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The effect of the airflow rates and of the aeration mode on the respiration activity of four organic wastes: Implications on the composting process

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Abstract

The aim of this study was to assess the effect of the airflow and of the aeration mode on the composting process of non-urban organic wastes, namely: (i) a fresh, non-digested, sewage sludge (FSS), (ii) an anaerobically digested sewage sludge (ADSS), (iii) cow manure (CM) and (iv) pig sludge (PS). This assessment was done using respirometric indices. Two aeration modes were tested, namely: (a) a constant air flowrate set at three different initial fixed airflow rates, and (b) an oxygen uptake rate (OUR)-controlled airflow rate. The four wastes displayed the same behaviour namely a limited biological activity at low aeration, whilst, beyond a threshold value, the increase of the airflow did not significantly increase the dynamic respiration indices ($DRI_{1\ max}$, $DRI_{24\ max}$ and AT_4). The threshold airflow rate varied among wastes and ranged from 42 NL air kg^{-1} DM h^{-1} for CM and from 67 to 77 NL air kg^{-1} DM h^{-1} for FSS, ADSS and PS. Comparing the two aeration modes tested (constant air flow, OUR controlled air flow), no statistically significant differences were calculated between the respiration activity indices obtained at those two aeration modes. These results permit to establish a general procedure to measure the respiration activity avoiding any limitation by airflow, valid for urban and non urban representative organic wastes. This will permit other researchers to provide consistent results on this parameter. At the same time, better respiration activity results can be obtained with the lowest aeration rate possible, that can be translated to energy savings and other problems related to an excessive aeration rate can be avoided in full scale composting plants.

Keywords: dynamic respirometric index, oxygen uptake rate, composting, airflow, biological activity.

1. Introduction

Current legislation on solid waste management has highlighted the importance of recycling and recovering these wastes as a sustainable management practice to substitute traditional final disposal through incineration and landfilling. The alternatives are biological treatments, based on composting, anaerobic digestion or both combined treatments. In all cases, it is important to know the biological activity of the waste, because it will determine the type of operation, the energy requirements and recovery, and its exploitation costs (Barrena et al., 2011a).

Composting is a natural process where microorganisms decompose organic matter into their simple elements. Compost, the final product, is stable and sanitized. Several studies highlight the importance of stablishing a reliable measure of the waste biological activity and its biodegradability (Lasaridi and Stentidord (1998), Barrena et al. (2009), Pognani et al. (2011)), because other chemically-based parameters such as TOC (total organic carbon), COD (chemical oxygen demand), total organic matter content (OM, expressed as volatile solids) and DOC (dissolved organic carbon) are not precise enough because not all organic matter is biodegradable in real operation times. In consequence, there would be an overestimation of its biodegradability using these

parameters (Barrena et al., 2009). Actually, measures of biological activity are a way to have a realistic value on the overall efficiency of the biological treatment process either in composting or in anaerobic digestion processes (Ponsá et al., 2008). Having a reliable method to assess these indices is of crucial relevance for critical issues related to waste management such as final quality and environmental impact assessment as previously remarked (Colón et al., 2012; Scaglia and Adani, 2008). Although a consensus is not reached yet, there are different suggested methodologies in scientific literature, all of them based on biological activities.

Ponsá et al. (2008) found a good correlation between aerobic and anaerobic indices. Barrena et al. (2009) also found a significant correlation between cumulative oxygen consumption and ultimate biogas production. Both correlations were found using samples from mechanical-biological treatment (MBT) plants treating municipal solid wastes. This indicates that both indices can be used to express the degree of biological stability. Aerobic indices were recommended for its shorter time of assay. In general, aerobic respiration indices have been highlighted as the most suitable tool for biodegradability and stability assessment, to monitor the process and to implement new improvements (Ponsá et al., 2010a, Barrena et al., 2009). Dynamic Respiration Indices (DRI) are well established (Scaglia2011?)and used in composting research because of their advantages over static respiration indices or BOD with solids samples, such as the presence of a continuous airflow during the measurement, that do not limit the oxygen transfer through the biomass layer (Adani et al., 2003 and 2006).

Barrena et al. (2011b), studied the behaviour of respiration activity on different wastes, classified in four groups: municipal solid wastes, wastewater sludge, manure, bulking agents and other wastes. Authors observed that municipal solid wastes with higher percentage of organic matter showed higher respiration ctivity. This biological activity

90 increased when studying the source-selected organic fraction of municipal solid wastes
91 (OFMSW). With regard to wastewater sludge, the anaerobic digestion process decreases
92 the respiration activity by 60-70% (Ponsá et al., 2008). Fresh wastewater sludge
93 biodegradability can change depending on the treatment applied or its origin, but
94 digested wastewater sludge is usually more homogeneous. Manure shows a moderate
95 respiration activity, far from those obtained with OFMSW and non-digested wastewater
96 sludge (Barrena et al. 2011b). Part of this activity can be lost during their storage, as a
97 part of its treatment (Bonmatí and Flotats, 2003). In summary, organic wastes from
98 different origins, organic matter content and history will present different level of
99 respiration activity. This will directly affect the aeration requirements and the
100 composting process overall performance.

101 Aeration rate is expected to have an important effect on the microbial respiration,
102 thus in biological activity and stability of the material. In Komilis and Kanellos (2012),
103 a positive correlation between the dynamic respiration index DRI_{24} and unit airflow
104 rates (range XXXX) was observed, as well as a negative correlation between CO_2 index
105 and unit airflow rate.

106 Almeira et al. (2015), studied the effect of different airflow rates (range XXXX) and
107 different aeration modes on the microbial respiration activity. Three different organic
108 wastes derived from the OFMSW were studied, using constant airflow and an OUR
109 (oxygen uptake rate) controlled airflow, which is continuously adjusted to keep the
110 oxygen uptake rate optimized (Puyuelo et al., 2010). Results showed that a constant
111 airflow below 20 L kg^{-1} DM h^{-1} limited respiration activity, while airflows above that
112 value resulted in statistically similar respiration activities.

113 Aeration conditions also influence the composting process performance in terms of
114 biodegradation rate, process time and GHG emissions from the composting process.

115 Insufficient aeration can lead to oxygen limitations that lead to poor biodegradation
116 rates. Excess of aeration can eventually cause major water losses and hamper moisture
117 control (Ruggieri et al., 2008). It is considered as one of the most important factors, as
118 insufficient aeration can lead to anaerobic condition, resulting in an increase of CH_4
119 emissions (Jiang et al. 2011). Jiang et al. (2015) observed that higher aeration rates
120 increased NH_3 and N_2O losses, but showed a higher mitigation on CH_4 emissions, when
121 composting pig feces.

122 The aim of this study is to evaluate the effect of different airflow rates and different
123 aeration modes on the microbial respiration using different organic wastes via several
124 DRI. Four parameters were analysed: DRI_1 (1-hour Dynamic Respirometric Index
125 average), DRI_{24} (24-hours Dynamic Respirometric Index average), AT_4 (cumulative
126 oxygen consumed in four days) and lag phase. Four non-urban type organic wastes were
127 tested and their performance was compared with the organic fraction of municipal solid
128 waste tested by Almeira et al. (2015). Wastes used in this study were selected because
129 of their high production volume. For instance, Catalonia region, with 7 million
130 inhabitants, produces per year 2 million tons of wastewater sludge on dry mass basis
131 and 20 million tons of manure, being cow and pig manure the main components. In
132 consequence, these materials have been selected as representative wastes to illustrate the
133 different typology of non-urban and livestock organic wastes (Campos et al. 2004,
134 Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, 2012). Two
135 aeration regimes were used: i) a constant unit airflow rate and ii) a continuous and
136 variable airflow rate as adjusted by the OUR controller. Results obtained will help to
137 stablish the necessary amount of air in order to measure with accuracy the microbial
138 respiration in the laboratory. In addition, results will aid to calculate the aeration

139 necessary at full scale to provide an effective stabilization for different types of
140 agricultural and industrial organic wastes.
141
142 **2. Materials and Methods**
143
144 2.1. Organic wastes
145 Four different non-urban organic wastes were used in this work:
146 (i) a fresh, non-digested, sewage sludge (FSS) from the wastewater treatment plant
147 in Olot (Girona, Spain),
148 (ii) an anaerobic digested sewage sludge (ADSS) from the wastewater treatment
149 plant in Sabadell (Barcelona),
150 (iii) cow manure (CM) obtained from a local farm in Catalunya, and
151 (iv) pig slurry (PS) from a farm of Vic (Barcelona).
152 FSS and ADSS were sampled in their respectively wastewater treatment plant, while
153 cow manure and pig slurry were sampled on a storage pile and a storage pond,
154 respectively.
155 . Table 1 shows their characterization.
156
157 2.2. Respiration tests
158 90 g of sample from each of the aforementioned substrates were used in each
159 individual respiration run (i.e. per replicate). To ensure a good porosity of the material,
160 9 g of inert bulking agent were added and manually mixed with FSS, ADSS and PS.
161 The bulking agent consisted of small pieces (1 x 2 cm) of dishclothes (Spontex)
162 (Puyuelo et al., 2011). All tests were run in triplicate.

163 The dynamic respirometer consisted of 12 500 mL custom made reactors, as
164 described elsewhere (Ponsá et al, 2010b), used to measure the respiration activity.
165 Briefly, the individual waste sample or mixture was placed in each 500 mL reactor.
166 Each reactor consisted of an Erlenmeyer flask, containing a plastic net to support the
167 organic waste and to provide an air distribution chamber, placed in a water bath at 37ºC
168 (Fig. 1). Airflow to the reactor was adjusted by means of an airflow controller
169 (Bronkhorst Hitec, The Netherlands). Air was passed through a humidifier at the same
170 temperature of the reactor to avoid water losses and moisture changes. Exhaust air from
171 the reactor was sent to a dehumidification water trap and later to an oxygen sensor. Air
172 flow meters and oxygen sensor were connected to a data acquisition system to
173 continuously record the on-line calculations of the selected respiration indices.
174
175 2.3. Respiration Indices
176 Dynamic respiration index (DRI) can be calculated from oxygen and airflow data for
177 a given time (Eq. [1]) (Ponsá et al., 2010b).

178 $$DRI_t = \frac{\left(O_{2,i} - O_{2,0}\right) \cdot F \cdot 31.98 \cdot 60 \cdot 1000^{a}}{1000^{b} \cdot 22.4 \cdot DM} \quad \text{Eq. [1]}$$

179 Where: DRI_t, dynamic respiration index for a given time t (mg O_2 g^{-1} DM h^{-1}); ($O_{2,i}$ –
180 $O_{2,0}$), difference in oxygen content between airflow in and out the reactor at that given
181 time, molar fraction; F, volumetric airflow measured under normal conditions (1 atm
182 and 273 K) (mL min^{-1}); 31.98, oxygen molecular weight (g mol^{-1}); 60, conversion factor
183 (minutes h^{-1}); 1000^{a}, conversion factor (mg g^{-1}); 1000^{b}, conversion factor (mL L^{-1});
184 22.4, volume occupied by one mol of ideal gas under normal conditions (L); DM, dry
185 mass of the substrate under study that is loaded in the reactor (g).

186 Total cumulative oxygen consumption (AT_u) was determined through the numerical
187 integration of the continuous DRI_t data obtained. It was calculated according Eq. [2]
188 (Puyuelo et al., 2010).

189 $$AT_u = \int_0^t DRI_t \, dt \quad \text{Eq. [2]}$$

190 Where AT_u, is the total oxygen consumption between time 0 and t beyond the initial
191 lag phase (g O_2 g^{-1} DM); t, the final experimental time (h); DRI_t, dynamic respiration
192 index for a given time t (mg O_2 g^{-1} DM h^{-1}).

193 The three respiration indices studied in this work were: (a) DRI_1, which is the
194 average of the instantaneous oxygen uptake rate during a 1-hour period, (b) DRI_{24},
195 which is the average of the instantaneous oxygen uptake rate during the most intense 24
196 hours of biological activity (Barrena et al., 2009) and (c) AT_4, which is the total oxygen
197 consumed over a 4 day period beyond the initial lag time (Almeria et al., 2015).
198 Respiration tests were run for 5 to 7 days so AT_4 could be calculated. Another important
199 parameter calculated was the lag phase (h). Lag phase is finished when the observed
200 respiration activity is 25% of the value results in the region of largest increase in oxygen
201 consumption within the first four days (Federal Government of Germany, 2001).

202

203 2.4. Aeration modes

204 In the constant airflow regime, airflow was adjusted to maintain the initial value
205 throughout the experiment. In the OUR control airflow regime, airflow was
206 continuously adjusted to optimize oxygen uptake rate by an authomatic controller.
207 Puyuelo et al., (2010) developed and optimized the algorithm for this new control
208 strategy and validated it in the composting of different wastes. Almeira et al., (2015)
209 successfully used this same OUR-controller in respiration tests. The OUR controller

compares the variations of different OUR measures in different cycles according to the airflow applied and establishes an airflow according to the measure and the comparison of the flow applied between two consecutive cycles. A safety secondary loop is included to ensure that the oxygen level does not fall below 5%. The oxygen level was always over 15% in the experiments reported in this work. This strategy has demonstrated to be the most suitable in terms of lower air consumption, final biological stability and process gas emissions (Puyuelo et al., 2014). The use of two methods of aeration were selected for observe the difference between a limited oxygen system (constant airflow regime) and a non-limited oxygen system (OUR control airflow regime).

2.5. Experimental design and statistical analysis

Three constant airflows were tested for each sample: 5 ml min^{-1}, 15 ml min^{-1} and 30 ml min^{-1}. An additional not-constant aeration strategy was included based on the OUR-controller. Table 2 shows each airflow expressed as NL air kg^{-1} DM h^{-1} to express the volumetric flow in more easily extrapolated units. These ranges were selected to cover a wide range of aeration values according to the expected biological activity of the five substrates. The experimental period was 5-7 days. Three independent replications per treatment were done. Statistical analysis was performed with basic ANOVA techniques while pairwise comparisons were based on the Tukey test (at $p < 0.05$). Statistics were performed with MINITAB^{TM} V17 .

3. Results and Discussion

The characterisation of the organic wastes is shown in Table 1. While organic matter content is similar for all wastes tested, the percentage of moisture varies according to the type of waste. CM presents a lower water content than the rest of the wastes (FSS,

ADSS, PS). Thus the same constant volumetric airflow represents a lower specific aeration rate for CM than for the rest of the samples (Table 2). The moisture of the samples at the end of the respiration test was analysed. No water loss was observed according to the respirometer configuration described. Regarding pH, the materials were slightly alkaline, confirming that no acidification occurred during storage (Rudrum, 2005).

3.1. Oxygen uptake profiles

Figure 2 presents one full respiration profile for each waste under a constant aeration rate of 15 mL min^{-1}. Similar profiles were obtained for each waste in all the experiments regardless the applied airflow. According to Fig. 2, the OUR profile of the four wastes followed the typical ascent to a peak value, which usually coincides with the rise of the temperature in the real composting process (Puyuelo et al., 2010), and is followed by a progressive decrease. The OUR peaks in the first 5-10 hours for FSS, ADSS and PS, and later in the case of CM, at around 20h of process. In the case of pig slurry only, a second peak was observed. Dabert et al. (2010) and Esteve at al. (2009) reported that successive respiration peaks could occur but would have nothing to do with environmental conditions, such as moisture or temperature. Denes at al. (2015) led the hypothesis that the second respiration peak corresponds to the growth of a different microbial community and occurs when the most recalcitrant part (slowly hydrolysed) becomes available to biodegradation. Another fact to remark is that in all those homogeneous wastes, lag phase was very brief or virtually non-existent.

3.2. Effect of airflow rate on respiration indices

Figures 3 to 6 describe the effect of different airflow rates on three main respiration indices (DRI_1, DRI_{24} and AT_4) and on the lag phase. Two statistical analyses were performed with the goals to a) compare the behaviour of each individual waste under the different aeration rates (controlled, constant) and b) to compare the behaviour of all wastes tested under different aeration rates. Both analyses were based on ANOVA principles.

Figure 3 presents the DRI_1 for the four materials under the 4 different aeration regimes. In all cases, respiration indices increased when the feeding airflow increased, as had been also observed by Komilis and Kanellos (2012). The difference was significant when increasing airflow from 5 to 15 mL min^{-1}. However further rise to 30 mL min^{-1} did not significantly increase the DRI_1. This is in accordance with results reported by Almeira et al. (2015) who had used the organic fraction of municipal solid wastes (fresh, partially degraded and composted) in their experiments. The OUR-based aeration strategy led to higher DRI_1 values in all cases, although no statistically different. On the contrary, Almeira et al. (2015) reported a significant increase in respiration indices under the OUR aeration mode when analysing OFMSW and compost.

Same behaviour was observed for DRI_1, DRI_{24} and AT_4 (Figures 3, 4 and 5). That is, increasing aeration upon a given threshold did not further improve the respiration indices. 5 mL min^{-1} was insufficient, probably due to mass transfer limitations within the reactor. Increasing to 15 mL min^{-1} or higher aeration rates favoured air distribution in the reactor and thus enhanced the oxygen uptake rate. This means that maximum respiration activity is reached around 15 ml min^{-1} and there is no need for an extra air supply. Furthermore, higher aeration rates lead to higher energy consumptions and process emissions. For instance, Jiang et al., (2015) reported an increase of NH_3 and

N_2O emission when increasing aeration rates in the composting process. Colón et al. (2012) quantified the emissions related to energy consumption in providing aeration. In all cases, OUR aeration mode ensured a good respiration result. In this sense, this strategy is advisable to avoid aeration limitations when using a new and unknown waste.

Table 3 summarizes the results obtained and presents the threshold specific aeration rate expressed as NL kg^{-1} DM h^{-1}. As expected, fresh sewage sludge exhibited a higher respiration activity than the anaerobic digested sewage sludge, since, during anaerobic digestion, biodegradable organic matter is transformed to biogas. Cow manure and pig slurry showed similar results to ADSS, as these three wastes are partially stabilised materials (Barrena et al., 2011a and 2011b). These are expected results, because we observe that wastes that are more biologically active, such as fresh sewage sludge, to present a high respiration activity; in consequence, high DRI_1, DRI_{24} and AT_4 values are observed as well. It was also expected that the previously anaerobically digested sludge would present a lower respiration activity compared to fresh sewage sludge (50% lower activity). This was true, since that waste has been already stabilized during the anaerobic digestion process and it lost respiration capacity. This observation agrees with Barrena et al. (2011b). In the case of cow manure and pig slurry, the relatively low respiration activity (as compared to sludge) was expected, because although these are normally biologically active wastes, they can lose respiration activity during their storage on farms (Bonmatí and Flotats, 2003). Specific air flows are slightly different (Table 3) due to the 10% difference in moisture content of the materials (76.2-86.7%, Table 1). Finally, comparing our results to those obtained by Almeira et al., (2015) that had used only the organic fraction of municipal solid waste (OFMSW), it can be noticed that although OFMSW is a very biologically active waste, its response was similar to

309 that of ADSS, CM and PS. Specifically, indices obtained for OFMSW under constant
310 aeration were: 3.2 g O_2 kg^{-1} DM h^{-1} (DRI_1), 3.1 g O_2 kg^{-1} DM h^{-1} (DRI_{24}) and 228.2 g
311 O_2 kg^{-1} DM (AT_4) (Almeira et al., 2015) which are values similar to the ones obtained
312 here for ADSS, CM and PS.

313 According to the results, we can categorize these organic materials according to their
314 biodegradability, as had been proposed by Barrena et al. (2011b). Fresh sewage sludge
315 would be categorized as a highly biodegradable waste, due to its respiration activity that
316 is higher than 5 g O_2 kg^{-1} DM h^{-1}, while the anaerobic digested sewage sludge, cow
317 manure and pig slurry would be categorized as moderately biodegradable wastes, given
318 the fact that their respiration activity is between 2 and 5 g O_2 kg^{-1} DM h^{-1}.

319 The purpose of the composting process is to stabilize and sanitize urban and non-
320 urban wastes. The European Commission uses parameters such as AT_4 or DRI to define
321 if the material is completely stabilized or not. According to proposals suggested by the
322 European Commission, a waste can be characterized as well stabilized if AT_4 is below
323 10 g O_2 kg^{-1} DM or if DRI is below 1 g O_2 kg^{-1} DM (European Commission, 2001).

324 Fig. 6 presents the lag phase observed in the respirometric tests for the four
325 materials. Lag time was reduced when increasing the aeration rate from 5 to 15 and to
326 30 mL min^{-1} in all cases. The OUR aeration mode led to slightly higher lag times.

327 When comparing the two aeration modes, the constant airflow and the airflow with
328 OUR control, we can observe that there is not a statistically significant different
329 response between 15 and 30 ml min^{-1} airflow mode and with the airflow OUR control
330 mode. The value that wastes achieve in 15 and 30 ml min^{-1} is the same value that is
331 achieved with an airflow OUR control mode. So airflows below 15 ml min^{-1} appear to
332 limit microbial respiration activity. In Almeira et al. (2015) similar results had been

obtained, since a constant airflow below 20 L kg^{-1} DM h had been found to limit the microbial respiration activity in municipal solid wastes.

4. Conclusions

In conclusion, the study demonstrated the following:

- There is not a continuous linear relation between the airflow supply and the respiration activity. Actually, there is a flowrate threshold, above which any further increase does not affect biological activity. This threshold is achieved at a constant airflow of 67 NL air kg^{-1} DM h^{-1}, in the case of FSS and ADSS, 42 NL kg^{-1} DM h^{-1} in the case of CM and 77 NL kg^{-1} DM h^{-1} in the case of PS. Below those specific air flowrate thresholds, the respiration activity is limited and is positively correlated to the air flowrate.
- The DRI_{24} ranged from 2 to 6 g O_2 kg^{-1} DM h^{-1}. FSS was the substrate with the highest respiration activity, followed by the cow manure. No clear correlation between respiration activity and organic matter content can be deduced from this work.
- Comparing the two aeration modes tested (constant air flow, OUR controlled air flow), no significant difference is observed between the respiration activity indices obtained by those two aeration modes.
- Comparing urban waste (from a previous study) and non-urban wastes, non-urban wastes were more biologically active, with FSS being the most biologically active one among all.

These results determine the procedure for a proper measurement of the respiration activity in organic wastes, allowing other researchers to provide consistent results on this parameter. This has implications in providing a reliable measure of biological

358 stability; assessing the proper aeration in composting facilities in the full scale
359 improving the process economics; and avoiding environmental impacts of the
360 composting process and the use of the final product.
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459 Precision determination for the dynamic respirometric index (DRI) method used for
460 biological stability evaluation on municipal solid waste and derived productsOriginal
461 Research Article
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Tables

Table 1. Initial moisture, organic matter and pH of the four substrates tested (mean ± stdev).

Substrate	Moisture (% wb)	Organic matter (% db)	pH
FSS	85.0 ± 1	85.0 ± 1	7.51
ADSS	85.3 ± 0.03	78.4 ± 0.1	8.21
CM	76.2 ± 0.1	91.9 ± 0.2	7.98
PS	86.7 ± 0.2	83.0 ± 7	8.14

FSS: fresh sewage sludge; ADSS: anaerobically digested sewage sludge; CM: cow manure; PS: pig sludge.

Table 2. Specific airflow achieved (in NL air kg^{-1} DM h^{-1}) at the two aeration modes (constant, OUR controlled).

Waste	Constant airflow (5 ml min^{-1})	Constant airflow (15 ml min^{-1})	Constant airflow (30 ml min^{-1})	OUR-controlled airflow
FSS	22.2	66.7	133.3	55 – 238
ADSS	22.2	66.7	133.3	64 – 336
CM	13.9	41.7	83.3	40 – 187
PS	25.6	76.9	153.8	75 – 511

FSS: fresh sewage sludge; ADSS: anaerobically digested sewage sludge; CM: cow manure; PS: pig sludge

Table 3. Summary of respirometric indices obtained at the threshold airflow of 15 mL min^{-1}.

Substrate	Threshold airflow (NL kg^{-1} DM h^{-1})	$DRI_{1\ max}$	$DRI_{24\ max}$	AT_4	Lag phase
FSS	67	6.4 ± 0.9^{B}	4.9 ± 0.7^{E}	312 ± 45^{H}	0.9 ± 0.2^{LM}
ADSS	67	3.7 ± 0.4^{C}	2.5 ± 0.3^{FD}	158 ± 25^{I}	0.7 ± 0.6^{M}
CM	42	3.7 ± 0.6^{C}	3.3 ± 0.6^{F}	241 ± 44^{J}	1.2 ± 0.1^{LM}
PS	77	4.2 ± 0.5^{C}	3.2 ± 0.5^{F}	209 ± 31^{GI}	1.5 ± 0.2^{L}

FSS, fresh sewage sludge; ADSS, anaerobic digested sewage sludge; CM, cow manure; PS, pig sludge; means with the same latter at statistically similar at $p < 0.05$.

Legends to Figures

Figure 1. Experimental setup of the dynamic respiration measurement system.

Figure 2. Comparison of different oxygen consumption profiles of: a) FSS (fresh sewage sludge) and ADSS (anaerobically digested sewage sludge) and b) CM (cow manure) and PS (pig sludge).

Figure 3. Comparison of maximum 1-hour average Dynamic Respiration Indices ($DRI_{1\ max}$) versus 5, 15 and 30 ml min^{-1} constant airflow rate and an Oxygen Uptake rate (OUR) airflow control, obtained by FSS (fresh sewage sludge), ADSS (anaerobically digested sewage sludge), CM (cow manure) and PS (pig sludge). Same letters indicate statistically similar means at $p < 0.05$ (comparison is made among all means shown in the graph).

Figure 4. Comparison of maximum 24-hour average Dynamic Respiration Indices ($DRI_{24\ max}$) versus 5, 15 and 30 ml min^{-1} constant airflow rate and an Oxygen Uptake Rate (OUR) airflow control, obtained by FSS (fresh sewage sludge), ADSS (anaerobically digested sewage sludge), CM (cow manure) and PS (pig sludge). Same letters indicate statistically similar means at $p < 0.05$ (comparison is made among all means shown in the graph).

Figure 5. Comparison of total oxygen consumed over a 4 day period beyond the initial lag phase (AT_4) versus 5, 15 and 30 ml min^{-1} constant airflow rate and an Oxygen Uptake Rate (OUR) airflow control, obtained of FSS (fresh sewage sludge), ADSS (anaerobic digested sewage sludge), CM (cow manure) and PS (pig sludge). Same letters indicate statistically similar means at $p < 0.05$ (comparison is made among all means shown in the graph).

Figure 6. Comparison of lag phase (h), versus 5, 15 and 30 ml min^{-1} constant airflow rate and an Oxygen Uptake Rate (OUR) airflow control, obtained of FSS (fresh sewage sludge), ADSS (anaerobic digested sewage sludge), CM (cow manure) and PS (pig sludge). Same letters indicate statistically similar means at $p < 0.05$ (comparison is made among all means shown in the graph).

FIGURE 1

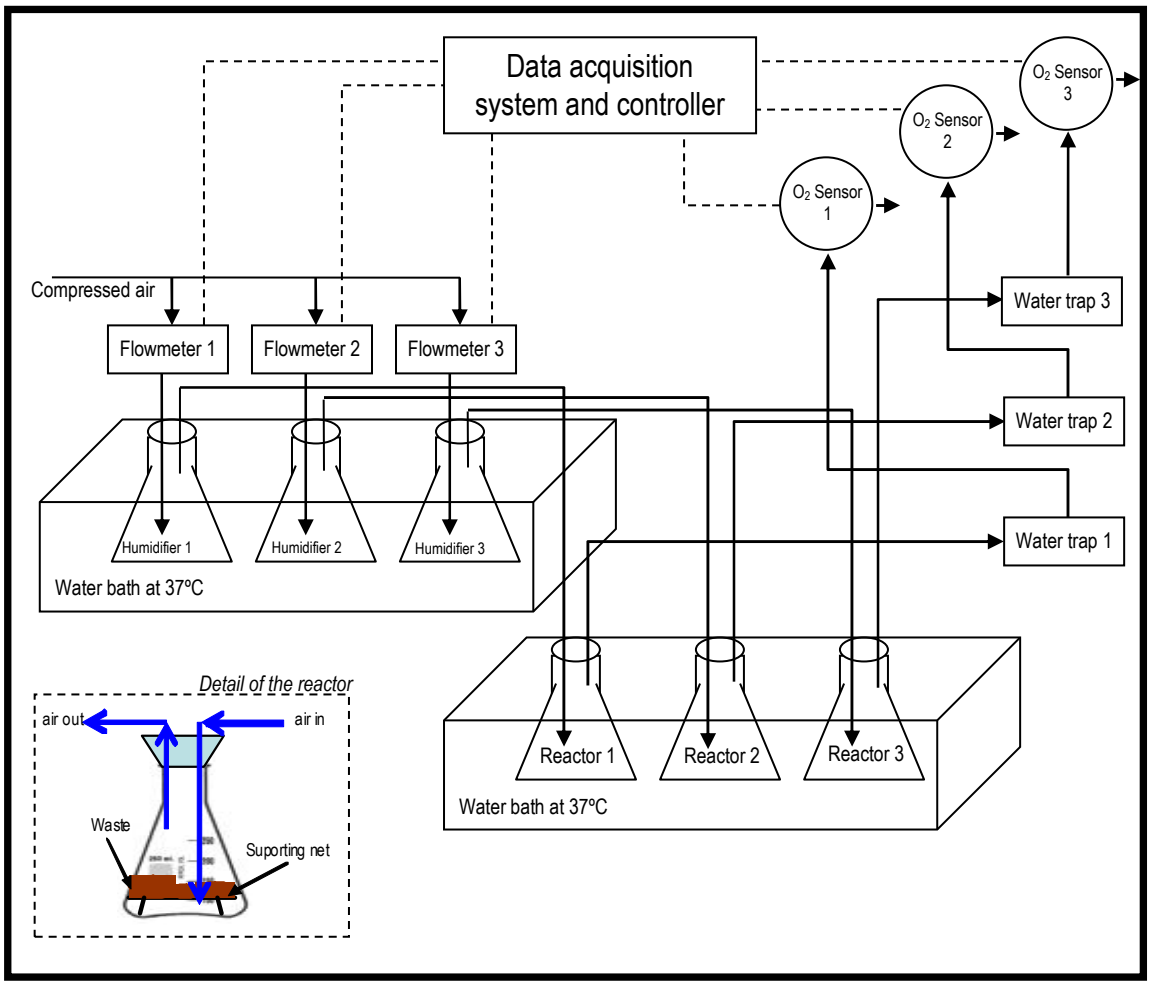
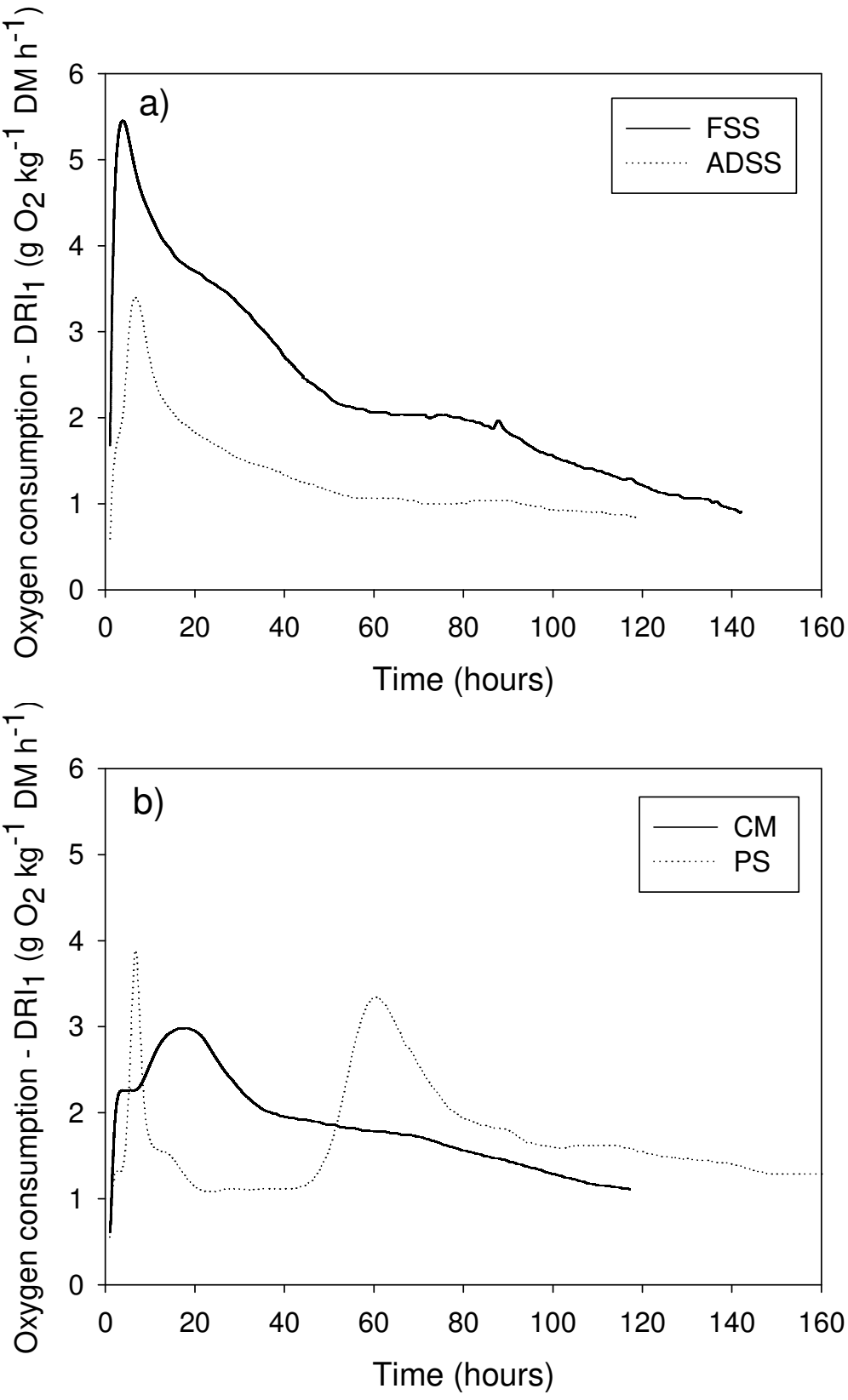


FIGURE 2


a)
FSS
ADSS
Oxygen consumption - DRI1 (g O2 kg-1 DM h-1)
Time (hours)
b)
CM
PS
Oxygen consumption - DRI1 (g O2 kg-1 DM h-1)
Time (hours)

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635 FIGURE 3

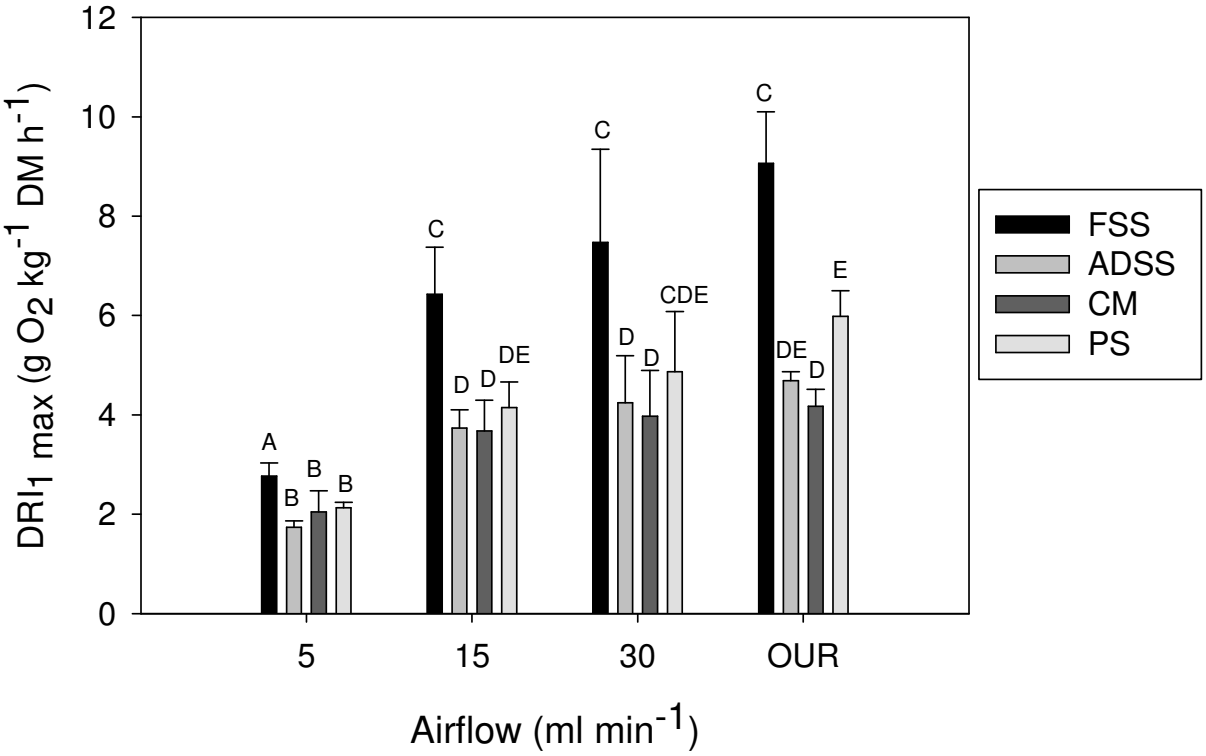

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FIGURE 4

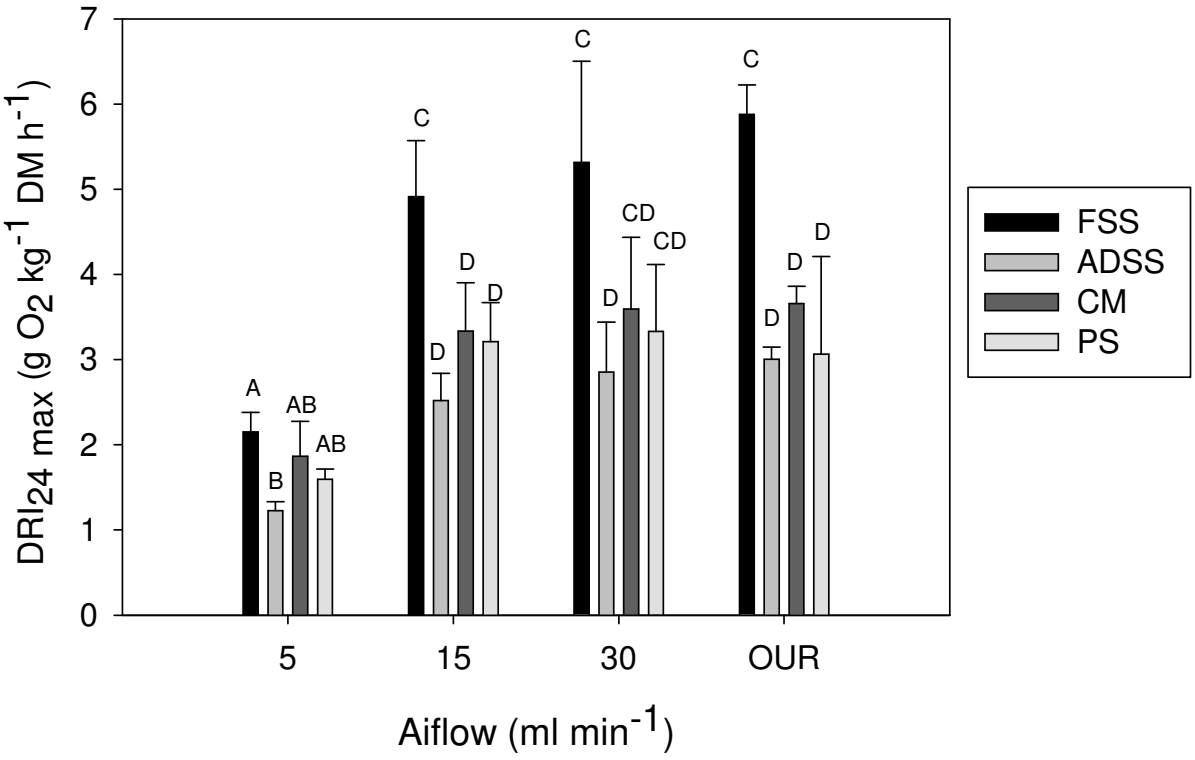
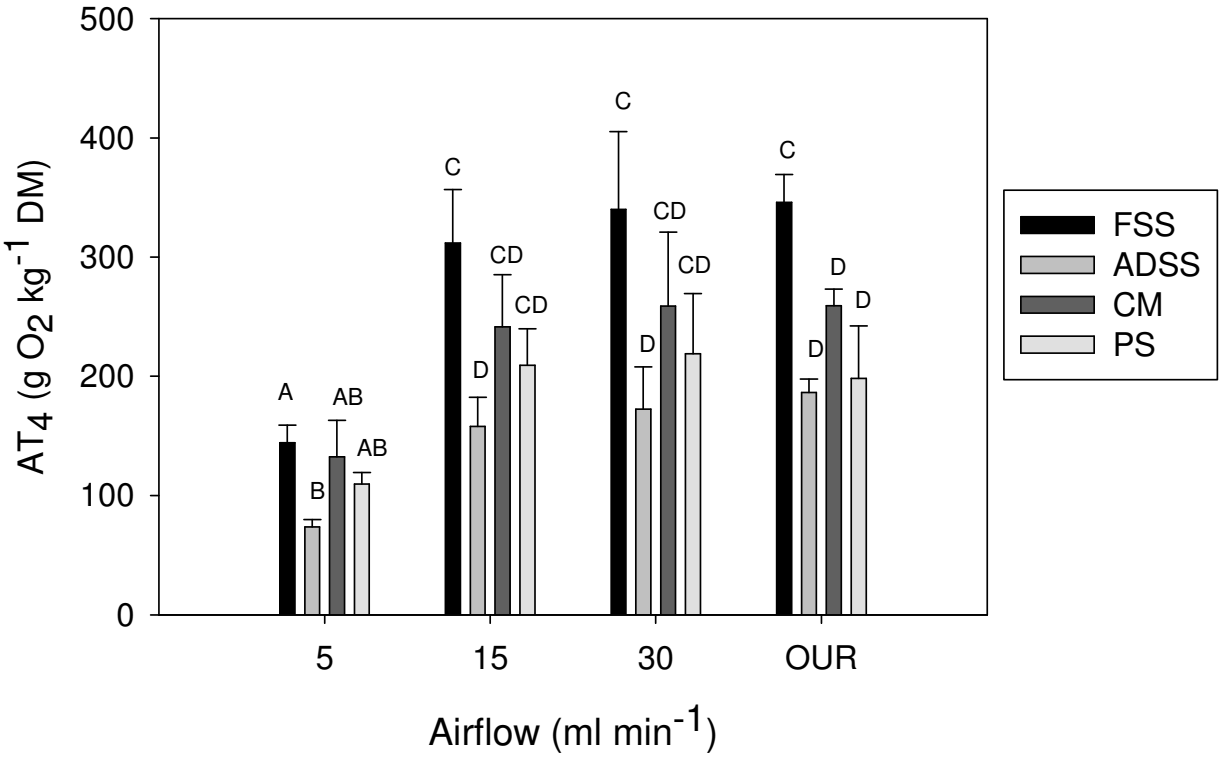

DRI24 max (g O2 kg-1 DM h-1)
Aiflow (ml min-1)
5
15
30
OUR
FSS
ADSS
CM
PS
A
B
AB
AB
C
D
D
D
C
D
CD
CD
C
D
D
D

FIGURE 5


500
400
300
200
100
0
AT4 (g O2 kg-1 DM)
A
B
AB
AB
C
D
CD
CD
C
D
CD
CD
C
D
D
D
5
15
30
OUR
Airflow (ml min-1)
FSS
ADSS
CM
PS

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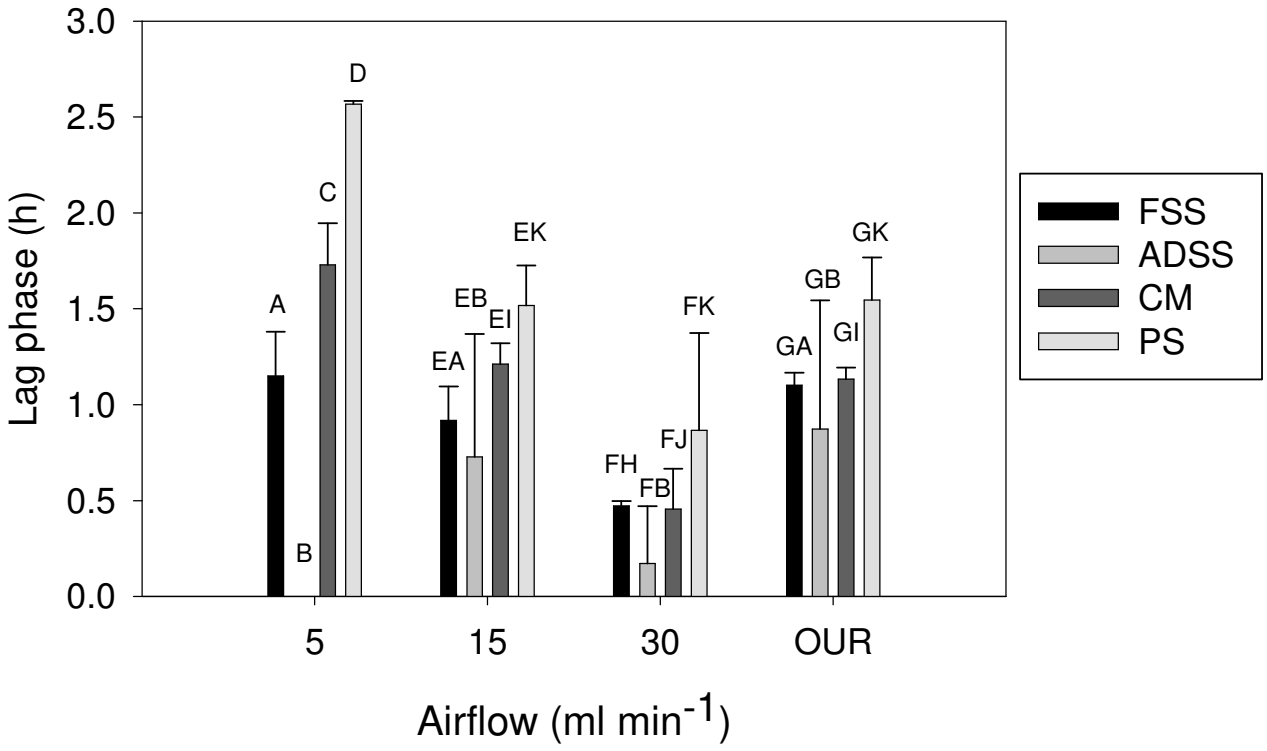
683 FIGURE 6



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