DIFFERENT INDICES TO EXPRESS BIODEGRADABILITY IN ORGANIC SOLID WASTES

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Abstract

Respiration indices are suggested in literature as the most suitable stability determination and are proposed as a biodegradability measure in this work. An improved dynamic respiration index methodology is described in this work. This methodology was applied to 58 samples of different types of waste including municipal solid wastes and wastewater sludge, both raw materials and samples collected in a mechanical-biological treatment plant at different stages of biodegradation. Results were analyzed in terms of long and short term indices and index expression: dynamic respiration indices expressed as average oxygen uptake rate (mg $O_2 \cdot g^{-1}$ $DM \cdot h^{-1}$) at one and 24 hours of maximum activity (DRI_{1h}, DRI_{24h}); and cumulative oxygen consumption in 24h of maximum activity and 4 days (AT_{24h}, AT_4). Indices and wastes were also statistically compared. Raw sludge presented the highest biodegradability followed by organic fraction of municipal solid waste and anaerobically digested sludge. All indices correlated well but different correlations were found for the different wastes analyzed. The information in the dynamic respiration profile allows for the calculation of different indices which provide complementary information. The combined analysis of DRI_{24h} and AT_4 is presented here as the best tool for biodegradable organic matter content characterization and process requirements estimation.

Abbreviations

ADS: anaerobically digested sludge.

AT_{24h}: cumulative oxygen consumption in the 24 hours of maximum activity (corresponding to DRI_{24h}).

AT_4: cumulative oxygen consumption in four days after lag phase.

DM: dry matter.

DRI_{1h}: dynamic respiration index as an average of the one hour of maximum activity.

DRI_{24h}: dynamic respiration index as an average of the 24 hours of maximum activity.

DRI_{max}: maximum dynamic respiration index.

OF: source-selected organic fraction of municipal solid waste (mainly food and yard wastes).

MBT: mechanical-biological treatment.

MSW: municipal solid waste.

MBT-MSW: samples from a MBT treating MSW.

MBT-OF: samples from a MBT treating OF.

RS: raw sludge.

SRI: static respiration index.

1. Introduction

The number of treatment facilities based on biological processes has been increasing the last years. These installations are receiving municipal and industrial organic wastes with the common main goal of reducing their biodegradable organic matter content. Composting, anaerobic digestion and mechanical-biological treatment plants contribute to organic matter recycling and energy recovery and avoid unstable organic matter landfilling.

The general goal of those facilities would then be to stabilize the organic wastes. Stability is defined as the extent to which readily biodegradable organic matter has decomposed (Lasaridi and Stentiford, 1998). A consensus has not been reached yet about which shall be the most suitable measurement of the biodegradable organic matter content in a solid organic waste. The measure of biodegradable organic matter content is of most importance for the proper analysis and design of the above mentioned treatment facilities and it is required to evaluate their efficiency. Some references can be found where different methodologies are suggested as a measure of biodegradable organic matter, based on chemical and biological assays. However some of those methodologies such as the volatile solids content are suitable only as a total organic matter measurement. They can not express the potential biodegradability since they include volatile materials which are not degraded in the operation time (e.g., the bulking agent in a composting plant) or are not biodegradable at all (e.g., plastics present in municipal solid wastes) (Wagland et al., 2009). The methodologies based on biological assays appear as more suitable and some standards have been suggested by different authors or European countries legislation documents (Barrena et al., 2006).

Among the biological methodologies suggested, aerobic respiration indices have been highlighted as the most suitable tool for biodegradabity and/or stability assessment

(Barrena et al., 2009; Wagland et al., 2009). Indeed, they have been used in recent works to analyze the performance of different treatment processes. For instance, Ponsá et al. (2008) used the static respiration index (SRI) proposed by Barrena et al. (2005) and based on a previous work by Ianotti et al. (1993) to assess the efficiency of a mechanical-biological treatment (MBT) plant treating municipal solid waste (MSW) and source-selected organic fraction of municipal solid waste (OF). Ruggieri et al. (2008) used the same index to compare the performance of different aeration systems to enhance OF composting. Ponsá et al. (2009) also applied this methodology to analyze the composting system of wastewater treatment sludge when using different bulking agent ratios.

Besides the obvious usefulness of this SRI as demonstrated by the above mentioned works, other authors have suggested dynamic approaches for respiration activity measurement (Adani et al., 2003; Tremier et al., 2005). Furthermore, SRI correlates well with dynamic respiration index (DRI) (Barrena et al., 2009) and with anaerobic indices such methane generation potential (Ponsá et al., 2008). The main difference among static and dynamic methodologies is that SRI presents a single value of biological activity potential while the dynamic approach generates an activity profile which might permit a deeper analysis of organic materials biodegradability: this should include both total biodegradable organic matter content and information on at which rate the biodegradation can occur.

In this work, an improved dynamic methodology is presented with the objective to offer a reliable measurement of the biodegradable organic matter content in organic solid materials, useful for researchers and industrial operators. The aim of this work is to establish whether respiration indices can be used as a measure of the biodegradable organic matter content and stability of organic materials as well as to define the most suitable form of expression for those indices.

2. Materials and Methods

2.1. Organic Wastes

Fifty-eight samples of different organic wastes collected at different stages of biodegradation were used in this work. Raw materials were: source-selected organic fraction of municipal solid waste (OF, mainly food and garden wastes); municipal solid waste (MSW); and sludge from wastewater treatment plant, both raw sludge (RS) and anaerobically digested sludge (ADS). Additional samples were collected at different processing points in a MBT plant treating MSW (MBT-MSW) and OF (MBT-OF). This plant has been previously described elsewhere (Ponsá et al., 2008) and the main processing steps are mechanical pre-treatment, anaerobic digestion and composting, in this order. Table 1 shows the average dry and organic matter content for each type of raw material. MBT samples are not included because they present a high deviation since this label includes diverse materials such as MSW after mechanical pre-treatment, digestate from anaerobic digestion or final compost.

Samples were collected and analyzed along one year period (2008). All OF and MSW samples were grinded to 15 mm particle size to increase available surface and maintain enough porosity and matrix structure. All samples were frozen at -18ºC within the first 12 hours after sampling. Prior to analysis samples were thawed at room temperature for 24 hours.

2.2. Dynamic Respiration Index

The procedure established for dynamic respiration indices determination and calculation was based on previous work by Adani et al. (2003, 2004, and 2006) and Barrena et al. (2005) and designed with the aim to analyze three replicates simultaneously. Figure 1 shows a scheme of the experimental set up built for dynamic respiration index determination with capacity for three samples. A 100 g waste sample was placed in a 500 mL reactor. In the case of low porosity materials such as sludge, porosity was corrected manually by mixing 25 g of wooden rods (cut in two) for 100 g of sludge and the resulting 125 g of mixture were used for DRI determination. Wooden rods are considered inert material since their biodegradation is negligible in the time of assay. Reactors (Figure 1) consisted of an Erlenmeyer flask, containing a plastic net to support the organic waste and provide an air distribution chamber, placed in a water bath at 37ºC (Barrena et al., 2005). Airflow in the reactors was manually adjusted by means of an air flow controller (Bronkhorst Hitec, The Netherlands) to provide constant airflow, and modified when necessary to ensure a minimum oxygen content in exhaust gases of 10% v/v (Leton and Stentiford, 1990). According to the biodegradability of the samples, initial air flow selected was 30 mL min^{-1} for active samples and 20 mL min^{-1} for more stable samples such as compost. Exhaust air from the reactors was sent to an oxygen sensor prior dehumidification in a water trap. Both air flow meters and oxygen sensors were connected to a data acquisition system to continuously record these values for DRI calculation.

Dynamic respiration index can be calculated from oxygen and air flow data for a given time (Equation 1).

$$DRI_t = \frac{(O_{2,i} - O_{2,o}) \times F \times 31.98 \times 60 \times 1000^a}{1000^b \times 22.4 \times DM} \quad \text{(Equation 1)}$$

Where: DRI_t, Dynamic Respiration Index for a given time t, mg $O_2 \cdot g^{-1}$ $DM \cdot h^{-1}$; ($O_{2,i}$-$O_{2,o}$), difference in oxygen content between airflow in and out the reactor at that given time, volumetric fraction; F, volumetric airflow measured under normal conditions (1 atm and 273 K), ml min^{-1}; 31.98, oxygen molecular weight, g mol^{-1}; 60, conversion factor, minutes/hour; 1000^a, conversion factor, mg g^{-1}; 1000^b: conversion factor, mL L^{-1}; 22.4, volume occupied by one mol of ideal gas under normal conditions, L; DM, dry mass of sample loaded in the reactor, g.

A dynamic respiration index curve can be built from on-line collected data as shown in Figure 2. From these data, several respiration indices can be calculated as follows, divided into two categories: oxygen uptake rate indices and cumulative consumption indices.

Oxygen Uptake Rate Indices - DRI

- DRI_{max}: maximum DRI_t obtained.
- DRI_{1h}: average DRI_t in the one hour of maximum activity.
- DRI_{24h}: average DRI_{1h} in the 24 hours of maximum activity (Adani et al., 2003).

Cumulative Consumption Indices - AT

- AT_n: Cumulative oxygen consumption in n days calculated as shown in Equation 2:

$$AT_n = \int_{t_l}^{t_l+n} DRI_t \cdot dt \quad \text{(Equation 2)}$$

Where t_l is time when lag phase finishes. Lag phase (Federal Government of Germany, 2001) ends when oxygen uptake rate reaches 25% of the maximum uptake rate calculated as the average of three hours (Figure 2).

- AT_4: cumulative oxygen consumption in four days (after lag phase).

- AT_{24h}: cumulative oxygen consumption in the twenty-four hours of maximum activity, i.e., the twenty-four hours period when DRI_{24h} is calculated.

Two replicates were analyzed for each sample. A third replicate was undertaken when deviation among duplicates was over 20%.

2.3. Analytical methods

Water content, dry matter (DM) and organic matter content were determined according to the standard procedures (The US Department of Agriculture and The US Composting Council, 2001). Three replicates were analyzed for each sample.

2.4. Statistics

Anova test was performed to compare different indices and substrates. Mean values for the different DRI were compared for a given substrate. In addition, OF, RS and ADS mean values were compared for a given index. If Anova test resulted in statistically significant differences, Tukey test was performed in pairwise comparisons. A confidence level of 95% was selected for all statistical comparisons. Statistical tests were conducted with SPSS 17.0.0 (SPSS Inc., USA).

3. Results and Discussion

3.1. Respiration indices values and correlations

Figure 3 presents DRI_{max}, DRI_{1h} and DRI_{24h} and Figure 4 presents AT_{24h} and AT_4 for the 58 samples analyzed. It was not possible to calculate AT_4 in all cases due to insufficient test time. In general higher indices values are observed for OF and RS samples. In the case of MBT samples, the high variability among indices values reflects the different stage of stability of samples collected along a mechanical-biological treatment process.

From the presented values, a qualitative classification of indices can be established, based on the intrinsic characteristics of the materials, the existence of a pretreatment or storage stage, and the analyzed indices values:

i) *highly biodegradable wastes*, respiration activity higher than 5 mg $O_2 \cdot g^{-1} DM \cdot h^{-1}$ (which includes source-selected organic fraction of municipal solid waste, non-digested municipal wastewater sludge and animal by-products)

ii) *moderately biodegradable wastes*, respiration activity within 2 to 5 mg $O_2 \cdot g^{-1} DM \cdot h^{-1}$ (including mixed municipal solid waste, digested municipal wastewater sludge and several types of manure)

iii) *wastes of low biodegradability* (respiration activity lower than 2 mg $O_2 \cdot g^{-1} DM \cdot h^{-1}$)

The indices in Figures 3 and 4 were analyzed in order to establish whether they correlate. Indices were analyzed together and divided into groups according to the type of material. Results obtained for linear correlation, slope, p and R^2, are presented Table 2. For instance, for OF and MBT-OF samples, AT_4 and DRI_{24h} correlated according to $AT_4 = 71.8137 \cdot DRI_{24h}$, with a R^2 of 0.9063 and $p<0.0001$. All indices correlated significantly when all data from the 58 samples were considered. When respiration indices were analyzed according to the type of sample, the correlations found were different but still significant, except for the case of ADS where a high dispersion was observed and no significant linear correlation was found among the five different indices considered. The observed variability in ADS could be explained by the different biodegradation level achieved in anaerobic digesters working under different conditions and with a different biomass. In general the slope for the linear correlation among DRI_{1h}

and DRI_{max} was close to 1 for the different materials analyzed. DRI_{24h} was the 65% of DRI_{max} when all data was considered, however this ratio varied between 49.3 and 89.3% depending on the type of sample. This variation was also observed for DRI_{24h} or DRI_{1h} with AT_4 (65.8 for all data and 71.8 to 101.2 for different types of waste). Short-term indices obtained for one type of waste have been correlated to long-term ones and proposed as useful prediction tools (Mohajer et al., 2009). The observations here presented and discussed highlight the need for specific correlations for each material. They also indicate that although strongly correlated the indices considered might provide different information. Thus, a deeper analysis of their meaning and expression form was undertaken and is presented in following sections.

3.2. Oxygen Uptake Rate Indices – DRI

Figure 5 presents the statistical comparison of DRI_{max}, DRI_{1h} and DRI_{24h} for three different organic wastes typologies, OF, RS and ADS. The indices DRI_{max} and DRI_{1h} were not statistically different for the three materials considered. The index DRI_{24h} was statistically different to and lower than the other two indices for ADS while it was found not different for OF and RS. In the case of highly biodegradable wastes as OF and RS, high respiration activity can be maintained for longer periods of time. In these cases, DRI_{max}, DRI_{1h} and DRI_{24h} are equivalent. Contrary, moderately biodegradable materials as ADS might reach a considerable activity at a given moment but the lack of enough energy content will not allow for the maintenance of that respiration level. In this case, a long term index as DRI_{24h} is expected to be lower than DRI_{max} and DRI_{1h}, as demonstrated in this work (Figure 5). In consequence, DRI_{24h} is considered more sensitive to discriminate among different biodegradability levels. This conclusion points to the hypothesis that a longer time index such as AT_4 could be more sensitive too and a better tool for stability and/or biodegradable organic matter content determination.

3.3. Cumulative Consumption Indices – AT

Figure 6 presents the variation with time of cumulative oxygen consumption (AT_n) expressed as a ratio of long time oxygen consumption test (AT_{12}, cumulative consumption in 12 days). These results were obtained correlating AT_n to AT_{12} for 22 organic samples including OF, RS, ADS, MBT-OF and MBT-MSW.

Data in Figure 6 was fitted to the modified Gompertz model (Equation 3), which describes microbial growth and is often used in anaerobic digestion systems (Buendía et al., 2009; Zwietering et al., 1990).

$$AT_n / AT_{12} = \mathrm{P} \cdot \exp\left\{ -\exp\left[\frac{\mathrm{R} \cdot \exp}{\mathrm{P}} (\lambda - \mathrm{t}) + 1 \right] \right\} \qquad \text{(Equation 3)}$$

Where AT_n/AT_{12} is the ratio of cumulative oxygen consumed at time t (days) to the final cumulative oxygen consumption; P is the ratio of the ultimate oxygen consumption potential (dimensionless); R is maximum oxygen uptake rate, day^{-1}; and λ is the lag phase (days).

The results of the Gompertz fitting were $P = 1.01$, $R = 0.13\ d^{-1}$ and $\lambda = -0.92$ d ($p<0.0001$, $R^2 = 0.9921$). The absence of a lag phase (mathematically, a negative lag phase) indicates the rapid growth of aerobic microorganisms in highly biodegradable substrates. In this sense, an aerobic method is expected to allow for a more rapid biological activity estimation than an anaerobic procedure (Ponsá et al., 2008). Gompertz model should be used when a lag phase is observed, for instance, when processing long term frozen samples.

In the cases where a lag phase is not observed a simple exponential rise model (Equation 4) is considered more suitable to model AT evolution. Figure 6 shows data fit to this model.

$$AT_n / AT_{12} = P \cdot [1 - \exp(-R \cdot t)] \qquad \text{(Equation 4)}$$

Experimental data in this study fitted well to the exponential model ($p<0.0001$ and $R^2 = 0.9956$). Model parameters obtained were P = 1.07 and R = 0.22 d^{-1}. The expression obtained is valid for all the analyzed samples which include different organic materials collected at different stages of biodegradation. Consequently this model can be considered a general expression suitable for aerobic biodegradation process modeling.

As observed in Figure 6, AT_4 corresponds to 65% of the final cumulative oxygen consumption. In the wastewater field the parameter biological oxygen demand at 5 days (BOD_5) is widely used (Metcalf and Eddy, 2003). The BOD_5 represents a 65% of total biological oxygen demand for municipal wastewater. Hence, four days is a convenient duration for the respiratory test in solid phase since it quantifies a considerable amount of total oxygen consumption avoiding longer analysis times.

3.4. DRI vs AT. Which index should be used?

Figure 7 shows the statistical comparison of the biodegradability of three different types of organic wastes according to the index selected to express it. According to Figure 7, OF and ADS would be considered as equivalent in terms of biodegradability when considering DRI_{max}, DRI_{1h}, DRI_{24h} or AT_{24h}. However, when a longer term cumulative index as AT_4 was used, the classification appeared different, being OF and RS not statistically different and ADS statistically less biodegradable. This last finding would be in agreement with the classification suggested in section 3.1

of this paper as well as with the behavior of these materials under composting conditions (Gea et al., 2004). As previously explained, highly biodegradable materials maintain a high activity level for a longer time than moderately biodegradable wastes. This is illustrated by the ratio AT_{24h}/AT_4, which is 34.2, 34.5 and 37.8% for OF, RS and ADS respectively, as calculated from average data on Figure 7.

Consequently, long term cumulative indices would better represent the overall biodegradable organic matter content of a given sample than short term indices, either cumulative or rates. Consequently, AT_4 provides a reliable measure of biodegradable organic matter. However, it is crucial to know the maximum biodegradation rates for a complete biodegradability assessment and in the initial stage of a treatment process to optimize operation. Dynamic respiration methodology allows for a complete biodegradability analysis combining DRI_{max}, DRI_{24h} and AT_4 information, that is, biodegradation rate and biodegradable organic matter content. If one index shall be selected, DRI_{24h} is sensitive enough to discriminate among highly and moderately biodegradable wastes and can be determined in a short period of 24 hours. Afterwards, correlations presented in section 3.1 can be used for AT_4 estimation from DRI_{24h} values specifically for the different types of wastes presented here.

Conclusions

All indices obtained from dynamic respiration methodology correlate well but can reveal differences among organic substrates in a diverse manner. The information provided by DRI profile is a useful tool for a precise biodegradability analysis. The index DRI_{24h} shall be selected as a fast and sensitive measure of biodegradability level while AT_4 quantifies the biodegradable organic matter content of a given sample. The combined information provided by both indices should be used whenever is possible.

Specific correlations for a given material should be used as prediction tools avoiding general relationships.

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Tables

Table 1. Dry matter and volatile solids content for the different types of sample considered, expressed as average with standard deviation in brackets.

Sample code	**Type of sample**	**Number of samples**	**Dry matter (%)**	**Volatile solids (%, dmb)***
OF	organic fraction of municipal solid waste	6	36.2 (5.4)	73.7 (8.8)
RS	raw sludge	10	21.4 (6.0)	73.3 (7.7)
ADS	anaerobically digested sludge	10	21.4 (3.7)	55.4 (8.8)

* dmb: dry matter basis

Table 2. Linear correlations (Y = s·X) found among different dynamic indices according to type of waste (n: number of samples; s: slope; Y: dependent variable; X: independent variable; DRI, mg $O_2 \cdot g^{-1}$ DM$\cdot h^{-1}$; AT, mg $O_2 \cdot g^{-1}$ DM).

OF and MBT-OF samples
n=24, p<0.0001 for all correlations

Y → X↓	DRI$_{1h}$	DRI$_{24h}$	AT$_{24h}$	AT$_4$
DRI$_{max}$	s:0.9698 R^2:0.9965	s:0.6687 R^2:0.8857	s:16.1484 R^2:0.8991	s:47.4244 R^2:0.8017
DRI$_{1h}$		s:0.6927 R^2:0.8970	s:16.7315 R^2:0.9114	s:49.2708 R^2:0.8116
DRI$_{24h}$			s:24.1736 R^2:0.9972	s:71.8137 R^2:0.9063
AT$_{24h}$				s:2.9787 R^2:0.9154

RS samples
n=10, p<0.05 for all correlations,
except * p<0.0001 and $^+$ p>0.10

Y→ X↓	DRI$_{1h}$	DRI$_{24h}$	AT$_{24h}$	AT$_4$
DRI$_{max}$	s:0.9968* R^2:0.9999	s:0.4904 R^2:0.5528	s:11.8046 R^2:0.5547	s:4.2057 R^2:0.9132
DRI$_{1h}$		s:0.4928 R^2:0.5547	s:11.8618 R^2:0.5556	s:53.4010$^+$ R^2:0.5074
DRI$_{24h}$			s:24.0276* R^2:1.0000	s:101.2485 R^2:0.9142
AT$_{24h}$				s:4.2057 R^2:0.9132

MBT-MSW samples
n=12, p<0.0001 for all correlations, except * p<0.001

Y→ X↓	DRI$_{1h}$	DRI$_{24h}$	AT$_{24h}$	AT$_4$
DRI$_{max}$	s:0.998 R^2:1.0000	s:0.8915 R^2:0.9663	s:20.5811* R^2:0.9192	s:71.7897* R^2:0.9246
DRI$_{1h}$		s:0.8934 R^2:0.9668	s:20.6284* R^2:0.9199	s:71.9317* R^2:0.9247
DRI$_{24h}$			s:23.8990 R^2:0.9714	s:80.0834* R^2:0.9017
AT$_{24h}$				s:3.3564* R^2:0.9313

ADS samples
n=10, p>0.10 for all correlations, except * p<0.0001

Y→ X↓	DRI$_{1h}$	DRI$_{24h}$	AT$_{24h}$	AT$_4$
DRI$_{max}$	s:0.9830* R^2:0.9985	s:0.3622 R^2:0.2008	s:11.3557 R^2:0.2901	s:-10.4543 R^2:0.1870
DRI$_{1h}$		s:0.3710 R^2:0.2038	s:11.5285 R^2:0.2894	s:-10.4712 R^2:0.1757
DRI$_{24h}$			s:25.6461* R^2:0.9670	s:51.1704 R^2:0.2920
AT$_{24h}$				s:0.2315 R^2:0.0054

All data
n=58, p<0.0001 for all correlations

Y→ X↓	DRI$_{1h}$	DRI$_{24h}$	AT$_{24h}$	AT$_4$
DRI$_{max}$	s:0.9900 R^2:0.9986	s:0.6325 R^2:0.8496	s:15.3432 R^2:0.8492	s:44.7059 R^2:0.7068
DRI$_{1h}$		s:0.6400 R^2:0.8539	s:15.5174 R^2:0.8496	s:45.6593 R^2:0.7135
DRI$_{24h}$			s:24.0525 R^2:0.9970	s:65.8188 R^2:0.8698
AT$_{24h}$				s:2.7205 R^2:0.8664

Figures

Figure 1. Experimental set up for dynamic respiration indices determination.

Figure 2. Typical curve for dynamic respiration index evolution and calculation.

Figure 3. Dynamic respirometric indices for 58 organic waste samples, expressed as: DRI_{max}, maximum DRI measured; DRI_{1h}, DRI average of the one hour of maximum activity; DRI_{24h}, DRI average of the twenty-four hours of maximum activity. Vertical lines separate different waste typology.

Figure 4. Cumulative oxygen consumption indices for 58 organic waste samples, expressed as: AT_{24h}, cumulative consumption in the twenty-four hours of maximum activity; AT_4, cumulative consumption in four days. Vertical lines separate different waste typology.

Figure 5. Statistical comparison of different indices obtained for three different organic wastes. Different letters indicate statistically different means.

Figure 6. Evolution with time of cumulative oxygen consumption as a fraction of ultimate cumulative oxygen consumption: experimental data and exponential fit.

Figure 7. Statistical comparison of three different organic wastes dynamic indices. Different letters indicate statistically different means.

Figure 1

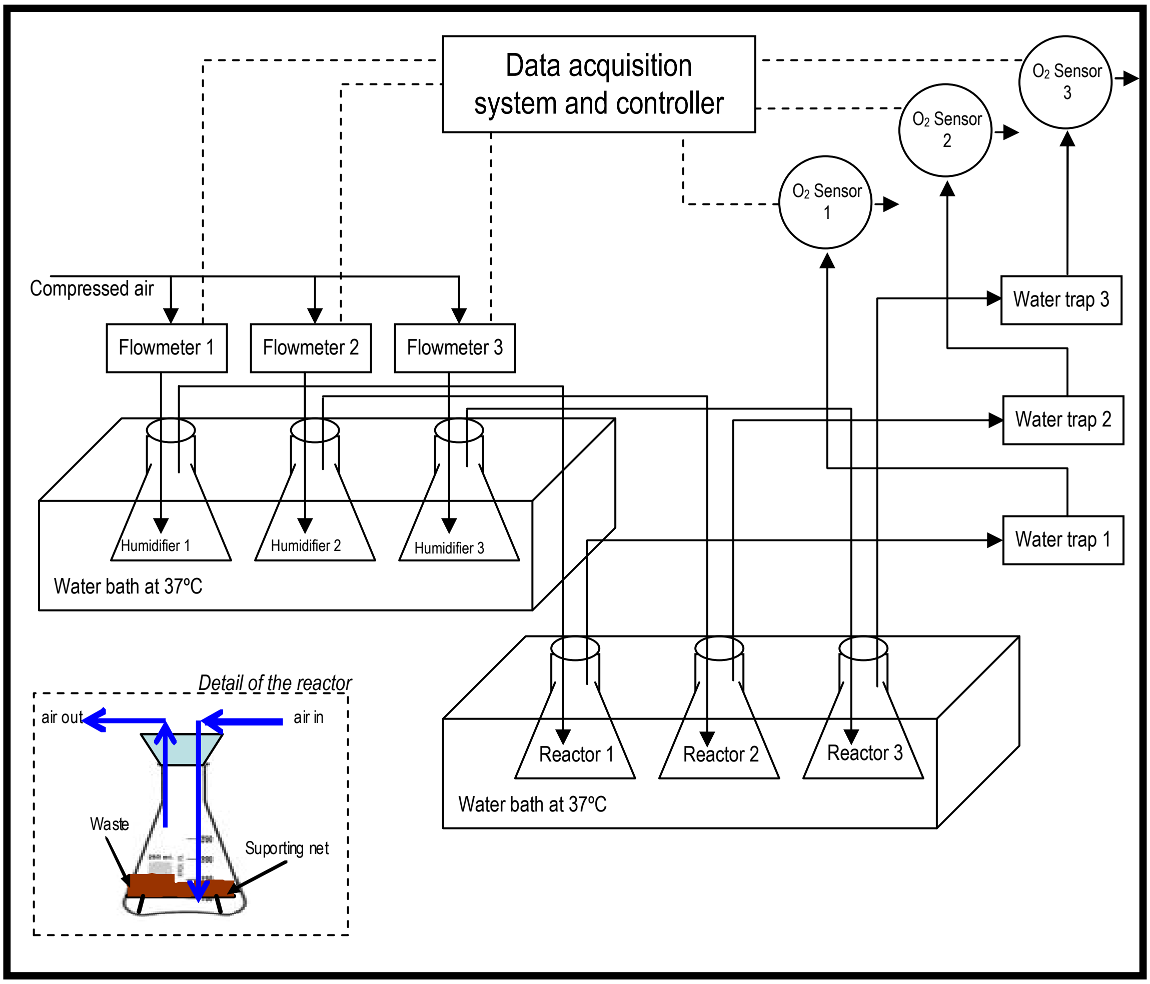

Data acquisition system and controller
O2 Sensor 3
O2 Sensor 2
O2 Sensor 1
Compressed air
Flowmeter 1
Flowmeter 2
Flowmeter 3
Water trap 3
Water trap 2
Water trap 1
Humidifier 1
Humidifier 2
Humidifier 3
Water bath at 37ºC
Detail of the reactor
air out
air in
Waste
Suporting net
Reactor 1
Reactor 2
Reactor 3
Water bath at 37ºC

Figure 2

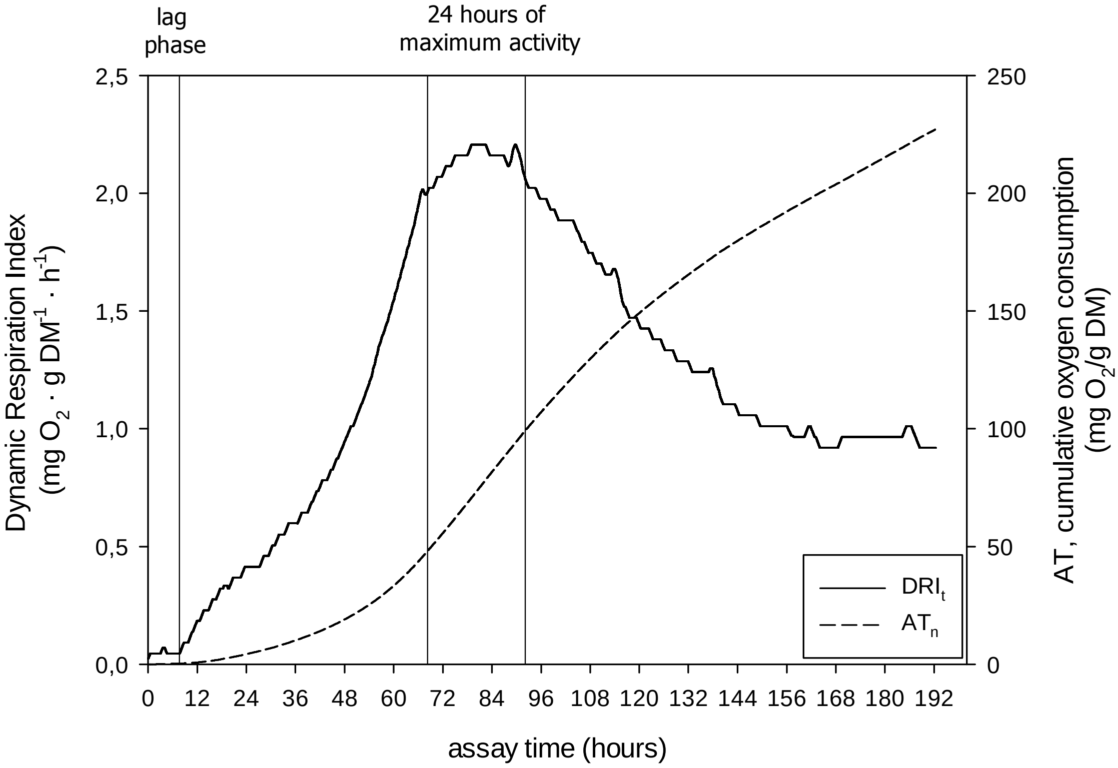

lag phase
24 hours of maximum activity
Dynamic Respiration Index (mg O2 · g DM-1 · h-1)
2,5
2,0
1,5
1,0
0,5
0,0
AT, cumulative oxygen consumption (mg O2/g DM)
250
200
150
100
50
0
0 12 24 36 48 60 72 84 96 108 120 132 144 156 168 180 192
assay time (hours)
DRIt
ATn

Figure 3

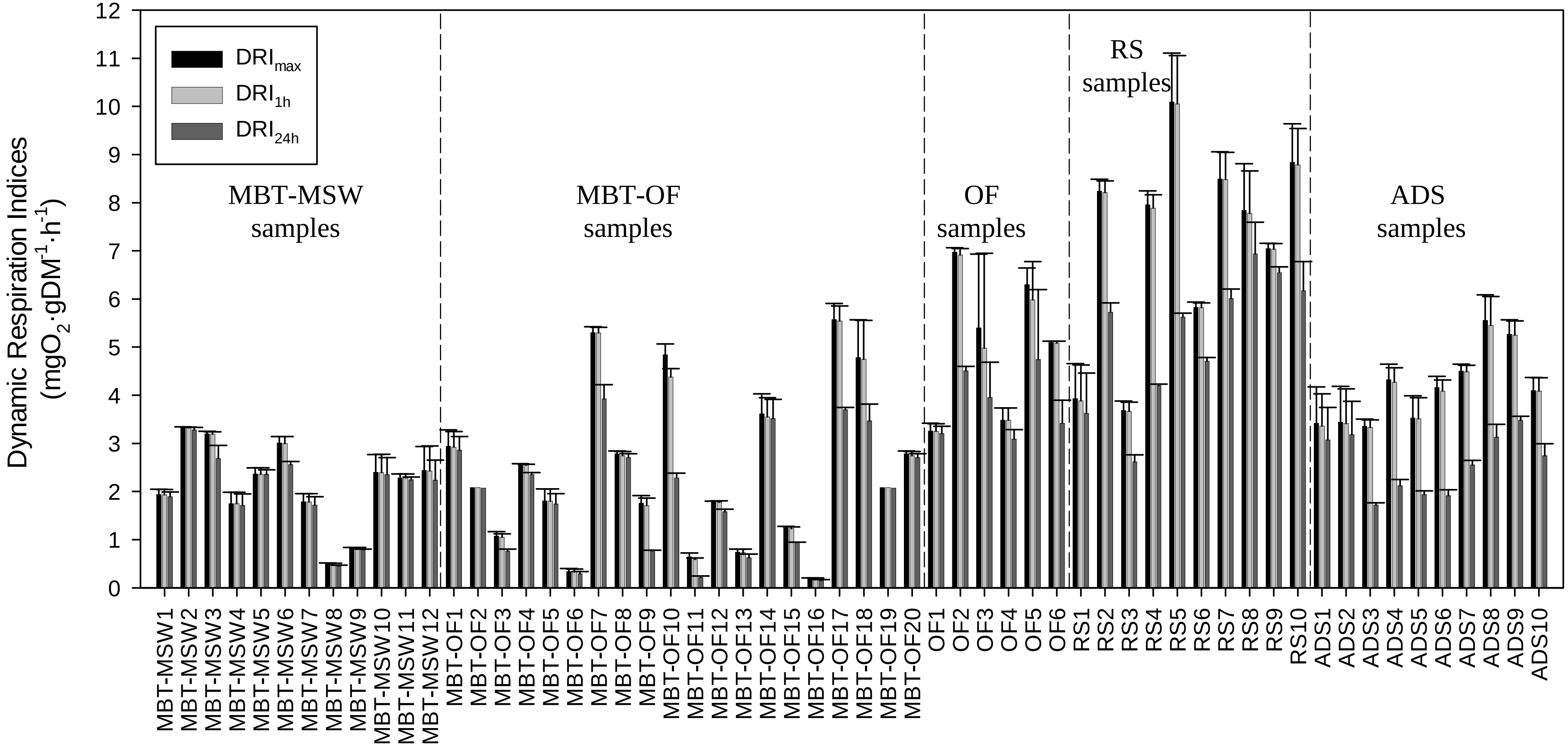
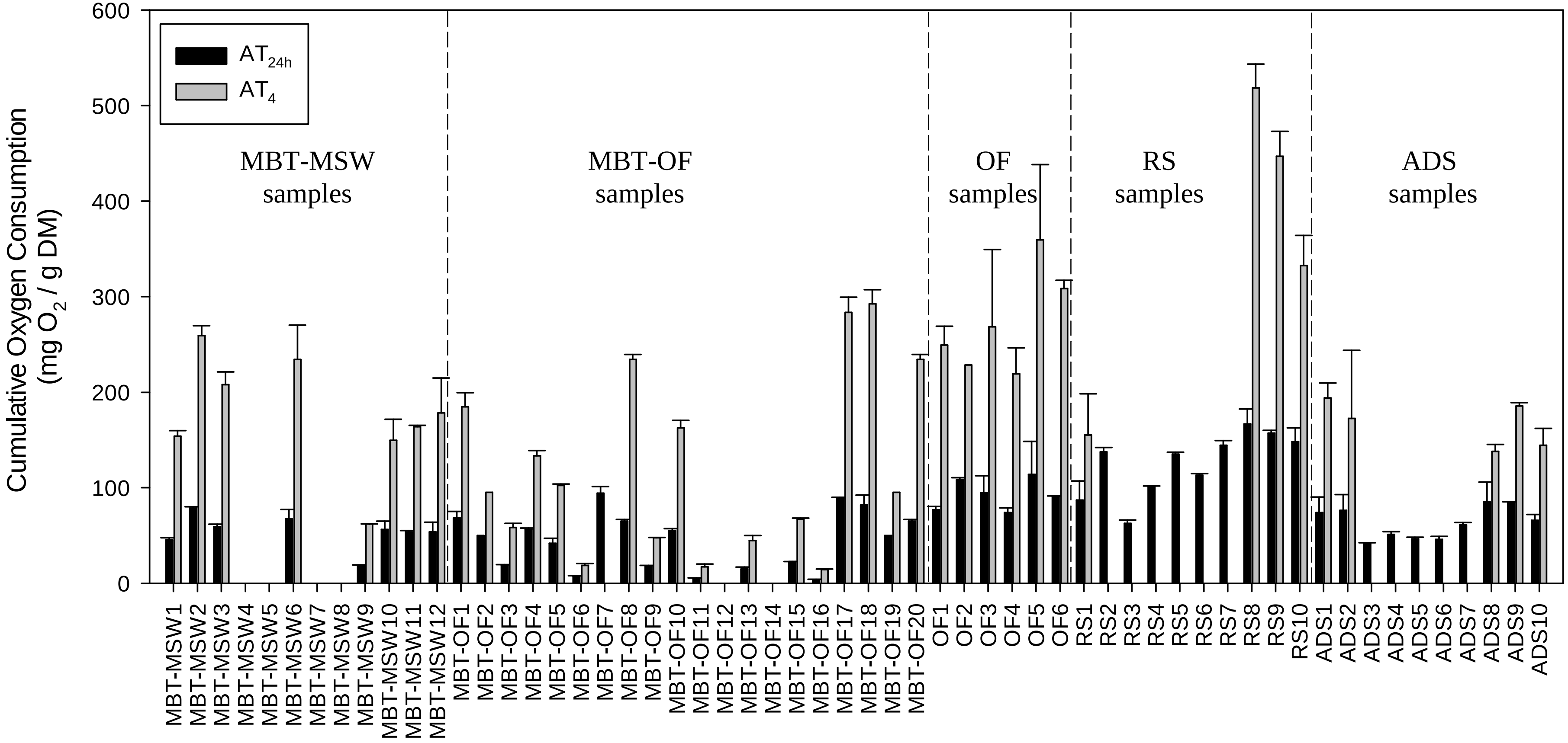
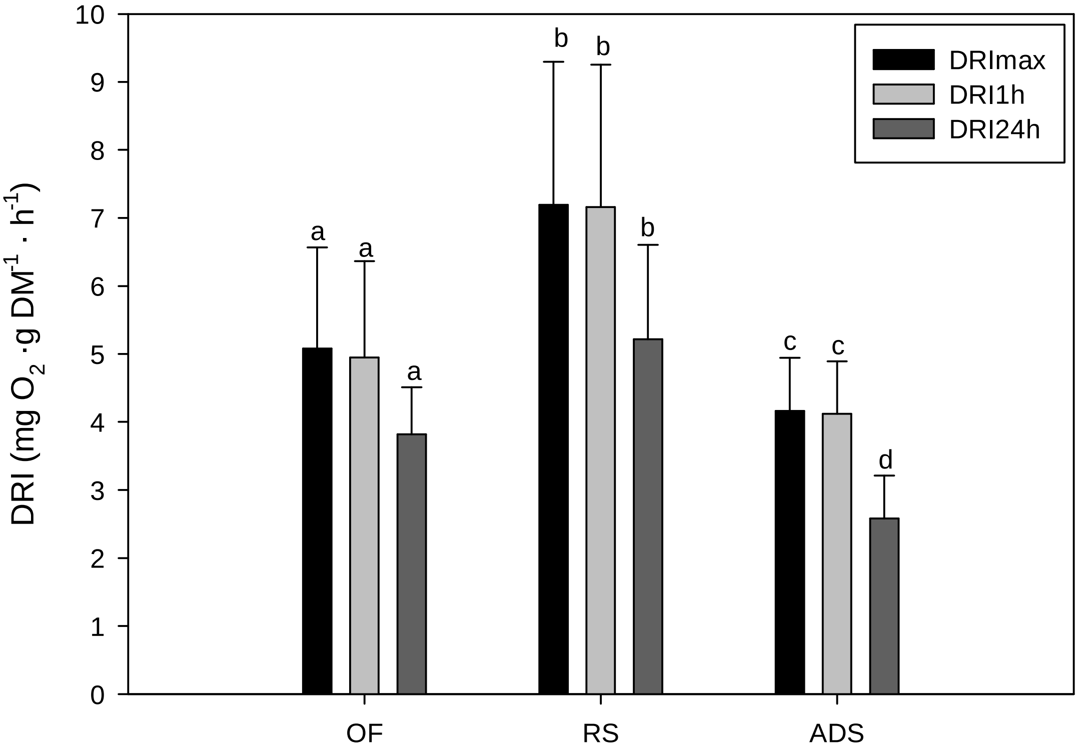

Dynamic Respiration Indices
($mgO_2 \cdot gDM^{-1} \cdot h^{-1}$)
0
1
2
3
4
5
6
7
8
9
10
11
12
DRI_{max}
DRI_{1h}
DRI_{24h}
MBT-MSW samples
MBT-OF samples
OF samples
RS samples
ADS samples
MBT-MSW1
MBT-MSW2
MBT-MSW3
MBT-MSW4
MBT-MSW5
MBT-MSW6
MBT-MSW7
MBT-MSW8
MBT-MSW9
MBT-MSW10
MBT-MSW11
MBT-MSW12
MBT-OF1
MBT-OF2
MBT-OF3
MBT-OF4
MBT-OF5
MBT-OF6
MBT-OF7
MBT-OF8
MBT-OF9
MBT-OF10
MBT-OF11
MBT-OF12
MBT-OF13
MBT-OF14
MBT-OF15
MBT-OF16
MBT-OF17
MBT-OF18
MBT-OF19
MBT-OF20
OF1
OF2
OF3
OF4
OF5
OF6
RS1
RS2
RS3
RS4
RS5
RS6
RS7
RS8
RS9
RS10
ADS1
ADS2
ADS3
ADS4
ADS5
ADS6
ADS7
ADS8
ADS9
ADS10

Figure 4



600
500
400
300
200
100
0
Cumulative Oxygen Consumption (mg O_2 / g DM)
AT_{24h}
AT_4
MBT-MSW samples
MBT-OF samples
OF samples
RS samples
ADS samples
MBT-MSW1
MBT-MSW2
MBT-MSW3
MBT-MSW4
MBT-MSW5
MBT-MSW6
MBT-MSW7
MBT-MSW8
MBT-MSW9
MBT-MSW10
MBT-MSW11
MBT-MSW12
MBT-OF1
MBT-OF2
MBT-OF3
MBT-OF4
MBT-OF5
MBT-OF6
MBT-OF7
MBT-OF8
MBT-OF9
MBT-OF10
MBT-OF11
MBT-OF12
MBT-OF13
MBT-OF14
MBT-OF15
MBT-OF16
MBT-OF17
MBT-OF18
MBT-OF19
MBT-OF20
OF1
OF2
OF3
OF4
OF5
OF6
RS1
RS2
RS3
RS4
RS5
RS6
RS7
RS8
RS9
RS10
ADS1
ADS2
ADS3
ADS4
ADS5
ADS6
ADS7
ADS8
ADS9
ADS10

Figure 5



10
9
8
7
6
5
4
3
2
1
0
DRI (mg O2 ·g DM-1 · h-1)
DRImax
DRI1h
DRI24h
a
a
a
b
b
b
c
c
d
OF
RS
ADS

Figure 6

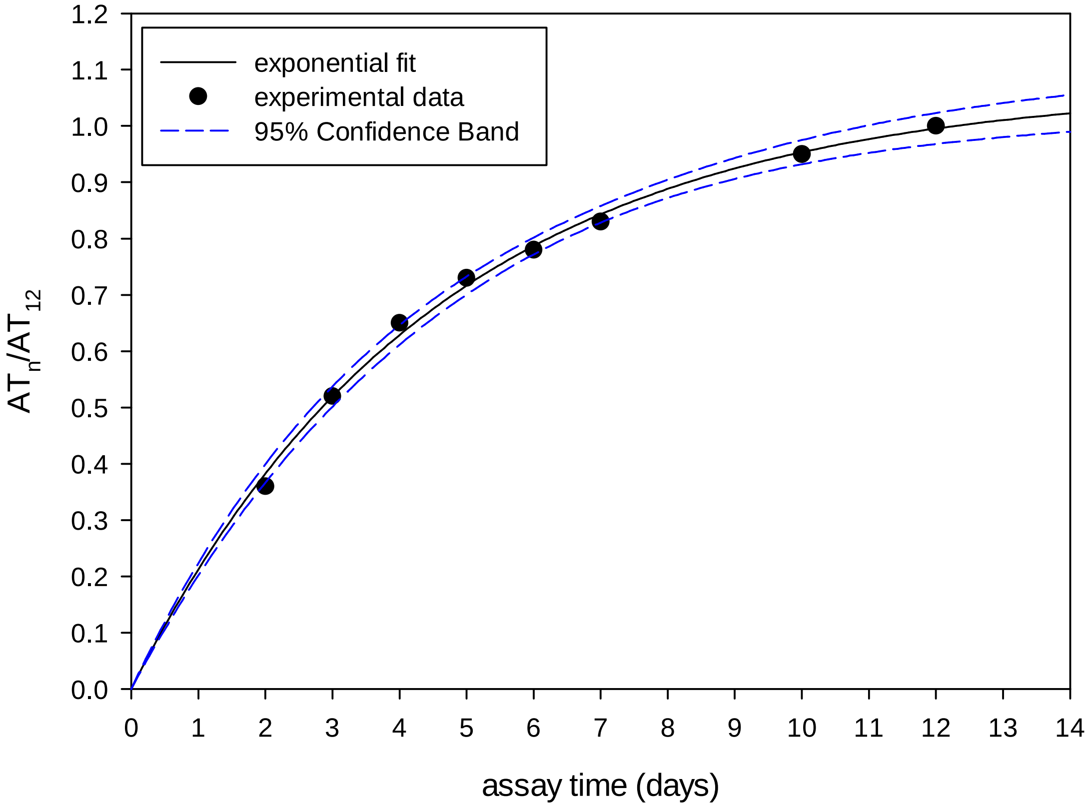
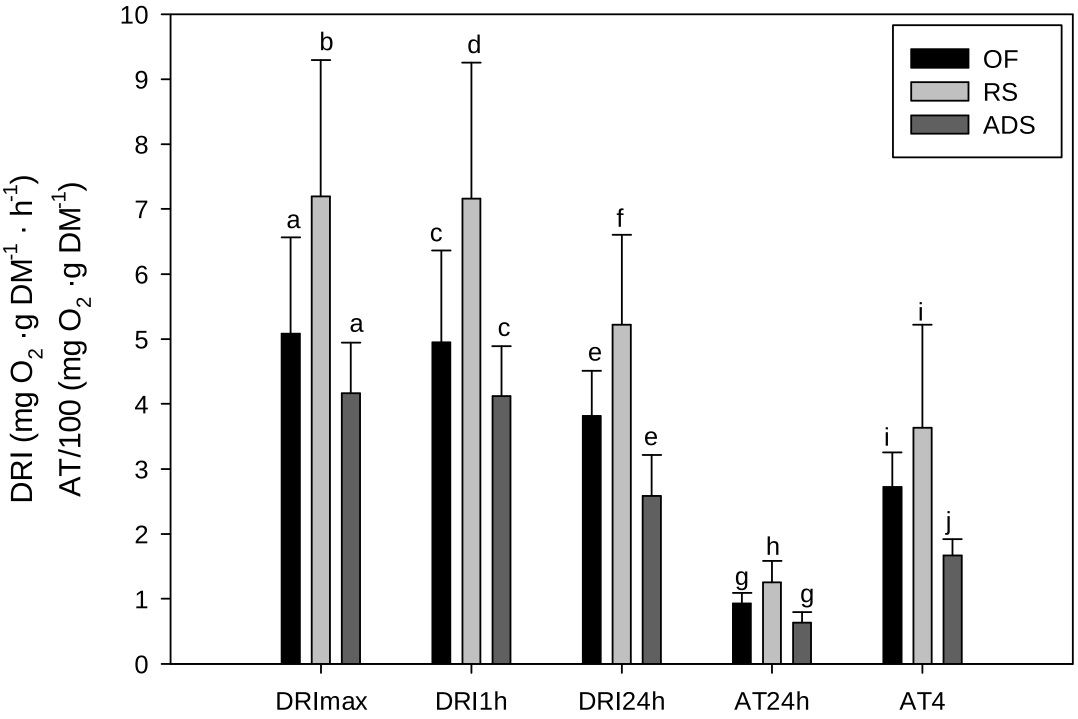

exponential fit
experimental data
95% Confidence Band
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
AT_n/AT_{12}
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
assay time (days)

Figure 7


DRI (mg O$_2$ ·g DM^{-1} · h^{-1})
AT/100 (mg O$_2$ ·g DM^{-1})
0
1
2
3
4
5
6
7
8
9
10
DRImax
DRI1h
DRI24h
AT24h
AT4
OF
RS
ADS
a
b
a
c
d
c
e
f
e
g
h
g
i
i
j