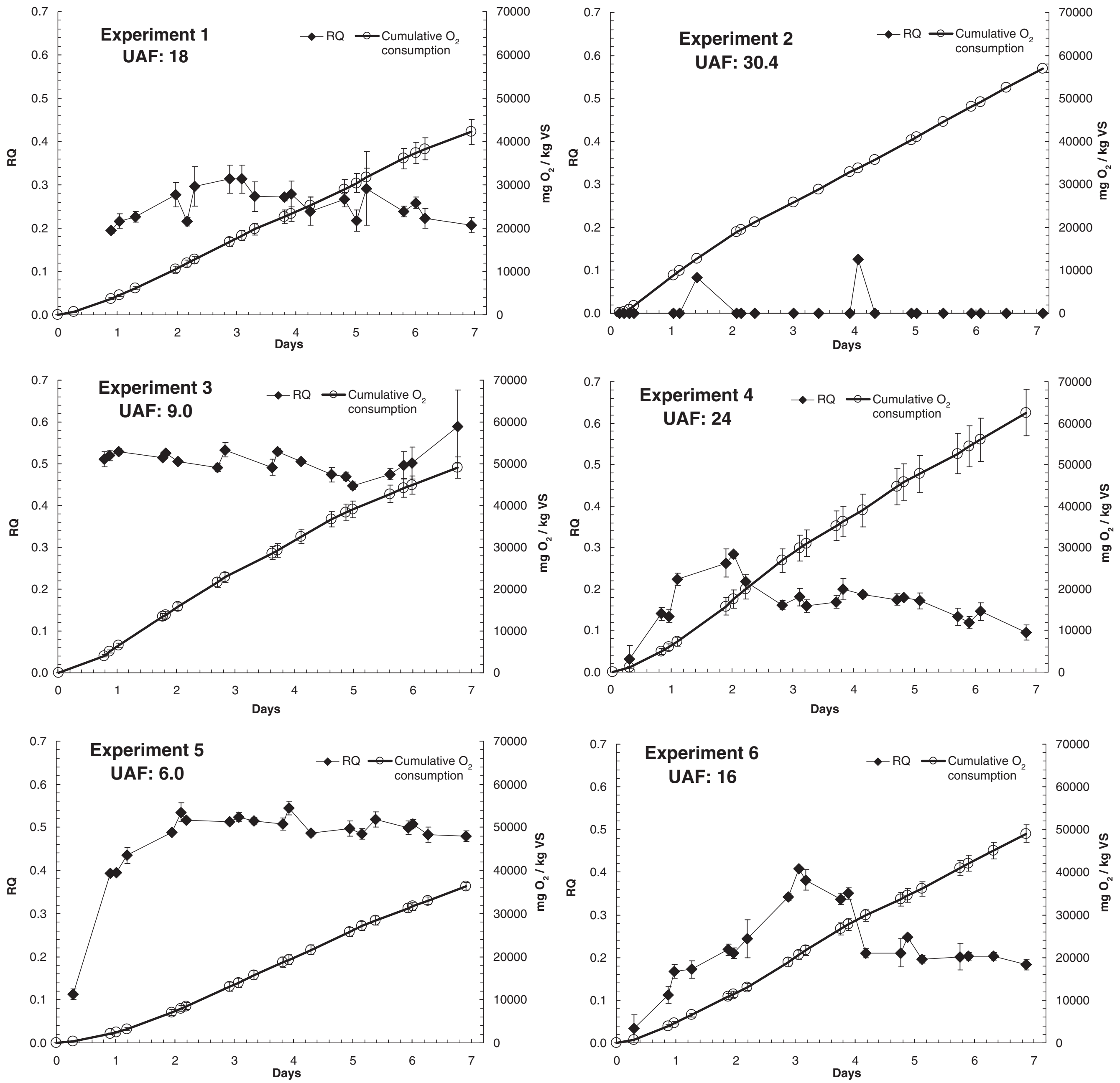


**Fig. 4.** Profile of RQ and cumulative oxygen consumption over the 7-day experimental period (UAF: Unit air flowrate).

MSW. Using the same methodology, Barrena et al. (2009) had measured $DRI_{24}$ of around 1300 mg kg $VS^{-1}$ $h^{-1}$ for an end-product derived from a MSW MBT facility. Pognani et al. (2012) measured the $DRI_{24}$ for the composted organic fraction of MSW (that had a VS content of 49.4% dw) which was equal to approximately 800 mg $O_2$ kg $VS^{-1}$ $h^{-1}$. This is a value higher than – but still comparable to – the $DRI_{24}$ measured in this work. On the other hand, Ponsá et al. (2009) reported a $DRI_{24}$ equal to 4400 mg $O_2$ $kg^{-1}$ VS $h^{-1}$ for fresh MSW after mechanical pretreatment.

Fig. 3 illustrates the $O_2$ consumption and $CO_2$ generation rates of the 6 experiments versus time. Note that the minor amounts of $CO_2$ generation and $O_2$ consumption that were recorded during the "blank" runs, as a result of the presence of branches, were subtracted from the gross amounts calculated per reactor. Therefore, the values shown in the fig. are the net respiration activities due to the compost only.

According to Fig. 3, experiment 2, which had the highest UAF among all runs (30 L air $kg^{-1}$ VS $h^{-1}$), had the highest $O_2$ consumption rates as well. On the other hand, the $CO_2$ contents that were detected in the reactor outlet were always 0.0%, except in a couple of sampling events that the $CO_2$ content went only up to 0.1% v/v; this inevitably led to the calculation of almost zero $CO_2$ generation rates for experiment 2. Experiment 4, with the next highest UAF (24 L air $kg^{-1}$ VS $h^{-1}$), had also relatively high $O_2$ consumption rates. In almost all runs, the $O_2$ consumption rates observed a gradual increase during the first couple of days, and remained steady throughout the rest of the process. This steady $O_2$ consumption rate throughout the 7 day experimental period is characteristic of stabilized composts, as has been shown and discussed in Komilis et al. (2011a) (who, however, had used static respiration tests). Except from experiments 2 and 4 (experiments with the highest UAF), the profile of the $CO_2$ generation rate was parallel to that

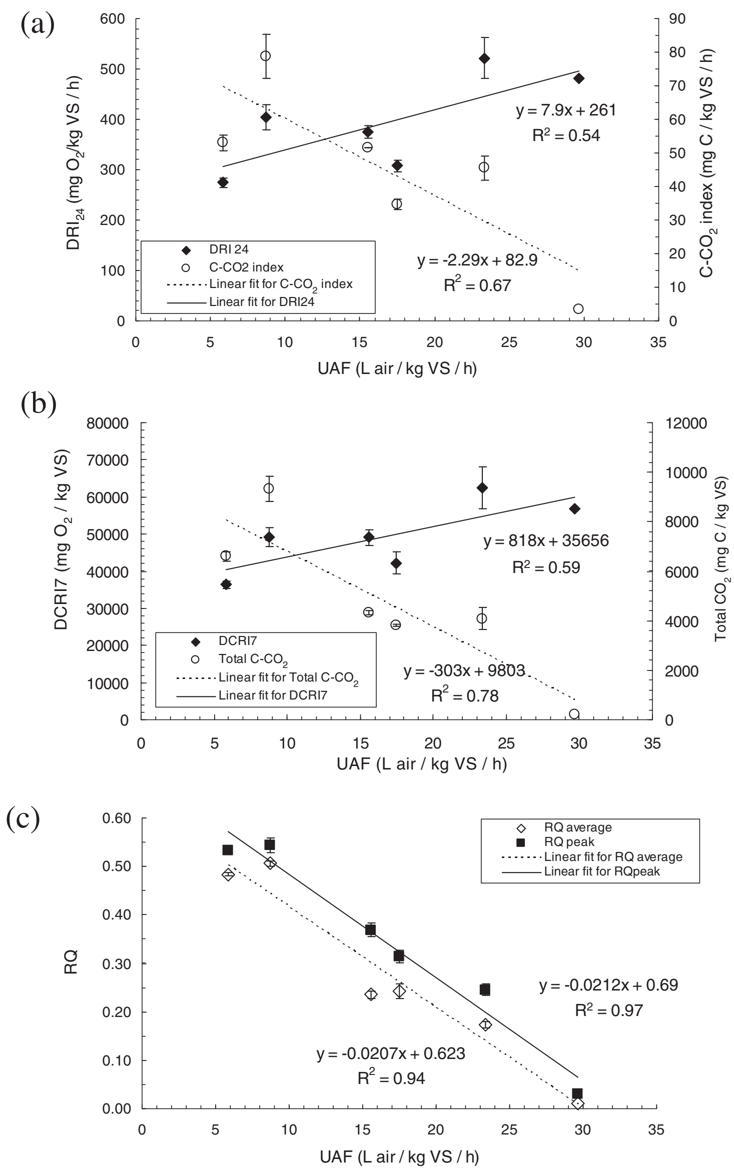


**Fig. 5.** (a) $DRI_{24}$ and the C–$CO_2$ index versus UAF; (b) $DCRI_7$ and total $CO_2$ versus UAF; (c) $RQ_{peak}$ and $RQ_{average}$ versus UAF.

of the $O_2$ consumption rate. The highest instantaneous $O_2$ consumption rate was 640 mg $O_2$ $kg^{-1}$ VS $h^{-1}$ and was recorded in experiment 4. The highest instantaneous $CO_2$ generation rate was recorded in experiment 3 and was 100 mg C $kg^{-1}$ VS $h^{-1}$. The time periods over which the $DRI_{24}$ and C–$CO_2$ indexes were calculated coincided for most (but not all) runs.

It would be interesting to compare the $DRI_{24}$ calculated in this work with corresponding static respiration indexes (SRI). The 24-h based SRIs reported in Komilis et al. (2011a) were calculated following the same principle as here and were found to range from around 56 to 270 mg $O_2$ $kg^{-1}$ VS $h^{-1}$ for 10 composts (2 of which were also stable MSW composts). Therefore, the dynamic respiration indexes were greater than indexes calculated via static tests, which agrees to the findings of other researchers (Gea et al., 2004; Scaglia et al., 2000). The values are also comparable to some of the values reported by Ponsá et al. (2010a) for mechanically pretreated MSW.

Fig. 4 illustrates the cumulative oxygen consumption and the momentary RQs versus time. Experiment 4 had the highest $DCRI_7$ equal to 63000 mg $O_2$ $kg^{-1}$ VS followed by experiment 2. The lowest $DCRI_7$ (36000 mg $O_2$ $kg^{-1}$ VS) was recorded for experiment 5. Interestingly, much lower $DCRI_7$ (from 6000 to 26,000 mg $O_2$ $kg^{-1}$ VS) had been recorded for 10 composts using static respiration tests over a 7-day experimental period (Komilis et al., 2011a). The RQ appeared to slightly increase in the beginning of the process and remained stable later on for some of the runs. After an initial peak, RQs decreased with time for experiments 4 and 6.

**Table 4**
Correlation matrix of the respiration activity indexes.*

| | $DRI_{24}$ | $DCRI_4$ | $DCRI_7$ | $CO_2$ index | Total $CO_2$ | $RQ_{peak}$ |
|---|---|---|---|---|---|---|
| $DCRI_4$ | 0.98 | | | | | |
| $DCRI_7$ | 0.98 | 0.97 | | | | |
| $CO_2$ index | ns | ns | ns | | | |
| Total $CO_2$ | ns | ns | ns | 0.94 | | |
| $RQ_{peak}$ | −0.53 | ns | −0.56 | 0.82 | 0.90 | |
| $RQ_{average}$ | −0.50 | ns | −0.55 | 0.78 | 0.92 | 0.97 |

ns: not statistically significant; correlations were based on $n = 16$.
* All Pearson correlations coefficients shown are statistically significant at $p < 0.05$.

**Table 5**
Empirical equations to describe the respiration activity indexes as a function of the air flowrate (ml min$^{-1}$) and of the initial organic matter of the substrate (kg).*

| Equation | Dependent variable | Best reduced model | F ratio of regression model** |
|---|---|---|---|
| (1) | $DRI_{24}$ | 990 (156) VS + 11 (1.0) Flow − 34 (4.5) VS · Flow | 236 (3.41) |
| (2) | C-$CO_2$ index | 220 (22.1) VS | 96.7 (4.54) |
| (3) | $DCRI_7$ | 131400 (19490) VS + 1320 (125) Flow – 4080 (557) VS · Flow | 239 (3.41) |
| (4) | Total $CO_2$ | 23100 (2890) VS | 64.2 (4.54) |
| (5) | $RQ_{peak}$ | 1.7 (0.16) VS | 115 (4.54) |
| (6) | $RQ_{average}$ | 1.4 (0.17) VS | 64.5 (4.54) |

VS: Organic matter (volatile solids) of compost placed in the reactor (kg); Flow: Air flowrate into the reactor at the incubator's temperature; $DRI_{24}$ in mg $O_2$ kg$^{-1}$ VS h$^{-1}$; C–$CO_2$ index in mg C kg$^{-1}$ VS h$^{-1}$; $DCRI_7$ in mg $O_2$ kg$^{-1}$ VS; Total $CO_2$ in mg C kg$^{-1}$ VS; RQs are unitless.
* Only the statistically significant predictors (at $p < 0.05$) are included in the models; values in parentheses are the standard errors of the corresponding coefficients; the p values of all regression models were less than $10^{-6}$.
** Parentheses include the critical F values at 1 and 15 degrees of freedom (for models 2,4,5,6) and at 3 and 13 degrees of freedom (for models 1, 3) at $\alpha = 0.05$.

Fig. 5a reveals that there was a slight positive correlation between the UAF and the $DRI_{24}$. The corresponding $R^2$ of the linear equation shown in Fig. 5a is 0.54, which is statistically significant at $a = 10\%$. The above finding agrees with Adani et al. (2006) as well as with Villaseñor et al. (2011). In particular, Villaseñor et al. (2011) had observed that as the UAF increased from 0 to 4200 and then to 7200 L air kg$^{-1}$VS h$^{-1}$, during sludge composting, the oxygen uptake rate and the cumulative oxygen consumption, increased as well. The increased UAF is expected to increase the air–water oxygen transfer, which is considered the rate limiting step in solid state biodegradation (Villaseñor et al., 2011). The $DCRI_7$ had a similar profile to $DRI_{24}$ when plotted versus the UAF (see Fig. 5b). The corresponding linear equation of Fig. 5b had a statistically significant $R^2$ equal to 0.59. A stronger negative correlation ($R^2 = 0.67$), on the other hand, existed between the C–$CO_2$ index and the UAF. That is, as the UAF increased, the C–$CO_2$ index decreased. Similarly to the C–$CO_2$ index, the cumulative $CO_2$ generation (Total $CO_2$) also decreased with increasing UAF (Fig. 5b), with a higher $R^2$ of the corresponding regression equation equal to 0.78. The above indicate that more oxygen is consumed per unit mass of material as the supply of oxygen to that material increases, probably as a result of the increased transfer of oxygen from air to water. On the other hand, the opposite is true for the carbon dioxide, indicating that organic carbon prefers to be oxidized to intermediate byproducts, instead of to $CO_2$, as oxygen supply increases. Komilis et al. (2011a) had reported a range of static cumulative $CO_2$ generations from 2700 to 7400 mg C kg$^{-1}$ VS, while the cumulative $CO_2$ generations measured in this work (Fig. 5b) ranged from around 200 to up to 9300 mg C kg$^{-1}$ VS. In particular, an MSW compost with a 41% (dw) organic matter content (a value close to the 43% dw VS content of the MSW compost used in this work) had a static cumulative 7-day $CO_2$ generation equal to 5100 mg C kg$^{-1}$ VS (Komilis et al., 2011a). Based on the above, it appears that the static and dynamic C–$CO_2$ cumulative generations are comparable. On the other hand, the dynamic $O_2$ consumptions (rates and cumulative values) are much higher compared to the static ones. This finding agrees with the finding of Scaglia et al. (2000) and Gea et al. (2004) who found that dynamic oxygen respiration rates can be up to 5 times higher that the static ones for the same compost.

As a result of the above, both RQs observed a strong negative linear correlation with the UAF, which is indicated by the relatively high $R^2$ values of the linear regression equations of Fig. 5c (0.94 and 0.97). This finding is of key importance, since it indicates that the UAF highly influences the stoichiometry of the oxidation of an organic substrate during composting. In this work, the RQs started from around 0.5 (at the lowest UAF) to less than 0.05 (at the high UAFs). Therefore, since RQs were found to be significantly affected by the UAF, a unique stoichiometric equation to represent the aerobic degradation of an organic substrate cannot be developed. The high variability of RQ indicates that this index cannot be used as a reliable stability index. This agrees with the conclusive remarks of Gea et al. (2004).

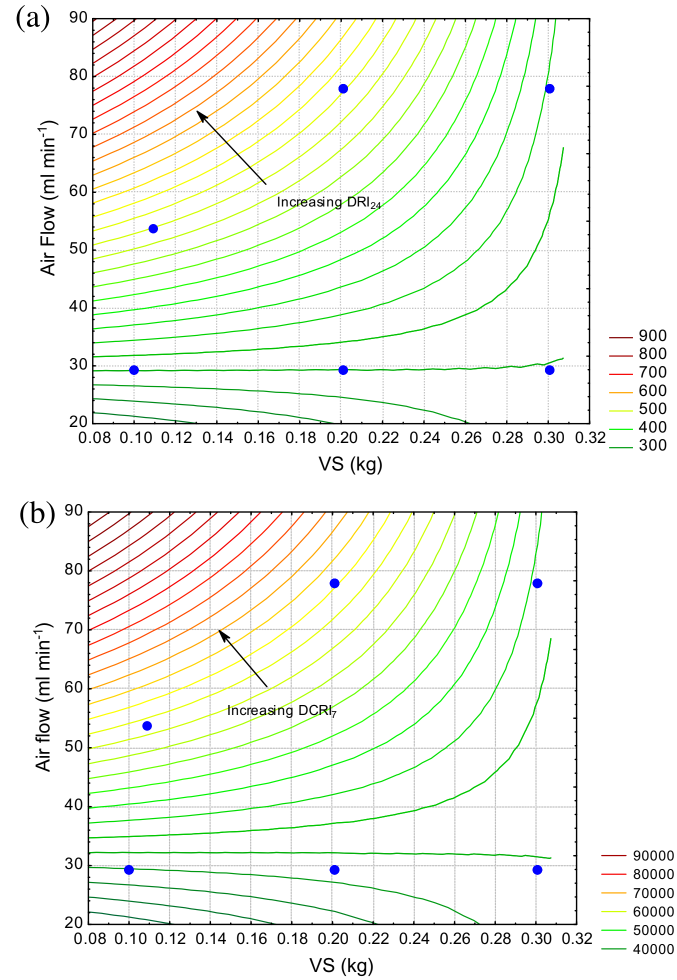


**Fig. 6.** $DRI_{24}$ (a) and $DCRI_7$ (b) versus the organic matter (or volatile solids, kg) and air flow (ml min$^{-1}$); the response surfaces correspond to equations 1 and 3 of Table 5, respectively. Dots indicate the "positions" of the experimental runs.

### 3.3. Correlation among indexes and empirical modeling

The linear Pearson correlation coefficients among all respiration indexes are shown in Table 4. The table shows that the correlations among all oxygen consumption indexes were both statistically significant as well as strong. The strongest one ($r = 0.98$) was between $DRI_{24}$ and $DCRI_7$, which agrees to the findings of other researchers (Adani et al., 2003; Ponsá et al., 2010a) as well as with previous works of the corresponding author (Komilis and Tziouvaras, 2009; Komilis et al., 2011a). On the other hand, no correlation was found between the oxygen respiration indexes and any of the $CO_2$ indexes or the RQ. This does not agree with the findings of Komilis and Tziouvaras (2009) and Komilis et al. (2011a). However, it is mentioned that in the aforementioned works, correlations had been attempted among respiration indexes of different composts. This is not the case here, since only one compost was used and the changing parameter was the UAF only.

Table 5 includes the empirical models that were developed to describe the respiration indexes as a function of both the organic matter weight placed in the reactor (kg) and the air flow (ml $min^{-1}$). Such a modeling procedure would allow studying the magnitude of the effect of the two parameters on respiration activities. Table 5 includes the best reduced models (i.e., the ones that contain only the statistically significant predictors). The full model that was initially tried had the form of $Z = X + Y + X * Y$, with X and Y being the predictors (organic matter weight and air flowrate) and Z being the response, i.e., each of the respiration activity indexes. Modeling was performed by fitting the responses from all 16 experiments to the equations. The non-statistically significant terms (i.e., with $p$ values greater than 0.05) were removed in order to finally produce the best reduced models that are shown in Table 5. The $p$ values of all resulting regression models were less than $10^{-6}$ which indicates their adequate descriptive capabilities. The regression F ratios achieved for each model are also included in Table 5. According to a practical rule (Berthouex and Brown, 2002), a model has predictive capabilities as long as the regression F ratios are at least 4 times greater than critical F values (also shown in Table 5). Apparently, all models of Table 5 have predictive capabilities; it is noted, though, that the equations are valid for the range of the values of the predictors used in this research.

The equations of Table 5 reveal that sample size and air flowrate were both statistically significant predictors only in the case of the $DRI_{24}$ and the $DCRI_7$ ($DCRI_4$ provided the same results with $DCRI_7$). However, an antagonism (negative interaction) appeared to exist between the organic matter and air flow for the above two parameters. On a practical basis, equations (1) and (3) indicate that as the organic matter decreases and the air flowrate increases, $DRI_{24}$ and $DCRI_{4,7}$ increase. The antagonistic terms of equations (1) and (3) indicate that the effects of sample size and air flowrate are not linear, as is also evident in Fig. 6 (curved response surfaces). This practically means that high sample sizes eventually lead to reduced oxygen consumption indexes. Apparently, with higher sample sizes, oxygen diffusion to the interior of the material is limited, leading to insufficient aeration and a reduced respiration activity.

On the other hand, the carbon dioxide generation indexes (the $C–CO_2$ index and the total $CO_2$) were not influenced by the flow (see equations 2 and 4 of Table 5), and they were only dependent on the organic matter weight of the material. That is, the higher the substrate (organic matter weight), the higher the $CO_2$ released; therefore, sample size affects carbon dioxide generation but in a reverse way to oxygen consumption. As a result of the above, both RQs ($RQ_{peak}$ and $RQ_{average}$) depended solely on the organic matter mass. An explanation is as follows: Organic carbon uses oxygen as an electron acceptor and is oxidized first to carbonaceous metabolic byproducts and ultimately to $CO_2$. Apparently, as the oxygen input to the system increases, less mineralization to $CO_2$ occurs in favor of the generation of intermediate carbonaceous metabolic byproducts (e.g. alcohols, organic acids). A speculation is made that the above may be related to the oxygen residence time, since as the $O_2$ residence time decreases (high flows), the ability of the microorganisms to sustain the oxidation of organic carbon to its final mineralization stage ($CO_2$) decreases too. The remaining equations of Table 5 are not illustrated graphically, since they have a simple linear form with only one term. Fig. 6 practically shows that the highest oxygen consumption indexes are found at the top left part of the figures, where low organic matter weights and high air flowrates (i.e., high UAF) occur.

The above results indicate that the $C–CO_2$ generation indexes and the RQ cannot be used as reliable compost stability indicators during DRT, due to their strong influence by the experimental conditions. On the other hand, the oxygen consumption related indexes ($DRI_{24}$ and $DCRI_7$) are not that strongly influenced by the UAF, as indicated in Figs. 5a, 5b, respectively; they could be used as compost stability indexes.

## 4. Conclusions

The $DRI_{24}$ and $DCRI_7$ reduced as the sample size increased. In addition, as air flowrate increased, these indexes increased too. Carbon dioxide generation was not significantly affected by the air flowrate and increased as sample size increased.
A positive correlation between the $DRI_{24}$ and the UAF and a strong negative correlation between the $CO_2$ index and the UAF were calculated.
The RQ reduced from 0.5 to less than 0.05 as the UAF increased.
The MSW compost used in this work is considered stable, according to already published stability limits.

## Acknowledgements

We acknowledge G. Paschalis, P. Gouvoussis and A.Petalas, employees of the MSW composting facility, and Mr. Alexandros Evangelou for his support during this project.

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