Respirometric screening of several types of manure and mixtures intended for composting

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Abstract

The viability of mixtures from manure and agricultural wastes as composting sources were systematically studied using a physicochemical and biological characterization. The combination of different parameters such as C:N ratio, free air space (FAS) and moisture content can help in the formulation of the mixtures. Nevertheless, the composting process may be challenging, particularly at industrial scales. The results of this study suggest that if the respirometric potential is known, it is possible to predict the behaviour of a full-scale composting process. Respiration indices can be used as a tool for determining the suitability of composting as applied to manure and complementary wastes. Accordingly, manure and agricultural wastes with a high potential for composting and some proposed mixtures have been characterized in terms of respiration activity. Specifically, the potential of samples to be composted has been determined by means of the oxygen uptake rate (OUR) and the dynamic respirometric index (DRI). During this study, four of these mixtures were composted at full scale in a system consisting of a confined pile with forced aeration. The biological activity was monitored by means of the oxygen uptake rate inside the material (OUR_{insitu}). This new parameter represents the real activity of the process. The comparison between the potential respirometric activities at laboratory scale with the in situ respirometric activity observed at full scale may be a useful tool in the design and optimization of composting systems for manure and other organic agricultural wastes.

Keywords: composting; manure; waste formulation; respiration activity; Dynamic Respiration Index; Oxygen Uptake Rate

1. Introduction

The intensive livestock production systems used in Catalonia (NE of Spain) involves the geographical concentration of livestock waste. In these areas, with a nutrient surplus due to high livestock density, a solid waste management planning is necessary (Teira-Esmatges and Flotats, 2003). Since the common practice of direct application of livestock waste to soil has resulted in contamination of soil and water ecosystems, other ways of management should be used. Among the available technologies to treat the livestock waste, composting is a suitable technology to reach a high degree of stability and to improve the agronomic value of manure and other agricultural wastes.

Manure and agricultural wastes may be used as soil amendments after composting due to its high organic matter, water holding capacity and nutrient content. However, raw manures and other agricultural wastes are also characterized by high water content and low free air space (FAS) that hamper the optimal development of the composting process. In order to prepare manure and agricultural wastes for composting mixing with other materials is required. For this reason, amendment materials and bulking agents from the same area have been typically used as complementary materials. Amendment materials are often used to add an additional source of energy and nutrients to the organic matrix. They also improve its physical properties including the regulation of moisture content observed in materials with a high water holding capacity. Bulking agents are used to give a support structure to the matrix and provide enough FAS inside the mixture for the optimal development of the composting process (Haug, 1993).

To optimize the compost formulation, the characterization of wastes and complementary materials before composting is necessary. It is of primary importance to balance the formulation in terms of moisture content to allow optimal aeration, pH for proper microbial environment, and carbon and nitrogen content (C:N ratio) for a proper microbial development (Adhikari et al., 2009).

Usually, the formulation of mixtures of different wastes are based on their physical and chemical properties in order to adjust the C:N ratio to optimal values, in the range of 20-25 (Huang et al., 2006), or to work in an appropriate range of moisture content (40-60%) (Adhikari et al., 2009). Nevertheless, in an optimal compost formulation, other physical properties, such as FAS or porosity, are also critical issues in determining compostability. These parameters have recently been identified as responsible for the success or failure of the composting of mixtures formulated with exclusively chemical criteria, typically C:N (Trémier et al., 2009; Mohajer et al., 2009). In fact, Trémier et al. (2009) indicate that a compost formulation must be formulated based on the biodegradability of the waste and the characteristics of the compost technology used. The selection of acceptable waste components and complementary materials with the optimal physical parameters will create an optimum environment for microbial activity development and, therefore, an optimal biodegradation will be achieved in the active phase of the composting process (Haug, 1993; Mohajer et al., 2009).

However, data obtained by a physicochemical characterization (pH, moisture, C:N, etc.) of substrates and mixtures are only partial, since the process of composting is a biological process. For this reason the characterization of the materials should be complemented by means of a biological characterization through evaluation of the respiration potential.

Aerobic respiration indices have been widely suggested in the literature as a measure of biodegradable organic matter content or stability (Adani et al., 2004;

Barrena et al., 2006a; Trémier et al., 2005; Wagland et al., 2009). There are numerous studies in which the biological activity has been monitored by means of respiration indices in the composting of municipal solid waste and sludge (Adani et al., 2006; Mohajer et al., 2009). Moreover, respirometric indices have been used in recent work to quantify the performance of different treatment processes (Ponsá et al., 2008; Ponsá et al., 2009; Barrena et al., 2009). However, to the authors' knowledge, there is no application of respirometric indices to study the potential biodegradability of manure wastes and to use it for the preparation of compost formulations with this type of material. Moreover, the use of direct on-line measurement of oxygen uptake rate (OUR_{insitu}) has not been reported in composting literature.

In this work, a complete physicochemical and respirometric characterization is presented for these organic wastes with the aim to formulate compostable mixtures. The objectives of this study were: i) the selection of parameters that can help in the preparation of a compost formulation, ii) to check the suitability of the proposed mixture and to predict its behaviour in full scale composting and iii) to study the suitability of on-line OUR_{insitu} measurements as a powerful tool to determine the exact situation of a real full-scale composting pile.

2. Materials and methods

2.1. Organic materials

Samples of wastes were obtained from the region of Osona (Catalonia, NE of Spain), which is one of the Catalan areas where the highest quantity of different wastes from animal farms are generated. Pig, cattle, turkey litter, and rabbit manures were analyzed and classified as raw wastes (Table 1). A fodder by-product was also incorporated to this group of materials due to its high content of easily biodegradable organic matter. This material was obtained from cattle fodder fabrication and is rich in cereal husks.

Amendment materials used in the mixtures were sawdust and barley straw (Table 1). Two different types of sawdust were used: sawdust A was obtained from the treatment of natural wood whereas sawdust B originated from the mixing of old shredded furniture. For this reason, sawdust B contains some impurities such as varnishes, paints, plastics and metals. Pruning wastes of different particle size were used as bulking agent. Two different particle sizes were used: i) < 10 mm and ii) between 10 to 20 mm. Semi-composted pruning wastes, corresponding to the pruning fraction under 10 mm that had been degraded during its storage, was also taken as a third bulking agent due to its different properties for composting.

A total of six mixtures were studied in this work. Table 1 summarizes the mixture proportions and the different materials used in each mixture. The composition of the mixtures and the amount of the different materials were selected according to the experience of the operators of the composting plant at farm-scale. The proposed mixtures are feasible and become a real and appropriate way to manage the waste produced in the studied area. For purposes of this study, mixtures were formulated based on the availability of wastes and the requirements of operational facilities. Other mixtures were feasible, but the objective of the work was to evaluate the feasibility of composting process with the materials and proportions typically used at full scale, once they are fully characterised.

2.2. The confined piles composting system (full scale)

The commercial composting technology used in this work was based on confined piles with forced aeration and leachate collection (*Val'id®* technology, France, optimized by *Agrotech® Biotecnología Aplicada*, Spain). The process consisted of a decomposition phase in confined piles with controlled aeration and watering. Specifically, the waste to be composted is placed in a concrete open trapezoidal container whose base is perforated to provide forced aeration and collect leachate that is stored in a separated tank. The waste is partially covered with a linen sheet that prevents water losses, minimizes odour emissions from the process and protects the pile from rainfall. The leachates stored are recirculated to the piles to guarantee the moisture content during the composting process under thermophilic conditions.

The composting process is controlled by a computer application, which controls the fresh air supply during different ventilation cycles depending on the needs of the process. The air is introduced to the system by means a set of electrovalves that provide an intermittent flow according to a predetermined schedule.

Mixtures were made with a mixer machine (model *Agrotech® Biotecnología Aplicada*, Spain) at the same farms as the wastes were generated.

2.3. Sampling of organic wastes

Analytical parameters in the full scale experiments were determined at the laboratory after extracting a representative sample of the material from the confined piles. For this purpose, at least four points were sampled extracting about 5 L of waste at each point. The total volume of sample (about 20 L) was manually mixed and a final volume of 2 L was used to carry out the analytical procedures. Amendment and bulking materials were directly obtained from the remaining stock used in the construction of the piles using the same sampling procedure.

2.4. Respirometric determinations

2.4.1. Oxygen Uptake Rate (OUR)

The respirometric activity of materials and mixtures was measured by a pressure sensor method (Oxitop®). The evolved CO_2 was absorbed by sodium hydroxide leading to a pressure drop in a closed-vessel that is proportional to the biologically consumed O_2. This static respirometric methodology was used to calculate the oxygen accumulated during four days (AT_4). It is based on the Standard German method (Federal Government of Germany, 2001), with some modifications. First, the assay temperature was fixed to 35ºC with the objective of comparing the results with other respirometric tests, especially with the dynamic respiration index (DRI). Previous studies (Barrena et al., 2009) found good correlations between static (SRI) and dynamic (DRI) respiration index when the SRI index was determined at similar temperatures. When the assay was performed with active samples, it was necessary to guarantee the availability of oxygen for the microorganisms. For this reason, the vessel was opened several times in order to regenerate the consumed oxygen. Consequently, in addition to the AT_4 value, it was possible to calculate the oxygen uptake rate (OUR) after the regeneration of the oxygen (vessel opening). The amount of solid sample used was between 30 and 40 g. The parameters determined with this method were the maximum observed OUR (OUR_{max}) and the cumulative oxygen consumption over four days (AT_{4-OUR}).

2.4.2. Dynamic respiration index

The dynamic respiration index (DRI) was determined in a 20 L adiabatic respirometric reactor (Costech International, Cernusco S.N., Italy; DiProVe, Milan, Italy) using the methodology suggested by Adani et al. (2001) and completely described in Ponsá et al. (2010). The instantaneous dynamic respiration index was determined by measuring the difference in oxygen concentration between the inlet and outlet airflow that had passed through the material. The degree of biological stability measured by DRI was calculated using three methods representing different ways of expressing DRI from instantaneous DRI values (Adani et al., 2004): (i) DRI_{24h}: the average value of 24 instantaneous respiration indices obtained during the most intense 24 h of biological activity, (ii) DRI_{1h}: average of the instantaneous DRI obtained during the hour of maximum activity and (iii) $AT_{4\text{-}DRI}$: the cumulative value of oxygen consumption recorded during 96 h (four days). This value was obtained by numerical integration of oxygen consumption (DRI) values obtained during 96 h. It represents the global consumption of oxygen at a given time (Ponsá et al., 2010). Tests were performed setting an O_2 concentration within 10-14% in the outlet airflow to ensure the prevalence of aerobic conditions during the assay by means of a feed-back control that automatically modified the input airflow rate.

2.4.3. *In situ Oxygen Uptake Rate* (OUR_{insitu})

The Oxygen Uptake Rate was also measured *in situ* in the confined piles at full scale. As already pointed out, the control system used in the confined piles, with intermittent ventilation, allowed the calculation of the oxygen uptake rate in situ (OUR_{insitu}) during the composting process by following the evolution of the oxygen content. With this objective the pile was fully aerated during 20 minutes. Afterwards, aeration was stopped and the interstitial oxygen concentration within the composting mass was monitored during 20 minutes. The slope of the oxygen decrease during the period of non aeration corresponds to the value of OUR_{insitu}. The obtained value is equivalent to a static respirometry (Iannotti et al., 1993; Barrena et al., 2005) with the advantage that the activity observed corresponds to the real activity in the confined pile since it is directly determined within this and considers all the composting mass. The oxygen content was measured with a portable O_2 detector (Port-O2matic-Pump-3052, Costech, Italy).

2.5. Routine analytical methods

Moisture content (MC), total solids (TS), organic matter (OM, on a dry matter basis), bulk density (BD), water holding capacity (WHC), water holding capacity occupied ($WHC_{occupied}$), pH, electrical conductivity (EC), Kjeldahl nitrogen (KTN), ammonium nitrogen ($N\text{-}NH_4$) and phosphorus (P) content were determined according to standard procedures (The US Department of Agriculture and The US Composting Council, 2001). Free air space (FAS) was estimated using an air pycnometer built according to Ruggieri et al. (2009). Total organic carbon (TOC), dissolved organic carbon (DOC) and chemical oxygen demand (COD) were determined according to standard procedures (Government of Italy, 2000; De Guardia et al., 2002; Zmora-Nahum et al., 2005; APHA, 1998).

2.6. Statistical analysis

All experimental tests were run in triplicate and the results are presented as an average value followed by standard deviation. All statistical analyses, otherwise reported in the specific point, were performed using the SPSS statistical software (version 17) (SPSS, Chigaco, IL). In Tables, number followed by the same letter in the same column are not statistically different (Test Tukey, $p<0.05$).

3. Results and discussion

3.1. Physical and chemical characterization

3.1.1. Bulking Agents, amendments and raw materials

Physical and chemical parameters determined for bulking agents, amendments and raw materials are shown in Table 2. Pruning wastes were materials characterized by containing high organic matter and low nitrogen content and consequently they present a high C:N ratio (42 and 52). Compared to raw pruning, semi-composted pruning presented lower organic matter content and higher nitrogen content, but the resulting C:N ratio was similar to that of raw pruning wastes (41).

In the group of amendment materials, straw and sawdust A were also characterized by high organic matter, low nitrogen content and high C:N ratio (89 and 95). Sawdust B presented a high KTN content (2.8% dry basis), presumably resulting from its more diverse composition. In consequence, its C:N ratio was lower (16). The highest amount of available organic matter of these materials can be used as additional carbon source to improve the C:N ratio of the mixtures (Eftoda and McCartney, 2004; Gea et al., 2003). Furthermore, due to its small particle size, when sawdust is mixed with slurry wastes it produces a homogeneous mixture with small-size aggregates and high porosity more accessible to microorganisms and air (Gea et al., 2003). These materials were also characterized by a high water holding capacity (3.4 to 7.1 g water/g TS) compared with the bulking agent (1.3 to 2 g water/g TS). The higher water holding capacity of these materials allows regulating the moisture content in the mixtures and prevents the generation of leachate. In addition to this, the percentage of water content in terms of the water holding capacity ($WHC_{ocuppied}$) was calculated (Table 2). This parameter gives an estimate of the space occupied by water referred to the maximum available water content. Compared with bulking agents, the $WHC_{occupied}$ of amendments was very low (3-4%) and, for this reason, their capacity for absorbing water can be considered higher.

Regarding the raw materials, which were the main purpose of this work, a high variability in their properties was observed. Despite these differences, they had a high organic matter and nitrogen content in common, which make them suitable for use as organic fertilizers. In relation to the nitrogen content, it is important to emphasize that the highest values were reported for pig slurry. The values obtained were around 10.5% KTN and 7.7% $N\text{-}NH_4$ and consequently the ratio $N\text{-}NH_4/KTN$ was very high (around 73), indicating that practically all the nitrogen content of these materials was in the form of ammonia. It is important to note that ammonia is one of the main compounds responsible for generation of offensive odours and atmospheric pollution during the composting of organic wastes with high nitrogen content (Pagans et al., 2006). For this reason, the mixture with other materials could reduce the environmental impacts associated to composting and, at the same time, allow the conservation of the nitrogen in the final product. For example, during the composting of mixtures of different organic materials, Sánchez-Monedero et al. (2001) observed that the mixtures with the highest lignocellulose content showed the lowest nitrogen losses.

The phosphorus content for practically all the raw materials (between 1 and 3%) ensures the presence of this nutrient in the mixtures. On the other hand, the FAS of the pig slurry and the turkey litter manure were near zero, indicating that mixing with other porous materials would be necessary to enable a composting process. Finally, raw manure was, in general, characterized by high moisture content (56-95%), high $WHC_{occupied}$ (50-100%) and frequently low FAS values (30%).

3.1.2. Mixtures

Initial properties of the composting mixtures are shown in Table 3. As can be seen, the mixing of materials has the positive effect of improving the initial conditions of raw materials for composting. The C:N ratio was adjusted in the range of 10-32, much more suitable for composting than that calculated for raw materials. However, it must be pointed that the C:N ratios in initial mixtures for composting are usually formulated on a total C:N basis, while not all the C is available to be degraded in the process (Sánchez, 2007). An adjustment of the nitrogen content of the mixtures, especially in the mixtures with pig slurry, was also observed. Thereby the potential nitrogen loss in the form of ammonia emissions should be reduced. FAS values estimated for the composting mixtures were around 65%, except for the mixture 5 where the FAS value was very high, around 87%. Although the optimum range reported for composting process is 30-35% (Haug, 1993) other studies show that there is no negative impact when higher FAS values are used (Ruggieri et al., 2009). In fact, in static systems (such as the one used in this study) a certain compaction of the material will take place during the process. Due to this compaction, the correct distribution of the air inside the pile could be affected. To avoid this, higher initial FAS value should be used (Ruggieri et al., 2009).

The moisture content in the mixtures were still high for the composting process (around 70%), although near the optimal values (Haug, 1993). For instance, Ahn et al. (2008) observed that, for similar materials, the optimum moisture content was in the range of 60-80% depending on the water holding capacity. In fact, wastes with moisture content up to 80% have been successfully composted by other authors (Fernandes et al., 1994; Zhu, 2006).

3.2. Respirometric characterization

3.2.1. Oxygen Uptake Rate

OUR_{max} and AT_{4-OUR} values obtained using the Oxitop method are shown in Table 4. As expected, the respirometric values for amendments and bulking agent materials were very low (0.2-0.7 g O_2 kg^{-1} OM h^{-1}). Even though high in organic matter, this was not degradable under the specific conditions of the assay. In general, this type of material has a high concentration of lignin that makes its biodegradability difficult (Komilis, 2006). For barley straw and fine pruning wastes, respirometric values were slightly higher, indicating that the organic content of these materials could be partially degraded during the process. If this is the case, these materials could effectively contribute in regulating the C:N ratio. Ros et al. (2006) observed that composting piles in which bulking agent was added showed higher values of biological activity than piles without bulking agent, suggesting that the carbon compounds incorporated with bulking agent, accompanied by a higher porosity, stimulated the development of microbial populations. The two types of sawdust used presented different respirometric values, being higher in the case of sawdust B. The presence of easily biodegradable material in the heterogynous composition of sawdust B could explain the results obtained.

In reference to pruning wastes, variable respirometric rates were obtained. The highest OUR_{max} was higher for the pruning waste with the particle size under 10 mm. The reason for this higher respirometric activity is the lower particle size which makes access to the material by the microorganisms higher (Ruggieri et al., 2009).

In reference to raw materials, more variability in the OUR_{max} values was found. This diversity indicates that the nature of the materials and their potential for composting were very different. The highest biodegradability was observed for the solid fraction of pig slurry (3.84 g O_2 kg^{-1} OM h^{-1}), whereas much less activity was observed for turkey litter (0.97 g O_2 kg^{-1} OM h^{-1}).

For the mixtures studied, a clear increase in the OUR_{max} values was observed compared with the raw materials (Table 4). This increase in the biological activity implies a higher biodegradation potential. However, significant differences in OUR_{max} were observed depending on the mixture considered. For instance, despite their similarity in composition, the potential of biodegradability was very different comparing mixture 2 and 3. The difference between these mixtures was the type of pig slurry used. In mixture 2, the pig slurry used came from a pig fattening farm whereas for mixture 3 originated from a pig closed cycle farm. This fact highlights the important differences existing in the content of biodegradable organic matter depending on the type of food and the farm management system. These differences have been also reported by Sánchez and González (2005), who determined the fertilizer value of pig slurry depending on the type of operation (maternity, closed cycle and fattening).

Problems with the respirometric methodology used were observed in the samples with high biological activity. The rates of oxygen consumption for these samples were very high and renovation of the air were probably insufficient. This fact highlights the limitations of static systems such as Oxitop. For example, for mixture 2 it was not possible to calculate $AT_{4\text{-}OUR}$.

On the other hand it is important to note that the sum of the OUR of each component of the mixture does not yield the overall resulting OUR. As previously reported, initial physical characteristics of the matrix have a strong influence on organic matter biodegradation. In fact, the oxygen distribution in the matrix and microbial access to biodegradable matter are critical factors (Trémier et al., 2009).

3.2.2 Dynamic respirometric index

To calculate the DRI of the selected mixtures, composting experiments were carried out in 20 L reactors covering 100 h. Due to equipment failure, the DRI value of mixture 6 could not be determined. Values of DRI_{24h}, DRI_{1h} and $AT_{4\text{-}DRI}$ for the studied mixtures are shown in the Table 5. Higher values of DRI_{24h} and DRI_{1h} were obtained for the mixtures 1, 2 and 4. For the mixtures 3 and 5 no differences between DRI_{1h} and DRI_{24h} were observed, suggesting that the components of these mixtures had a similar biodegradability profile. $AT_{4\text{-}DRI}$ values above 200 g O_2 kg^{-1} OM were obtained for the mixtures 1 and 5.

Temperature, oxygen content and DRI_{1h} evolution for the mixtures 1, 2, 3, and 4 are presented in Figure 1 as representative examples. Each parameter was determined hourly. Important differences were observed in the process evolution for these experiments. In the composting process of mixture 1 (Figure 1a) an initial peak of activity followed by a continuous and moderate activity during all the experiment was detected. This behaviour is also reflected by its temperature profile that shows a slight increase over 40ºC that it is maintained until the end of the experiment.

The trend observed for mixture 3 (Figure 1c) indicates a moderate biological activity. The temperature increases gradually exceeding 40ºC but not reaching the thermophilic range and decreasing at the end. The DRI_{1h} was about 2 g O_2 kg^{-1} OM h^{-1} and remains above 1 g O_2 kg^{-1} OM h^{-1} during the main part of the process.

In contrast, mixtures 2 and 4 (Figure 1b and 1d), showed profiles that followed a typical composting pattern on laboratory-scale (Barrena et al., 2005, Ruggieri et al., 2008). Thermophilic temperatures were quickly achieved and maintained for several hours. The DRI profiles indicate a higher metabolic activity at the beginning of the process, with a maximum DRI_{1h} close to 7 g O_2 kg^{-1} OM h^{-1}, followed by a fast drop.

After 50 hours the DRI_{1h} was low, with respirometric rates < 1 g O_2 kg^{-1} OM h^{-1}, while the temperature was maintained within 30 - 40ºC.

These examples show that the interpretation of the DRI can provide useful information on the degradation occurring throughout the composting process. In these cases the different levels of activity observed are related to the composition of the materials composted. The presence of more slowly biodegradable matter in the cattle manure could be the cause of the constant biological activity observed in Figure 1a. In fact, as it turned out, a large quantity of bedding materials had been placed on the floors of animal houses to provide some comfort to the animals and to absorb moisture. The biodegradation of these materials, normally straw that had been partially degraded in the farm, would be slower. Another factor that may influence its degradation would be an inappropriate matrix for composting. The mixture 1 presents a higher initial FAS (72%) compared with the mixtures 2 and 4 (around 65%). This higher porosity could make it difficult to maintain thermophilic temperatures in the 20 L reactor. On the other hand, mixtures 2 and 3 contain pig slurry as their main component, with very different compositions depending on its origin as can be seen in Table 2. As previously discussed, the main reason for this difference seems to be the different nature of organic matter. A careful analytical study of organic components of these materials might also explain the different level of biodegradability suggested by the respirometry assay for mixtures 2 and 3. Instead, for pig slurry of the mixture 3, the content of easily degradable compounds was lower, as indicated by its DRI profile. Furthermore, as in the previous case, an inappropriate initial structure (FAS around 71%) may make it difficult to achieve the thermophilic range at laboratory scale.

Nevertheless, and according to the obtained results, mixtures 1, 2, 3 and 4 are suitable for composting at full scale.

3.3. Composting experiments at full-scale (OUR_{insitu})

To confirm the results found in the previous experiments at laboratory scale, composting at full-scale of some selected mixtures was carried out in confined piles. Composting of mixtures 1 to 4 was followed during approximately one month in an industrial facility. As discussed previously, the system operation in confined piles allows the calculation of the oxygen uptake rate between two ventilation cycles. OUR inside the confined pile was calculated in different phases of the composting process. In this way, the OUR value obtained during the composting process reflects the true biological activity during the process, providing valuable information about its evolution. The temperature profile, oxygen content and OUR_{insitu} values obtained directly in the mass of the confined piles are shown in Figure 2.

Mixtures 1, 2 and 4 followed a typical composting pattern (Figure 2a, 2b and 2d) (Haug, 1993). The maximum OUR_{insitu} values obtained were about 6, 8 and 7.5 g O_2 kg^{-1} OM h^{-1} for mixtures 1, 2 and 4, respectively in the early stages of the process. For mixture 3 the biological activity observed was very low although the thermophilic range was achieved and maintained during the whole of the study period. As expected, the biological activity decreased during the process except for mixture 3. For mixtures 2 and 4, in contrast to the information provided from the temperature profile, two phases of different biological activity were clearly observed: an active phase, where the biological activity was very high, followed by a passive phase, where a marked decrease in the activity was observed. In the composting of mixture 1 this differentiation was not evident; however a gradual decrease of the respiration activity was clear. For mixture 3 no differences in the biological activity were observed through the process. The measurement of biological activity is of special relevance in full-scale facilities, where the temperature is maintained in the thermophilic range because of the limited heat transfer (Barrena et al., 2006b), even when biological activity has diminished.

Differences were observed in the evolution of interstitial oxygen content of the studied materials. In the composting of mixtures 1 and 4 the amount of air supplied to the system appears to be sufficient and it remains at levels above 10% during the first days of the process, which is usually the most critical stage. For the mixture 2, during the first 15 days, the oxygen content was < 10%. This phase corresponded to the period of maximum biological activity observed. Therefore, the aeration system used during the early days of process is not sufficient to maintain optimal levels of oxygen in the composting mixture. Instead, the oxygen content during the next 15 days of the process was about 20%. This result indicates that, in this phase of the process, where the biological activity observed was low, a lower flow rate would be enough to maintain the aerobic conditions and thus reduce energy costs in the process. For mixture 3, the measured oxygen content (< 10% throughout the process) limited the correct development of the process.

Other physicochemical parameters of the materials during the composting process are shown in Table 6. Moisture content was maintained at high values due to the process methodology. This methodology consisted of a recirculation system able to completely spray leachate over the composting material. A decrease in organic matter content was observed for all the mixtures. In any case, it is important to bear in mind the difficulty to take a representative sample of the material from the confined piles. Also, non-degradable organic matter from amended and bulking agent may lead to misleading results. The evolution of FAS and bulk density reflected the normal compaction of the material during the process for the mixtures 2 and 4. However, for mixtures with high initial FAS (1 and 3) no significant differences were observed. Finally, the pH was maintained in an adequate range for the composting in all the experiments.

Therefore, the results obtained at industrial scale indicate that the process evolution is correct for mixtures 1, 2 and 4. However, mixture 3 was typified by low activity, low oxygen content and only few changes in the parameters analyzed, indicating a non-ideal evolution of the composting process.

3.4. Comparison of potential and real respirometric values

When results obtained at laboratory scale and in confined piles are compared, similar trends in the evolution of the composting process can be observed. With the exception of mixture 3, a similar OUR_{insitu} peak was reached on both scales. The decline in the activity also seems to follow the same trend. For mixtures 2 and 4 the decrease was more pronounced than for mixture 1 and ends up with activity values lower than 1 g O_2 kg^{-1} OM h^{-1}.

A clear difference in the evolution of degradable organic matter can be observed between the mixtures. In mixture 1 a high DRI initial value followed by a moderate activity over some days was observed in both scales (Figure 1a and 2a). In fact, final OUR_{insitu} and DRI values indicate that biological activity at the end of process is still considerable, suggesting that further processing would be needed to reach appropriate stability. As commented, this trend was due to the nature of organic matter present in cattle manure. The bedding material used as deep litter on the floors of cattle housing could be partially degraded before starting the composting process and follow the decomposition in the confined pile (Tiquia and Tam, 2000). However, the low temperature reached in the reactor and the high FAS during all the experiments indicated that an improved mixture with other complementary materials might be more appropriate.

For mixture 3, the low biological activity and the low temperature reached in the reactor indicate that the process was not operating under optimal conditions. At full scale, this mixture presented operational problems. The low biodegradability potential together with a non-optimum physical matrix (excessive FAS) could slow down the process. The accumulation of leachate observed in the confined pile could be avoided with an improved matrix. Therefore, it would be appropriate to mix it with other complementary materials in order to adjust their properties according to Tables 1 and 2. Nevertheless, this case shows the usefulness of monitoring the OUR_{insitu} to quickly detect operational problems in composting systems.

In contrast, the results obtained with mixtures 2 and 4 indicate that the process was properly developed, reaching stable OUR_{insitu} and DRI values at the end of the process. The temperature profile in the reactor reached the thermophilic range and there was a high degree of organic matter reduction. In these mixtures, although the moisture content was also high, FAS values (around 65%) were more suitable for the composting process than those of mixtures 1 and 3. Anyway, both materials contain an important fraction of easily biodegradable organic matter as indicated by the OUR_{insitu} and DRI values.

DRI can be interpreted as a measure of the biodegradability level, while $AT_{4\text{-}DRI}$ can provide very useful information about the total amount of biodegradable matter in the sample (Ponsà et al., 2010). More specifically, DRI reflects the oxygen consumption associated to the easy biodegradable organic matter and it is consumed in few hours. According to this, the more biodegradable a waste is the higher its DRI value will be. On contrast, $AT_{4\text{-}DRI}$ is an average measurement of the oxygen consumption during a given period of time and reflects an overall amount of biodegradable organic matter. This value is similar to that of Biochemical Oxygen Demand (BOD) used in wastewater characterization.

For mixture 1 (Table 5), $AT_{4\text{-}DRI}$ was 220 g O_2 kg^{-1} OM whereas for the other mixtures it was lower (around 150 g O_2 kg^{-1} OM). In addition, the ratio between DRI_{24h} and $AT_{4\text{-}DRI}$ can also help to predict the evolution of the process at full-scale. For the materials studied this ratio varied from 36.0 to 77.4, indicating the different biodegradability of the organic matter present in each mixture. A good correlation between peak (DRI_{24h}) and accumulated consumptions ($AT_{4\text{-}DRI}$) was previously described by other authors (Barrena et al., 2009; Mohajer et al., 2009). However, these experiments were done with the same sample wastes. In a recent study, Ponsà et al. (2010) observed ratios between 71 and 101 for 58 samples of different organic wastes collected (municipal solid waste and wastewater sludge) at different stages of biodegradation. In this study the ratio was > 70 for mixtures 1 and 3 suggesting the presence of slower biodegradable organic matter in the mixtures. On the other hand, for mixtures 2 and 4 it was around 40 indicating the presence of easily biodegradable organic matter. These values are in agreement with the evolution observed at full scale and can provide useful information about the behaviour of the material when composting under these condtions. For instance, the oxygen requirements of the process (i.e. oxygen control/schedule) can be pre-set through the respirometric indices profiles.

The initial respirometric characterization performed with the Oxitop equipment anticipated in some cases the results obtained. However, the OUR values obtained with this method were in general lower than the DRI values. As mentioned, when active samples are analyzed the OUR method could not be used. Some authors have previously discussed the differences between static and dynamic respirometric methods

(Barrena et al., 2006a). In reference to the comparison between static and dynamic Respiration Indices in this study (Tables 4 and 5), it is clear that static values are always lower than the dynamic ones. This has been previously referred as a problem of oxygen diffusion in static systems (Adani et al., 2003). Therefore, it can be concluded that both values are statistically different.

However, in the case of DRI and OUR_{insitu} no statistical comparison is possible since the studied systems are completely different and the objectives of both methods are different: DRI corresponds to the full respiration potential at optimal conditions whereas OUR_{insitu} reflects the real state of a composting mass.

3.5. Waste Formulation mixtures

The combination of the parameters analyzed, with an acceptable cost and level of instrumentation, can be used in the formulation of manure waste formulations. When possible, the following steps are proposed as a strategy worth deploying 1) respirometric and physicochemical characterization of the wastes, 2) formulation of mixtures with other characterized materials (bulking agents, amendments, etc.) and 3) validation of the mixture's suitability, using key parameters such as DRI, FAS, moisture content and C:N. The ratio DRI/AT_4 is also a potential tool for predicting the behaviour of mixtures at full scale.

In this work the mixtures were formulated based on waste availability and the requirements of operational facilities at hand. It is clear that many mixtures could be proposed, but the experiments performed indicate that the respiration activity may be used as a useful tool for determining the suitability of materials for composting.

4. Conclusions

The results obtained in this study indicate that knowledge of the potential biological activity of a waste sample would be of considerable help in formulating balanced mixtures for composting. It has been demonstrated that the determination of respiration parameters such as DRI and OUR_{insitu} can be very useful to know the potential biodegradability and the real respiration activity in manure composting, respectively. According to the results, mixtures 2 and 3 are the most appropriate for composting, while mixtures 1 and 3 should be improved. Respirometric characterization shows that pig slurry is the most easily biodegradable material. Optimization of composting in mixtures can be done improving the matrix to obtain the highest biological activity.

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Tables

Table 1: Classification of the materials studied and composition of the mixtures under investigation.

Type		
Amendment	Sawdust	Sawdust type A Sawdust type B
	Straw	Barley straw
Bulking Agent	Pruning wastes	Pruning (<10 mm) Fine pruning (10-20 mm) Semi-composted pruning (<10 mm)
Raw wastes	Livestock waste	Different types of pig slurry Cattle manure Solid fraction mixed (pig and cattle) Solid fraction of pig slurry Turkey litter Different types of rabbit manure
	Other	Fodder by-product
Mixed wastes	Mixture 1: cattle manure (95%) and barley straw (5%)	
	Mixture 2: pig slurry (fattening) (75%), barley straw (8%), pruning (4%), sawdust A (6.5%), sawdust B (6.5%)	
	Mixture 3: pig slurry (closed cycle) (74%), barley straw (6.5%), pruning (6.5%), sawdust A (6.5%), sawdust B (6.5%)	
	Mixture 4: pig slurry + turkey litter (72%), barley straw (3%), pruning (18%), sawdust A (7%)	
	Mixture 5: solid fraction mixed (cattle and pig) (94%) and barley straw (6%)	
	Mixture 6: solid fraction of pig slurry (76%), barley straw (6%), Fodder by-product (6%), pruning (6%), sawdust A (6%)	

Table 2: Physical and chemical properties of different components of the mixtures studied. Results from triplicates are presented as mean ± standard deviation. Number followed by the same letter in the same column are not statistically different (Test Tukey, $p<0.05$).

Material	MC (%)	OM (%, db)	BD (g/L)	WHC (gwater/gTS)	WHCocc (%)	FAS (% v/v)	pH	CE (dS/m)	KTN (%, db)	N-NH$_4$ (%, db)	TOC (%, db)	DOC (%, db)	P (%, db)	OM/TOC	C:N	N-NH$_4$/KTN
Fine Pruning (<10 mm)	8±2a	88.8±4.8a	247±3a	1.3±0.1a	6.9±1.6a	64.0±2.1a	7.5±0.6a	1.7±0.1a	0.5±0.2a	0.1±0.0a	27.9±1.7a	0.5±0.0a	0.05±0.0a	3.2	52	19
Pruning (10-20 mm)	17±6b	74.8±7.1a	127±5b	1.92±0.1a	10.4±32a	77.1±2.7a	7.9±0.7a	1.1±0.1a	1.2±0.2a	0.1±0.0a	50.6±3.8b	0.7±0.0a	0.16±0.0b	1.5	42	10
Semicomposted pruning (<10 mm)	38±10c	53.3±8.7b	313±9c	2.0±0.1a	30.2±1.3b	67.5±3.7a	8.3±0.8a	1.0±0.1a	1.1±0.2a	0.1±0.0a	43.8±4.9b	0.5±0.0a	0.14±0.0b	1.2	41	8
Barley straw	10±5a	93.2±0.4a	17±1.4d	4.1±0.5b	3.0±0.7a	87.2±3.0b	7.4±0.4a	1.8±0.0a	0.5±0.1a	0.0±0.0a	44.1±0.6b	1.9±0.6b	0.04±0.01a	2.1	89	9
Sawdust type A	19±11b	90.9±5.4a	147±33b	7.1±1.0c	3.4±1.9a	76.4±5.2a	6.8±0.9a	0.9±0.5a	0.8±0.5a	0.1±0.0a	49.6±2.1b	0.4±0.1a	0.02±0.02a	1.8	95	10
Sawdust type B	12±3a	90.9±3.3a	248±11a	3.4±0.8b	3.9±0.1a	69.1±0.1a	6.8±0.8a	0.3±0.1b	2.8±0.2a	0.2±0.0a	44.4±4.7b	0.8±0.0a	0.04±0.02a	2.1	16	8
*Pig slurry (fattening)	96±1d	58.9±1.7b	-	-	-	-	7.4±0.2a	19.5±0.2c	10.3±0.3b	7.6±0.3b	54.1±1.8b	8.17±1.2c	1.65±0.5b	-	3.2	73
*Pig slurry (closed cycle)	95±2d	65.8±2.1b	-	-	-	-	7.3±0.3a	22.5±0.3c	10.5±0.4b	7.8±0.4b	39.0±1.7b	-	1.95±0.2b	-	3.5	75
Cattle manure	78±3d	86.5±1.5a	358±59c	6.1±0.2c	59.2±10.3c	68.8±4.1a	8.4±0.5a	2.3±0.6a	2.7±0.4a	0.6±0.2a	42.6±2.1b	2.4±0.6b	0.39±0.2a	2.0	16	23
Solid fraction mixed (pig and cattle)	78±2d	92.5±2.3a	506±20e	6.1±0.2c	57.4±5.2c	53.1±5.3a	8.4±0.3a	2.5±1.6a	7.5±2.3b	2.1±0.2b	41.4±1.6b	0.8±0.2a	1.24±0.5b	2.2	5.5	28
Solid fraction of pig slurry	79±1d	70.2±1.3a	750±33f	5.0±0.2c	70.9±3.4c	35.3±4.7c	8.2±0.2a	4.7±0.5a	5.6±0.0b	2.5±0.1b	37.7±1.6b	2.3±0.2b	3.25±0.7c	1.9	7	44
Turkey litter	78±3d	71.4±6.2a	1003±5g	-	-	0.0±0.0d	6.0b	3.6±0.4a	5.1±0.1b	1.0±0.2a	26.1±2.3a	3.8	1.60±0.4b	2.7	5	19
Rabbit manure (maternity rabbits)	56±0e	67.4±11.3b	750±45f	3.8±0.3b	33.3±1.9b	35.3±3.4d	8.5±0.2a	7.6±1.0a	2.4±0.1a	0.4±0.0a	30.6±6.4a	2.6±0.5b	1.13±0.3b	2.2	13	17
Rabbit manure (fattening rabbits)	73±4d	66.0±6.7b	708±37f	2.9±0.2b	108.1±1.2e	33.1±3.8d	8.6±0.2a	3.1±0.3a	2.1±0.2a	0.3±0.0a	31.9±3.3a	2.0±0.4b	1.07±0.3b	2.1	15	14
Fodder by-product	13±3b	84.2±5.2a	344±27c	2.5±0.1a	5.9±1.2a	62.1±2.6a	5.8±0.3b	2.5±0.3a	1.4±0.2a	0.3±0.1a	39.1±3.9b	5.6±0.9c	0.47±0.2b	2.2	28	19

* Liquid materials: COD (g/L) was calculated instead of TOC (%,db)
Abbreviations: MC: moisture content, OM: organic matter content; BD: bulk density; WHC: water holding capacity (occ: occupied); FAS: free air space; KTN: Kjeldahl total nitrogen, TOC: total organic carbon; COD: chemical oxygen demand; DOC: dissolved organic carbon; db: dry basis.

Table 3: Physical and chemical properties of the mixtures studied. Results from triplicates are presented as mean ± standard deviation. Number followed by the same letter in the same column are not statistically different (Test Tukey, $p<0.05$).

Mixture	MC (%)	OM (%, db)	BD (g/L)	WHC (gwater/gTS)	WHCocc (%)	FAS (% v/v)	pH	EC (dS/m)	NTK (%. db)	$N\text{-}NH_4$ (%, db)	TOC (%, db)	DOC (%, db)	P (%, db)	OM/TOC	C:N	$N\text{-}NH_4$/NTK
Mixture 1	73±5a	85.4±6a	335±15a	6.6±0.2a	37.6±3.1a	72.0±3.7a	8.3±0.4a	1.7±0.1a	1.4±0.2a	0.3±0.0a	43.4±2.2q	1.5±0.1a	0.20±0.1a	2.1	32	21
Mixture 2	73±6a	86.3±15a	311±10a	5.6±0.3a	51.1±4.2b	65.4±2.7a	8.3±0.4a	5.9±0.3b	3.1±0.3b	1.3±0.1b	30.8±2.7b	2.3±0.6a	0.42±0.2a	2.9	10	41
Mixture 3	74±5a	79.9±12a	268±7a	5.6±0.3a	49.8±3.7b	71.4±2.1a	8.4±0.3a	3.2±0.2c	1.9±0.2a	0.6±0.0a	28.0±1.6b	1.6±0.2a	0.22±0.1a	2.9	15	30
Mixture 4	75±4a	73.7±8b	369±11a	7.8±0.2a	38.1±2.5a	64.5±3.4a	8.3±0.5a	3.6±0.2c	1.7±0.2a	0.8±0.0a	39.2±1.9a	1.4±0.0a	0.31±0.0a	1.9	23	47
Mixture 5	70±6a	90.6±4a	262±12a	5.5±0.1a	42.3±3.9a	63.2±1.9a	8.8±0.3a	2.3±0.1c	2.2±0.0a	0.6±0.1a	40.3±2.0a	1.2±0.1a	0.23±0.1a	2.3	18	26
Mixture 6	72±7a	69.3±9b	153±9b	-	-	87.5±2.9b	7.9±0.3a	3.2±0.1c	3.2±0.1b	1.1±0.2b	34.4±2.0a	2.4±0.3a	1.47±0.3b	2.0	10	36

Abbreviations: MC: moisture content, OM: organic matter content; BD: bulk density; WHC: water holding capacity (occ: occupied); FAS: free air space; NTK: nitrogen Kjeldahl content, TOC: total organic carbon; DOC: dissolved organic carbon; db: dry basis.

Table 4: Respirometric characterization: maximum oxygen uptake rate observed (OUR_{max}) and cumulative O_2 consumption in four days (AT_{4-OUR}) for the materials studied. Results from triplicates are presented as mean ± standard deviation. Number followed by the same letter in the same column are not statistically different (Test Tukey, $p<0.05$).

Type of sample	**Sample**	**OUR_{max}** [g O_2 kg^{-1} OM h^{-1}]	**AT_{4-OUR}** [g O_2 kg^{-1} OM]
Amendment	Sawdust type A	0.16 ± 0.00a	14.4 ± 0.2a
	Sawdust type B	0.60 ± 0.00b	33.6 ± 0.4b
	Barley straw	0.71 ± 0.02b	61 ± 2.5c
Bulking agent	Pruning	0.21 ± 0.02b	19.4 ± 2.2a
	Fine pruning	0.70 ± 0.02b	65.1 ± 1.8b
	Semi-composted pruning	0.60 ± 0.00b	57.6 ± 0.2b
Raw materials	Pig slurry (fattening)	1.84 ± 0.31a	103.7 ± 8.3a
	Cattle manure	1.5 ± 0.03a	97.6 ± 1.3a
	Mixed solid fraction	2.18 ± 0.04a	120.9 ± 6.0a
	Solid fraction of pig slurry	3.84 ± 0.04b	164.3 ± 1.2b
	Turkey litter	0.97 ± 0.03c	43.9 ± 22.2c
	Rabbit manure (maternity)	1.72 ± 0.02b	146.9 ± 1.2d
	Rabbit manure (fattening)	1.83 ± 0.02a	74.8 ± 2.1a
	Fodder by-product	3.27 ± 0.03b	272.3 ± 3.3d
Mixtures	Mixture 1	2.07 ± 0.07a	116.3 ± 4.5a
	Mixture 2	6.5 ± 0.98b	-
	Mixture 3	2.36 ± 0.12a	137.5 ± 2.2a
	Mixture 4	1.84 ± 0.02a	128.8 ± 13.0a
	Mixture 5	1.7 ± 0.02a	137.1 ± 3.6a
	Mixture 6	2.34 ± 0.7a	198.0 ± 11.2b

Table 5: Dynamic respirometric index expressed as: DRI_{24h}, DRI average of the twenty-four hours of maximum activity; DRI_{1h}, DRI average of the one hour of maximum activity and AT_{4-DRI}, cumulative consumption in four days. Results from triplicates are presented as mean ± standard deviation. Number followed by the same letter in the same column are not statistically different (Test Tukey, $p<0.05$).

Sample	**DRI_{24h}** [g O_2 kg^{-1} OM h^{-1}]	**DRI_{1h}** [g O_2 kg^{-1} OM h^{-1}]	**AT_{4-DRI}** [g O_2 kg^{-1} OM]
Mixture 1	3.51 ± 0.04a	6.37 ± 0.01a	220.9 ± 3.4a
Mixture 2	4.31 ± 0.23b	7.19 ± 0.58a	155.1 ± 22.2b
Mixture 3	2.16 ± 0.05c	2.34 ± 0.02b	159.0 ± 2.4b
Mixture 4	3.28 ± 0.28a	7.00 ± 0.68a	140.8 ± 26.8b
Mixture 5	2.72 ± 0.28c	3.30 ± 0.58b	210.4 ± 36.4a

Table 6: Physical and chemical characteristics of the mixtures 1 to 4 during composting in confined piles. Results from triplicates are presented as mean ± standard deviation. Number followed by the same letter in the same row are not statistically different (Test Tukey, $p<0.05$).

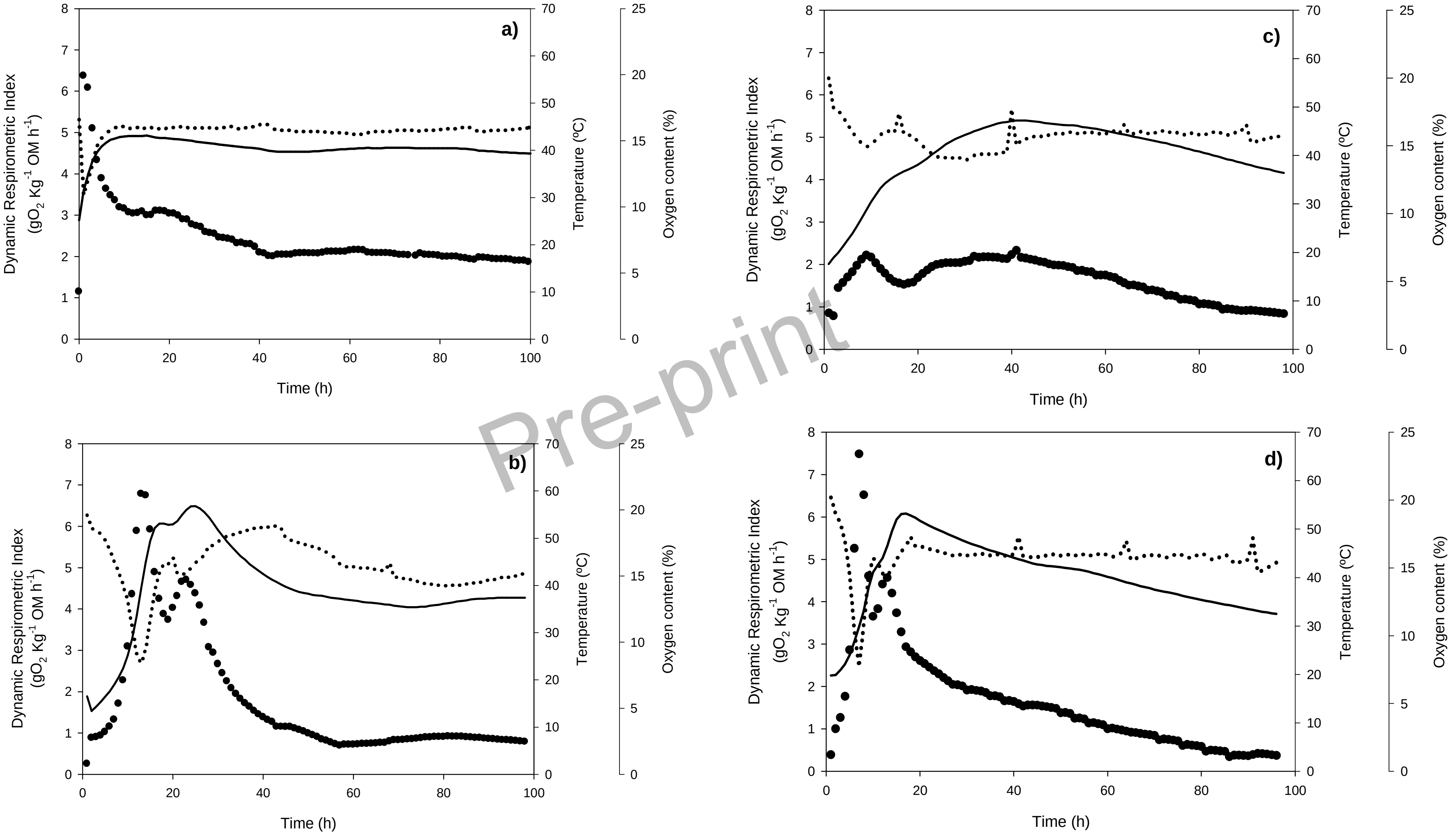
	Mixture 1					**Mixture 2**					**Mixture 3**					**Mixture 4**				
Process time (days)	**1**	**10**	**15**	**24**	**36**	**1**	**8**	**17**	**28**	**36**	**1**	**18**	**27**	**33**	**48**	**1**	**14**	**21**	**28**	**34**
Moisture (%)	73 ±5a	71.5 ±5a	74.5 ±6a	72.3 ±5a	68.6 ±3b	73 ±6a	73.8 ±7a	72.5 ±5a	71.1 ±3a	70.5 ±4a	73.7 ±5a	64.8 ±5b	57.5 ±4c	63.4 ±4b	58.2 ±2c	75 ±4a	72.4 ±6a	70.0 ±a	72.7 ±3a	70.7 ±3a
Organic matter (%, db)	85.4 ±6a	82.3 ±6a	82.6 ±5a	82.7 ±5a	82.3 ±5a	86.3 ±15a	75.4 ±12b	71.8 ±9b	71 ±7b	69.2 ±5b	79.9 ±12a	65.4 ±9b	65.3 ±9b	64.0 ±10b	63.5 ±7b	73.7 ±8a	71.6 ±8a	63.6 ±6b	67.7 ±5b	66.4 ±5b
Free air space (%)	72.0 ±3.7a	76.4 ±3.8b	72.1 ±2.5a	72.1 ±2.7a	71.0 ±1.7a	65.4 ±2.7a	64.7 ±3.1a	54.1 ±2.1b	42.2 ±2.0a	49.3 ±1.8a	71.4 ±2.1a	77.1 ±2.2a	73.2 ±2.4a	75.1 ±1.9a	76.1 ±2.0a	64.5 ±3.4a	58.5 ±2.4a	48.9 ±2.2b	47.5 ±1.2b	48.9 ±15b
Bulk density (g/l)	335 ±15a	338 ±17a	347 ±11a	361 ±6a	347 ±12a	311 ±10a	378 ±17b	442 ±20c	498 ±16c	503 ±15c	268 ±7a	299 ±12a	336 ±5b	333 ±8b	333 ±7b	369 ±11a	378 ±16a	477 ±7b	495 ±20b	487 ±12b
pH	8.3 ±0.4a	8.5 ±0.3a	8.5 ±0.2a	8.5 ±0.1a	8.5 ±0.1a	8.3 ±0.4a	8.8 ±0.4a	9.0 ±0.2a	8.7 ±0.1a	8.4 ±02a	8.4 ±0.3a	8.5 ±0.1a	8.3 ±0.2a	8.4 ±0.1a	8.5 ±0.1a	8.3 ±0.5a	8.8 ±0.4a	8.7 ±0.1a	8.7 ±02a	8.7 ±02a

db: dry basis

Legends to Figures

Figure 1: Evolution of dynamic respirometric index (DRI) (dots), oxygen content (dotted fine line) and temperature at the centre of the reactor (continuous line) of **a)** Mixture 1, **b)** Mixture 2, **c)** Mixture 3 and **d)** Mixture 4. Evolution is referred to the initial sample of each mixture.

Figure 2: Composting experiments at full-scale. Time evolution of Oxygen Uptake Rate in situ (OUR_{insitu}) (triangles), oxygen content (dots) and temperature inside the confined piles (squares) of **a)** Mixture 1, **b)** Mixture 2, **c)** Mixture 3 and **d)** Mixture 4. Average of OUR_{insitu} obtained during 2 and 3 hours of data acquisition is presented jointly with standard deviation. It represents at least the average of three OUR_{insitu} values.



a)
b)
c)
d)
Dynamic Respirometric Index (gO$_2$ Kg^{-1} OM h^{-1})
Temperature (ºC)
Oxygen content (%)
Time (h)
0
1
2
3
4
5
6
7
8
10
20
30
40
50
60
70
5
15
25
0
20
40
60
80
100

Figure 1

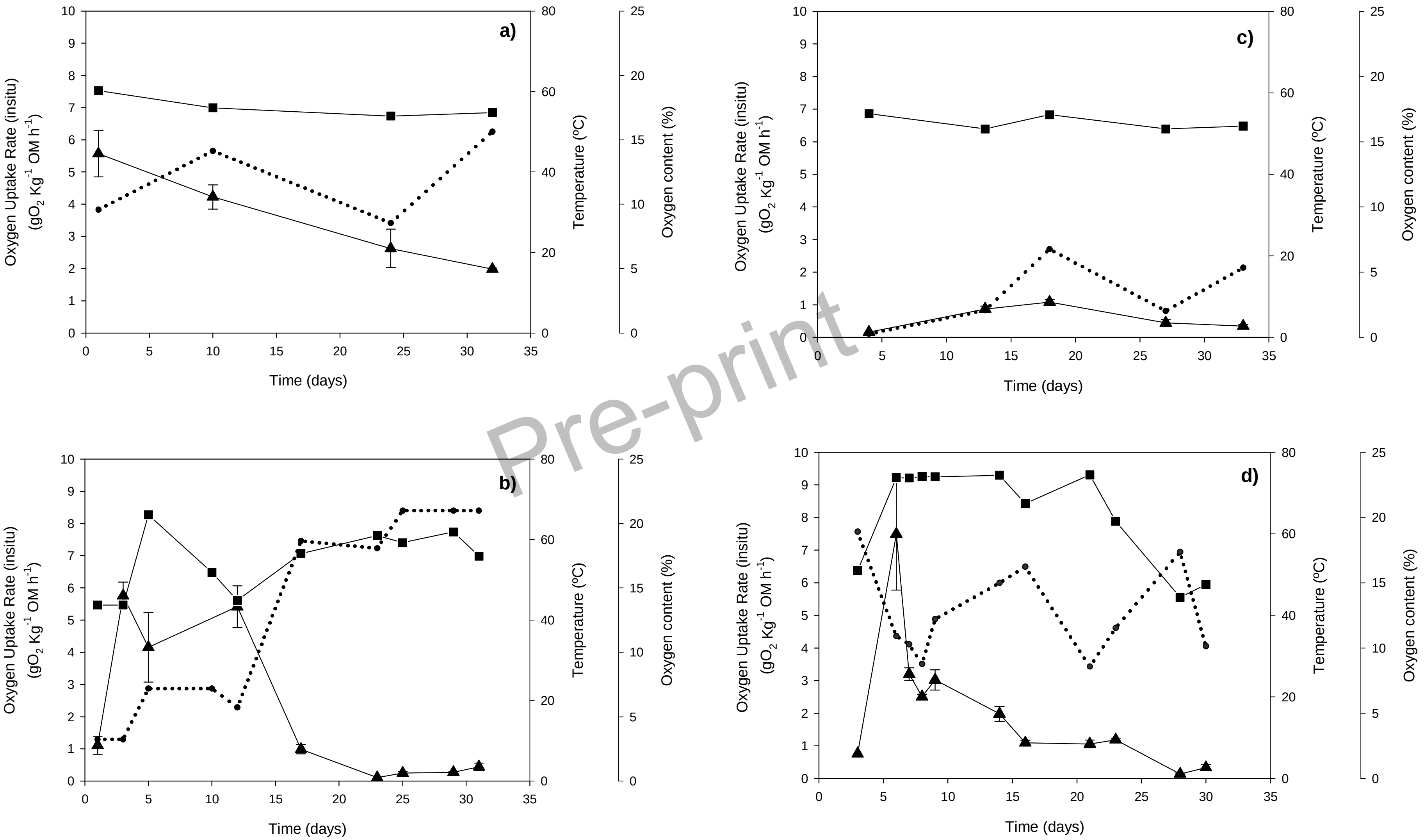

a)
b)
c)
d)
Oxygen Uptake Rate (insitu) (gO_2 Kg^{-1} OM h^{-1})
Temperature (ºC)
Oxygen content (%)
Time (days)
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6
7
8
9
10
0
20
40
60
80
0
5
10
15
20
25

Figure 2