Performance of different systems for the composting of the source-selected organic fraction of municipal solid waste

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Abstract

Performance of three pile composting systems at field-scale were studied and compared in the composting of source-selected organic fraction of municipal solid waste (OFMSW): turned pile, static forced-aerated pile and turned forced-aerated pile. Routine parameters such as temperature, oxygen content, moisture and porosity were monitored. Temperature was found to be higher in turned systems whereas oxygen content was higher in forced-aerated systems. Although the initial air filled porosity for all mixtures was high, around 70%, the material tended to compact in the static system. A high degree of heterogeneity was found in the non-turned system. Extent of biodegradation was measured by respiration techniques (from 5.3 to 1.1 mg [O_2] g [organic matter {OM}]$^{-1}$ h^{-1} in turned pile and from 4.7 to 0.7 mg [O_2] g [OM]$^{-1}$ h^{-1} in Turned Forced-Aerated Pile). The non-turned compost showed a low level of stability (3.6 mg [O_2] g [OM]$^{-1}$ h^{-1}) and the lowest maturity grade (I) measured by the self-heating test. In forced aerated systems a low intermittent aeration rate of 1 l kg [volatile solids{VS}]$^{-1}$ min^{-1} (5 minutes on, 30 minutes off) proved to be excessive, causing major water losses and hampering moisture control. Comparison of the results obtained for turned pile and turned forced-aerated pile demonstrated that the investment cost in a forced aeration system is not necessary for this waste. Hence, turned systems are recommended for OFMSW pile composting.

Keywords: organic wastes, municipal solid waste, pile composting, turned system, aeration, respiration index.

1. Introduction

According to European legislation (Directive 99/31/EC) the total amount of organic matter disposed in landfills must be gradually reduced. Many studies have shown that municipal solid wastes (MSW) contain a high proportion of organic materials, from 50% to 65% (Tchobanoglous et al., 1993). The source-separated organic fraction of MSW (OFMSW) presents 80-95% of organic material. This fraction can be treated and managed instead of sent to landfills or incinerated. Composting and recovering of organic material is an available technology which redirects a significant fraction of the organic wastes stream from landfills.

Composting is an aerobic thermophilic process, which requires oxygen to stabilize the organic wastes and optimal moisture content for microorganisms development (Haug, 1993). The common control variables at compost facilities are temperature, oxygen and moisture. The final product, the compost, is a stable, sanitised and humus-like material (Chefetz et al., 1996; He et al., 1995).

Composting stages are common for all composting systems. Initially high microbial activity produces heat which causes temperature within the compostable material to rise rapidly into the thermophilic range (above 45ºC). Usually temperature increases roughly up to 60ºC and remains there for several weeks depending on the size of the system and the composition of the raw materials (Finstein et al., 1980). After the rapidly degradable components are consumed, heat generation gradually declines during the maturation stage (Kaiser, 1996). At the end of this stage, the material is no longer self-heating, and the finished compost is ready for use (Barrena et al., 2006a).

Nowadays, several composting methods are applicable, and the selection of the method is dependent on the investment cost, operation cost, time required to reach compost stability and maturity and the availability of land and origin of raw materials. Among all the composting methods available, open-air pile systems are the most simple and require the lowest investment (Haug, 1993).

Several methods have been used to provide oxygen to composting material. In the passive aeration method, oxygen supply is achieved by means of the natural convective movement of the air through the pile (Mason et al., 2004). The size and porosity of the pile should be adequate to enable the aeration (Szanto et al., 2007). Turned composting methods are aerated by passive aeration but additional turning is used to maintain the proper porosity, to provide oxygen, to mix the material and to release excessive heat, water vapour and other gases (Haug, 1993). This method is the most common method to produce compost from organic wastes (Avnimelech et al., 2004). In static forced-aerated pile composting, forced aeration is applied through air ducts, and aeration is provided by blowing or sucking air through the composting material (Haug, 1993).

Forced aeration systems in composting process are claimed to enhance the process, and the active decomposition period can be reduced by almost 50% in the aerated static pile system compared to a turned system (Epstein et al., 1976; Epstein et al., 1978; Finstein et al., 1980). This reduction in active composting time is not only due to the aeration method used but it also depends on the other interactive factors controlling the composting process. Although some studies on the biological treatment of mechanically-separated OFMSW have been published (Norbu et al., 2005), there are only few systematic works on the comparison of composting systems for source-selected OFMSW published (Castaldi et al., 2008), which is an emerging material in European countries according to Directive 99/31/EC. In this work, a global biological tool such as respiration index was used to measure the extent of biodegradation and to compare the composting systems.

On the other hand, the main physical factor affecting the oxygen distribution in the organic matrix to be composted is its porosity. Porosity depends on the particle size, the structure of the particle and the water availability (Agnew and Leonard, 2003; Richard et al., 2004). Different authors suggest different values for minimum air filled porosity requirements within 30 and 60% (Haug, 1993; Annan and White, 1999). Also, material resistance must be adequate to reduce compaction over the process. The loss of material porosity during the process and the formation of preferential air path flows have been reported (Veeken et al., 2002; Cayuela et al., 2006). Pile turning can help to reduce compaction (Alburquerque et al., 2006).

The main objective of this work is to systematically analyse and compare the three pile composting configurations most widely used at composting facilities, i.e. turned pile (TP), static forced-aerated pile (SAP) and turned forced-aerated pile (TAP), in terms of evolution of temperature, oxygen concentration, moisture content, organic matter content, porosity and time required for material stabilisation measured according to the respiration index.

2. Materials and Methods

2.1. Composted materials and operation performance

Three different piles were built in two composting plants; the turned pile (TP) was located at the Jorba composting plant (Barcelona, Spain), while the static forced-aerated pile (SAP) and the turned forced-aerated pile (TAP) were processed at the La Selva composting plant (Girona, Spain). The volume of the three piles was approximately 200 m^3. They were built according to the windrow method with a trapezoidal shape of the following approximate dimensions: base: 4 m; height: 2 m; length 30-40 m. The piles were built on a slightly sloped concrete floor. Both plants are covered to avoid the effect of rainfall on the piles.

Each pile was built using 70-80 tons of OFMSW collected from surrounding municipalities during a week. OFMSW presented a 12-15% (by weight) of non-compostable fraction. The main characteristics of the used feedstock are presented in Table 1. In both composting plants, the OFMSW was mixed with wood chips from shredded pallets used as bulking agent at a volumetric ratio of 1.5:1 (OFMSW: bulking agent), as this is the optimized ratio used in the facilities were the trials took place for source-selected OFMSW composting.

In both turned pile systems (TP and TAP) turning was performed daily in the first two weeks, and every 2-3 days after two weeks and until the end of the process. This is a high turning frequency which is normally used in highly heterogeneous materials such as OFMSW (Barrena et al., 2006b). Turning was carried out by using a Backhus turner Model 15.5 (Edewech, Germany).

Forced air in both aerated piles (TAP and SAP) was provided in cycles of 5 min on and 30 min off (fixed rate) during the first 50 days of process and 5 min on and 60 min off during the remaining period (total composting time was 90 days). Air flow was provided at a rate of 1 l min^{-1} kg[volatile solids {VS}]$^{-1}$ to ensure aerobic conditions. A blower (positive pressure mode) was used, connected to two perforated PVC pipes of 100 mm of diameter embedded in the pile base. The pipes were covered with a layer of shredded wood chips to improve air distribution.

Moisture content was controlled during the composting process. It was carried out by spraying water on the piles. For turned piles, watering was provided simultaneously to turning when necessary. In the static pile, water was distributed on the surface of the pile as homogeneously as possible.

At the end of the process, final material was screened to 10 mm by means of a trommel (Model Mustang, Masias Recycling, Spain) to obtain the final compost. The material of size larger than 10 mm was composed of non-degraded bulking agent and non-compostable materials. In the case of SAP the material on the pile was homogenised prior to the sieving using a Backhus turner Model 15.5 (Edewech, Germany).

2.2. Temperature and oxygen measurements

To monitor the composting process, temperature and oxygen were daily measured in situ at two different depths, 400 cm and 1000 mm, in nine different points, 3 points in the top of the pile and 3 points for each lateral side, at approximate distances of 1/4, 1/2 and 3/4 along the total length of the pile. In the case of Static Forced-Aerated Pile monitoring at 1000 mm was not possible in many occasions due to compaction of the pile and consequently fewer data are available at this depth. Temperature and oxygen values are presented in Table 2 and Fig.1 as average values of the different monitored points of the pile. Standard deviation is also presented. Temperature was measured using a temperature probe (Pt-100, Desin Instrument, Barcelona, Spain) whereas oxygen concentration was measured using an oxygen sensor (QRAE Plus, Sensotran S.L., Barcelona, Spain) connected to a portable aspiration pump.

2.3. Pile sampling

Sampling was undertaken weekly during the first four weeks of the process and each 15 days until the end of the process (90 days). Sub-samples of 5 kg of the whole material (without sieving wood chips and without shredding) were extracted from seven points of each pile, 3 lateral points per each side at approximate distances of 1/4, 1/2 and 3/4 along the total length of the pile, and one point from the top middle of the pile, at an intermediate depth (approximately 600 mm). The seven sub-samples were mixed manually to obtain a representative sample of each pile. Moisture and organic matter content, respiration index, air filled porosity, pH and maturity grade were carried out an aliquot of at least 1 kg of this representative sample.

In the case of Static Forced-Aerated Pile material sampling was difficult since the material was compacted and the real depth of sampling was approximately 500 mm.

2.4. Respiration index

A static respirometer was built according to the original model described by Iannotti et al. (1993, 1994) and following the modifications and recommendations given by Standard Methods (U.S Department of Agriculture and U.S Composting Council, 2001). The configuration of the respirometer can be found elsewhere (Barrena et al., 2005). Approximately 250 ml of sample were placed in 500 ml Erlenmeyer flasks on a nylon mesh screen that allowed air movement under and through the solid samples. The setup included a water bath to maintain the temperature at 37ºC during the respirometric test. Prior to the assays, samples were incubated for 24 hours at 37ºC. During all the incubation period samples were aerated with previously humidified air at the sample temperature. The drop of oxygen content in a flask containing a sample was monitored with a dissolved oxygen meter (Lutron 5510, Lutron Co. Ltd., Taiwan) connected to a data logger. The rate of respiration of the sample (Oxygen Uptake Rate, OUR, based on organic matter content) was then calculated from the slope of oxygen level decrease according to the standard procedures (Iannotti et al., 1993). Results of the respiration index are expressed as mg O_2 consumed per hour and g of organic matter and are presented as an average value of three aliquots.

2.5. Air filled porosity (AFP)

Air filled porosity (AFP), also referred in literature as free air space (Agnew and Leonard, 2003), is expressed as the ratio of air filled pore volume of the sample to total sample volume. AFP was ex-situ measured using a representative sample extracted from the pile with a self-made constant volume air pycnometer according to the description of Annan and White (1999) and Oppenheimer et al. (1996) with an effective sample chamber volume of 14.85 l and using an initial pressure of 3, 4 and 5 bar. AFP data is presented as an average of a triplicate measure.

2.6. Analytical methods

Moisture content was analyzed by calculating the water loss when the sample was oven-dried at 105ºC during 24 hours, total organic matter content (OM) was analysed by sample ignition at 550ºC and pH was analyzed on a slurry of compost and deionised water (1:5 w/w). These parameters were determined in duplicates from the representative sample according to the U.S Department of Agriculture and the U.S Composting Council (2001). Dewar® self-heating test was used as a measure of compost maturity (U.S Department of Agriculture and the U.S Composting Council, 2001). The principle of the method is to precisely record the highest temperature achieved after placement of compost into a Dewar vessel for several days. Interpretation of the results is based on division into five-levels of 10ºC increments of the compost heating. For example, Class V (highest maturity) refers to 10ºC, IV is 20ºC and the lowest level of maturity (grade I) is 50ºC heating over ambient (Weppen, 2002).

2.7. Economical analysis

A basic economical estimation was carried out by calculating the investment cost required for each of the composting systems considered in this work. The treatment capacity was set to 20,000 tons of OFMSW per year. Surface requirement was calculated on the basis of 12 weeks of total process time and a 50% volume reduction in the first 4 weeks (decomposition phase). Both decomposition and maturation piles were dimensioned considering 70 m length and a trapezoidal section of 5.5 m^2. According to local providers the following costs were considered: turning machine, 250000 €; aeration system (blowers, fittings and pipes), 80000 €; standard pavement, 85 € m^{-2}; aeration pavement, 140 € m^{-2}.

3. Results

3.1. Temperature and oxygen content

Temperature evolution for each composting system is presented in Table 2, whereas oxygen content is presented in Figure 1. As can be observed in Fig.1, oxygen content in TP slowly decreased in the first three weeks of process, to remain below 3-8% for the next 4 weeks. The oxygen level was further reduced to 1-2% after watering the pile in days 49 and 52, which demonstrated an increase in the biological activity when adjusting the moisture content of the pile. Temperatures in the thermophilic range (over 45ºC) were registered since the beginning of the process (Table 2) for TP. Temperature raised over 55ºC in the third week and was maintained high until the end of process. Standard deviation of temperature values in TP was within 2 and 18ºC. Temperature oscillations corresponded mainly to pile turning; lower values were registered after turning and temperature increased afterwards due to the material homogenisation until the next turning. The opposite trend was found in oxygen level (Fig. 1): higher oxygen values were registered for lower temperatures coinciding with pile turning.

In the case of SAP, severe drying and compaction phenomena occurred in the pile and in consequence the material formed big aggregates. As a result, pile sampling and monitoring were extremely difficult. It was not always possible to introduce the temperature and oxygen probes so fewer measures are available for this pile. Thus, only the most external layer of SAP was actually monitored and sampled during most of the process. All these facts are important to interpret the obtained results. Of special relevance is the case of oxygen measurements, which were carried out by aspiration of the interstitial air. When material was very compacted it was impossible to introduce the oxygen probe and thus fewer measure points were obtained. It is also important to mention that a considerable decrease in pile volume due to mass biodegradation and compaction was observed in the first weeks of process, and the total height of the pile was approximately reduced to the half size. This was different in the case of turned piles, where the turning process rebuilt the piles to the same section dimensions every turning. Volume reduction was reflected in a reduction of 50% of the total length of the turned piles but the section, height and width, were held constant through the process. This maintained the geometric conditions of the pile during the composting process of turning systems. As observed in Fig. 1, oxygen concentration was high in SAP (values over 17%) during all the process, with a low dispersion value (standard deviation of oxygen measurements in SAP was 0.5-4.5%). The lower values were registered at the beginning of the process, before the mentioned compaction phenomenon occurred (first two weeks of process). Slightly lower values were also registered after forced aeration was reduced to 50% (day 50). Temperature values over 55ºC were achieved in the first two weeks but during the rest of the composting period average temperatures remained within 40-50ºC (Table 2). A high standard deviation for SAP temperature values was observed within 4-24ºC, reflecting an important dispersion of temperature values and, in consequence, a considerable heterogeneity in composting conditions.

Finally, in the case of TAP, average oxygen values reached 10% during the first two weeks to increase afterwards and until the end of the process (Fig. 1). In general, oxygen remained around 18%. Average temperature was maintained between 50-55ºC in most of the process except for the beginning when temperatures reached 65ºC coinciding with the lower oxygen level and the moment of highest biological activity. Standard deviation for TAP temperature values was 2-15ºC (Table 2).

3.2. Moisture and air filled porosity

In the case of TP, the operation performance allowed for moisture content control maintaining this parameter around 40% during all the process (Fig. 2). Air filled porosity was also maintained around 70% during all the process (Fig. 3). On the contrary, moisture content control was difficult in SAP (Fig. 2). It tended to decrease easily. Watering operations were not efficient since no homogenisation of the material is provided in static systems and moisture gradients appeared in the pile. For instance, on day 43 of process, the pile sample (obtained from different sub-samples and then homogenized) presented 46.3% of water content (standard deviation 3.3%), while a sample collected from the most external layer presented a water content of 23.1 %. On day 50, water content of the pile sample was 46.1% (standard deviation 2.1%), while that of the superficial layer was only 9.25%. In the case of TP and TAP, although no specific moisture measurements at different locations were carried out, the appearance of the collected samples was much more homogenous. Air filled porosity measured on the sampled material was high, between 70-80%. In the case of TAP, moisture content fell below 40% in several occasions (Fig. 2), whereas air filled porosity was within 70 – 80% in the process.

3.3. Organic matter, respiration activity and maturity grade

An important reduction in the organic matter content (OM) was observed for TP, from 69% to 45% in 90 days (Fig. 4). In relation to the Static Respiration Index (SRI), it reflected the evolution of the biological activity and the material stability (Fig. 5). Biological activity increased in the first stage of the process and a maximum value of 5.3 mg [O_2] g [OM]$^{-1}$ h^{-1} was reached, which corresponds to highly active materials (Barrena et al., 2005). The increase observed in biological activity after this stage can be related to the availability of labile compounds. From this moment, a gradual decrease of SRI was observed until day 65 when a SRI of 1.5 mg [O_2] g [OM]$^{-1}$ h^{-1} was achieved. From that moment, a slower increase in stability was observed until the end of the process with SRI values around 1 mg [O_2] g [OM]$^{-1}$ h^{-1}. The progressive stabilization of the material was also reflected by the self heating test, showing a slowly increasing maturity grade and reaching a grade III at the end of the process (Fig. 6). Final compost obtained after 90 days of process also showed a medium-high stability (Table 1) as shown by a low respiration index (1.3 mg [O_2] g [OM]$^{-1}$ h^{-1}) according to Adani et al. (2004) and a medium maturity grade (III in a scale from I to V).

Static respiration index and maturity grade also reflected a progressive tendency to stabilization during the SAP composting process. When the experience was finished (day 87) SAP was homogenized in order to obtained a global representative sample and contrast the results obtained with the sampling during the process. As observed in Figure 5, respiration index corresponding to that day was much higher than the previous last SRI obtained during the process (2.8 and 1.1 mg [O_2] g [OM]$^{-1}$ h^{-1} respectively). This result demonstrated that a non-uniform biodegradation had occurred due to the coexistence of well-degraded parts of the material and other dry parts in which no biodegradation had taken place. Then, when mixing all the material, the resulting biological activity expressed as SRI is still quite high. The problems of having a representative sample in static composting systems can be an important drawback for the use of this system in the composting of OFMSW. Final compost (Table 1) presented a high SRI (3.6 mg [O_2] g [OM]$^{-1}$ h^{-1}) and low maturity grade (I). The slight difference in SRI value from the final homogenized sample (2.8 mg [O_2] g [OM]$^{-1}$ h^{-1}) can be explained according to the concentration of organic matter after the sieving and refining process to obtain the compost with the removal of bulking agent and non-compostable materials present in OFMSW. In relation to maturity grade, the value found for final homogenised compost (I) is much lower than that obtained in the final samples of SAP material (IV-V), which again can be due to the difficulty in obtaining a representative sample in SAP (Fig. 6). A minor decreased in organic matter content was also observed for SAP (Fig. 4).

Finally, a considerable reduction of organic matter was observed for TAP, from 80 to 50%, which again supposes an important biodegradation of OFMSW (Fig. 4). Respiration index increased at the beginning of the process and decreased afterwards to reach a final value close to 1 mg [O_2] g [OM]$^{-1}$ h^{-1}. Also maturity grade increased to grade V in 63 days. Final compost presented a maturity grade II and a SRI of 2.4 mg [O_2] g [OM]$^{-1}$ h^{-1} (Table 1).

4. Discussion

Turned pile presented higher temperature and lower oxygen values than both aerated piles. International requirements suggested in the European legislative draft document for bio-waste (European Commission, 2001) on compost sanitation (temperature above 55ºC for a total period of 2 weeks and 5 turnings or 2 turnings and temperature above 65ºC for 1 week) were fulfilled in TP and TAP, but not in SAP where no turning was provided and temperature-time requirements were not achieved.

Composting requires oxygen for aerobic activity, and low concentrations of oxygen available can lead to anaerobic conditions. However, too much aeration can lead to excessive cooling, preventing the thermophilic conditions required for optimum rates of decomposition. Between these two extremes there is an optimum aeration rate, which provides sufficient oxygen for aerobic decomposition, while maintaining temperatures in the thermophilic range (Ahn et al., 2007). It has been stated that oxygen levels between 5% and 15% result in the highest sustained temperatures for rapid aerobic composting (Epstein et al., 1976; 1978). Oxygen levels below 5% can cause anaerobic conditions, while levels above 15% are indicative of excessive aeration which tends to cool the pile. On the contrary, other authors have reported that low oxygen levels are not detrimental for aerobic biodegradation in composting environments. Richard et al. (2006) found a higher biodegradation rate when oxygen concentration decreased under thermophilic conditions. Also Wang et al. (2007) stated that a microaerobic environment with enough dissolved oxygen available for microorganisms in a liquid biofilm provides a more effective biodegradation than a macroaerobic environment with high oxygen content in the gas phase. Although in microaerobic conditions thermophilic phase lasted longer, a higher degradation of some organic fractions like cellulose and hemicellulose was observed and the material reached a proper stability in less time.

From Fig. 1 it is evident that the core of TP worked in microaerobic conditions during the process. Thus, natural convection and the applied turning program were not able to supply a sufficient amount of oxygen to the core of the pile in order to maintain oxygen levels above 5%. It is also clear from Fig. 1 that forced aeration is more important than turning in order to have high interstitial oxygen content. However, the general development of the TP process was satisfactory and a good product in terms of stability product was obtained, as confirmed by the final respiration index (Table 1). In fact, it can be concluded that maintaining a high level of oxygen consumption (measured as SRI), the oxygen content can be relatively low, as observed in TP, which presented a similar SRI evolution compared to those of the forced-aerated systems (Fig. 5) but lower oxygen content (Fig. 1). In general, it can be observed that respiration index reflected the evolution of biological activity and material stability (Fig. 5) and it is a good indicator of the end point of a composting process, since temperature can be maintained for a long time in absence of biological activity in a large composting mass (Barrena et al., 2006a). The trend observed in respiration activity corresponds to highly active materials (Barrena et al., 2005). In the first stage of the composting process organic matter is hydrolysed to simpler easily biodegradable compounds (Hsu and Lo, 1999). Then, after a period of maximum activity related to the availability of these more degradable compounds, a gradual decrease of the respiration activity is observed until values around 1.5-2 mg [O_2] g [OM]$^{-1}$ h^{-1} are reached. From that moment on, a final slower decrease is observed until the end of the process that occurs for values of the respiration activity around 1 mg [O_2] g [OM]$^{-1}$ h^{-1}. This trend has been observed with other organic wastes (Gea et al., 2004).

A variety of aeration rates have been recommended to optimise forced-aerated composting processes. In general, these recommended rates are substrate-dependant. Hong et al (1983) recommended an optimum range of 0.87-1.07 l min^{-1} kg [VS]$^{-1}$ for the composting of dairy manure mixtures. Lu et al. (2001) reported that a flow rate of 0.43-0.86 l min^{-1} kg [VS]$^{-1}$ is more efficient than 1.74-3.47 l min^{-1} kg [VS]$^{-1}$ for maintaining temperature in the thermophilic range during food waste composting trials. Based on previous researches, aeration rate of 0.04-3.0 l min^{-1} kg [VS]$^{-1}$ could be generalized for all types of substrates (Ahn et al., 2007). The selected initial aeration rate for this work, 1 l min^{-1} kg [VS]$^{-1}$ was within this range. However, from the results obtained it can be deduced that a lower aeration rate could have been more adequate because of the attenuation in the reduction of pile cooling, drying and operating costs. This is more evident when considering SAP performance. Once volume reduction occurred, leading to a higher surface area to volume ratio available for heat losses, the used aeration rate became excessive (Mason et al., 2004; Mason and Milke, 2005). With the same aeration rate, TAP presented higher values of temperature and lower oxygen level. As previously described, turned piles section was recovered at every turning operation, which maintained the area to volume ratio.

In the forced-aerated piles, moisture content control was crucial in the process. As observed in Fig. 2, the moisture content decreased below 40% on several occasions in the forced-aerated piles and only three times in the turned pile. Hence, water requirements were higher in aerated systems resulting in a higher number of watering operations. Aeration and heat generated were able to decrease moisture content below 40%, which might have caused a lag or inhibition of the microbial activity. Maximum biodegradation rates have been reported at around 50-70% moisture (Hamoda et al., 1998; Richard et al., 2002), with an optimal value varying according to the type of material and the composting time.

Both turned systems presented a major organic matter reduction reflecting a more effective biodegradation process. On the contrary, in the SAP the decrease in organic matter content was very slow or negligible, indicating that the process was less effective.

AFP was within 70 and 80% in the three piles during all the process and AFP evolution did not show any particular profile or specific trend. However the three piles performed very different regarding oxygen levels within the pile, heterogeneity and compaction. From this experience it was concluded that AFP values obtained from a homogenized sampled material did not reflect the actual porosity within the pile. Thus, ex-situ AFP does not seems to be a reliable process control parameter since alteration of sample characteristics of this type of materials is unavoidable using this type of measurement. In enclosed systems, it is possible to complement AFP information with other measurements as resistance to compaction or permeability (Szanto et al., 2007). Other methodologies have been suggested in closed reactors in order to consider compaction resistance in AFP measurements (McCartney and Chen, 2002). However, it seems difficult that some of these systems may be suitable for non-enclosed piles, as those presented in this work. In any case, the obtained results reveal the importance of designing a suitable sampling procedure to obtain representative samples. In the case of AFP, the sampling procedure altered the material structure in the pile. This effect was especially important in SAP where large aggregates were formed due to drying and the absence of homogenisation in the process. It can be pointed out that optimal AFP depends on the type of system and TAP requires lower porosity than SAP or TP to avoid compaction and to ensure oxygen availability. Further research is necessary to discern between the porosity requirements for different pile composting systems and types of organic wastes.

In general, process development and operation performance in SAP was influenced in a large extent by the high degree of heterogeneity of the pile regarding physical structure, temperature, oxygen availability, moisture content and biodegradation degree. SAP presented important gradients reflected on higher standard deviation in temperature and oxygen measurements (Table 2, Fig. 1), which probably would have been higher if more readings at 1000 mm had been available. This handicap has been already reported in static systems (Albuquerque et al., 2006; Veeken et al., 2002). Turning is recommended to avoid formation of preferential air path flows, compaction and moisture content gradients (Albuquerque et al., 2006; Cayuela et al., 2006). This is of special importance when dealing with highly heterogeneous materials such as OFMSW.

Drawbacks associated to static systems were reflected also in the stability of the final product obtained. Compost obtained in turned systems presented a higher stability than SAP final product (Table 1).

Finally, a basic economical estimation was made considering local providers and prices for a treatment plant with a capacity of 20,000 tons of OFMSW per year and a total processing time of 12 weeks. Investment cost required for the three systems considered was calculated. The most expensive system was TAP (30.5 € t [OFMSW]$^{-1}$) while TP and SAP accounted for a 69% and a 59% of TAP investment cost respectively. TAP would also represent the highest operation cost, including labour, maintenance, energy, etc. Thus, according to the results obtained, the additional investment required for forced aeration in turned systems is not necessary. On the other hand, turning appears to be essential for pile composting of heterogeneous materials. In consequence, from the three pile systems considered, Turned Pile could be recommended for OFMSW composting.

Conclusion

The performance of three typical composting systems has been systematically studied using source-selected OFMSW as main substrate. Routine data (temperature, oxygen and moisture content), porosity and biological activity measurements have highlighted the importance of turning for this highly heterogeneous waste, whereas the benefits of forced aeration are minimal if a frequent turning is provided.

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Tables

Table 1. Characterisation of the initial organic fraction of municipal solid waste (OFMSW) and the final products obtained in turned pile, static forced-aerated pile and turned forced-aerated pile. Final compost properties are determined once non-decomposed bulking agent and non-compostable material were removed.

Property	Initial OFMSW	Final Compost Turned Pile	Final Compost Static Aerated Pile	Final Compost Turned Aerated Pile
Moisture Content, %	62.3 ± 5.7	36.8 ± 1.3	31.8 ± 5.4	45.5 ± 0.8
Dry matter, %	37.7 ± 5.7	63.2 ± 1.3	68.2 ± 5.4	54.5 ± 0.8
Total Organic Matter, % dry basis	70.6 ± 9.1	50.6 ± 0.2	68.7 ± 2.6	46.7 ± 2.9
pH	6.1	8.2	7.8	8.4
Static Respiration Index, mg $[O_2]$ g $[OM]^{-1}h^{-1}$	6.2 ± 1.8	1.3 ± 0.2	3.6 ± 0.4	2.4 ± 0.3
Maturity Grade	-	III	I	II

Table 2. Temperature evolution for the three systems studied. When available, standard deviation of temperature measurements at different pile locations is also presented.

Time (day)	Turned Pile	Static Aerated Pile	Turned Aerated Pile
1	52.3 ± 1.3	53.6 ± 6.4	69.4
8	44.7 ± 0.0	56.3	58.2
15	41.0 ± 3.0	21.3	46.5
22	64.4 ± 1.4	32.4 ± 13.1	52.3 ± 4.0
30	65.0 ± 4.2	34.5 ± 24.3	55.2 ± 3.5
37	76.3 ± 1.5	30.1 ± 12.8	52.2 ± 4.6
40	75.2 ± 1.8	36.5 ± 11.7	51.4 ± 15.7
47	45.9 ± 0.1	37.5 ± 8.7	63.8 ± 4.5
50	61.1 ± 0.8	43.5 ± 11.8	48.0 ± 5.8
58	64.3 ± 0.5	35.0 ± 11.1	51.7 ± 3.6
64	75.6 ± 0.3	37.7 ± 14.4	55.5 ± 3.6
70	65.2 ± 1.0	46.0 ± 19.5	52.3 ± 2.9
80	56.6 ± 0.4	40.2	-
86	68.1 ± 0.9	45.3 ± 16.6	-

Figures

Fig. 1. Evolution of oxygen content for the three studied composting systems. Standard deviation is presented as error bar. TP: turned pile, SAP: static aerated pile and TP: turned aerated pile.

Fig. 2. Evolution of moisture content for the three studied composting systems. TP: turned pile, SAP: static aerated pile and TP: turned aerated pile. Upper single symbols indicate watering of the piles.

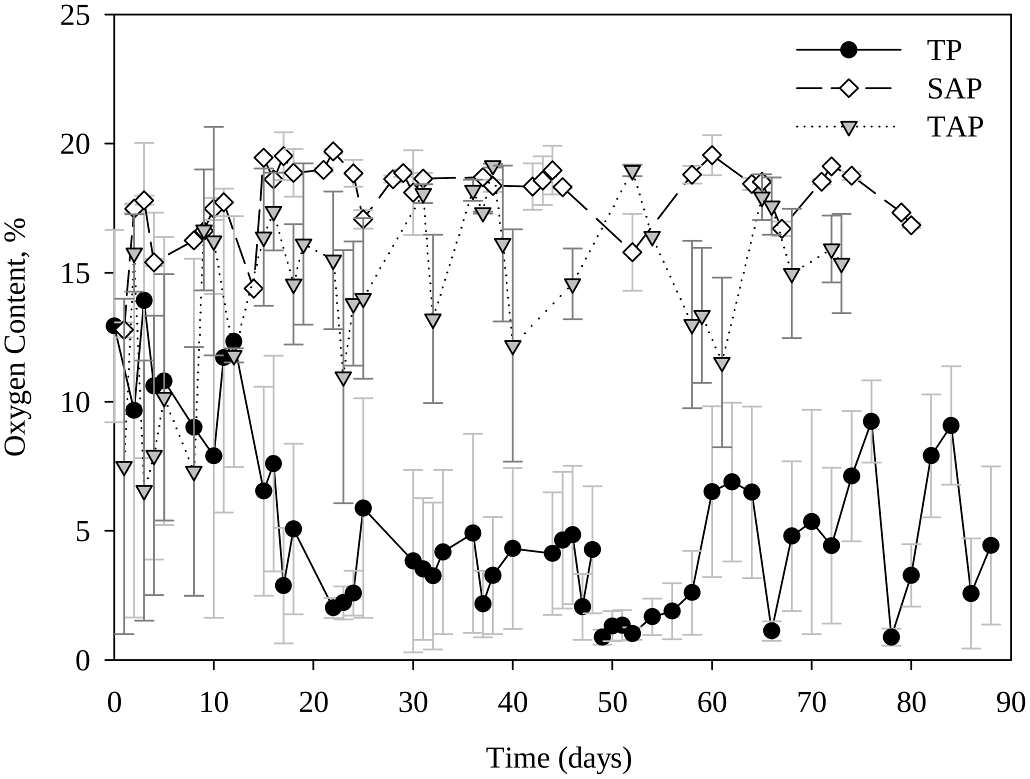
Fig. 3. Evolution of air-filled porosity for the three studied composting systems. TP: turned pile, SAP: static aerated pile and TP: turned aerated pile.

Fig. 4. Evolution of organic matter content for the three studied composting systems. TP: turned pile, SAP: static aerated pile and TP: turned aerated pile.

Fig. 5. Evolution of respiration index for the three studied composting systems. TP: turned pile, SAP: static aerated pile and TP: turned aerated pile.

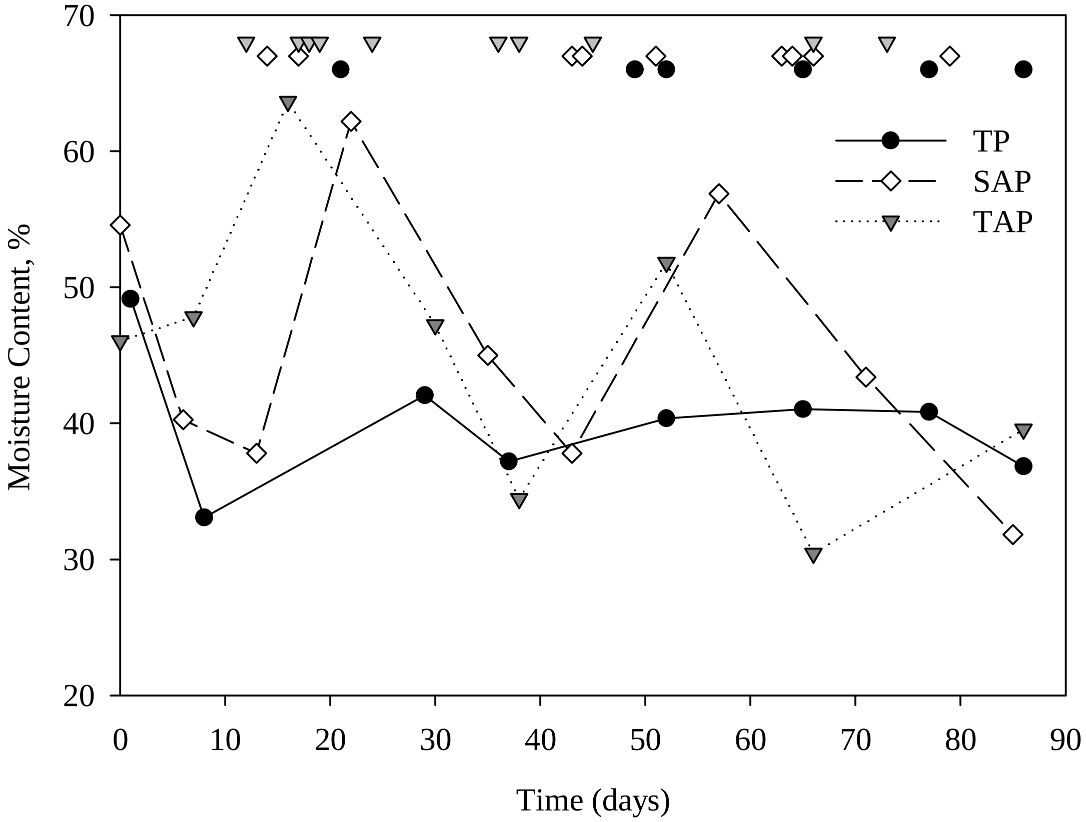
Fig. 6. Evolution of maturity grade for the three studied composting systems. TP: turned pile, SAP: static aerated pile and TP: turned aerated pile.

Fig. 1.



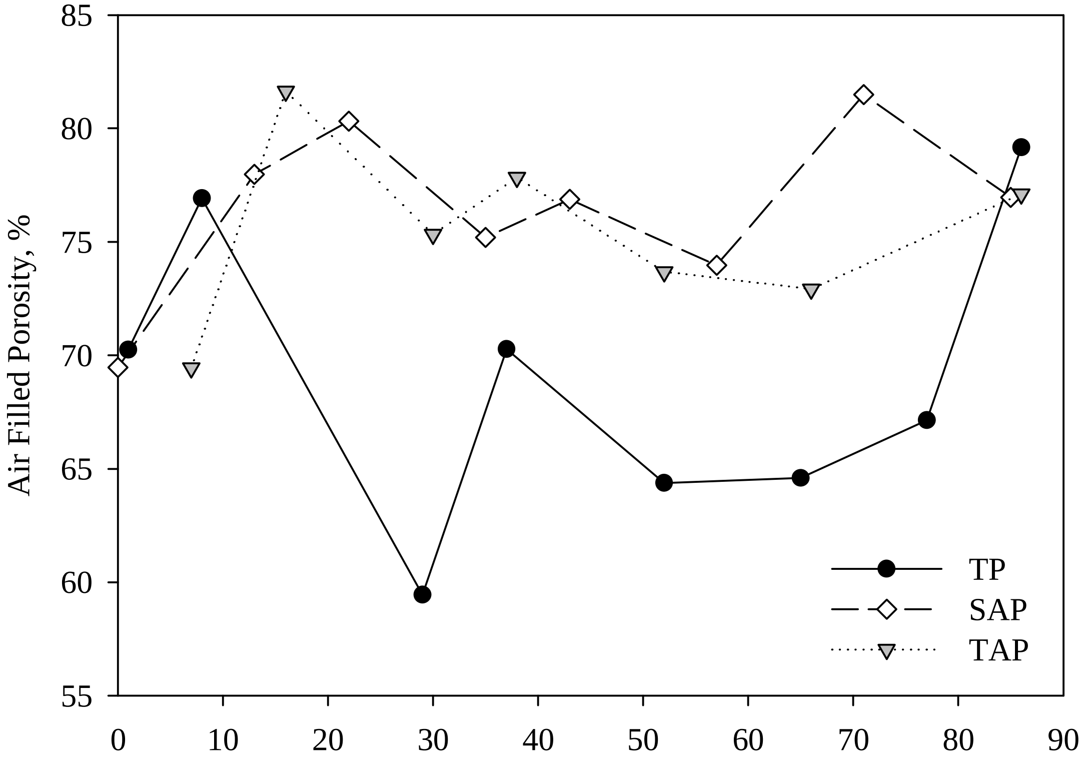
TP
SAP
TAP
Oxygen Content, %
0
5
10
15
20
25
Time (days)
0
10
20
30
40
50
60
70
80
90

Fig. 2.



Moisture Content, %
70
60
50
40
30
20
0
10
20
30
40
50
60
70
80
90
Time (days)
TP
SAP
TAP

Fig. 3.



85
80
75
70
65
60
55
Air Filled Porosity, %
0
10
20
30
40
50
60
70
80
90
TP
SAP
TAP

Fig. 4.

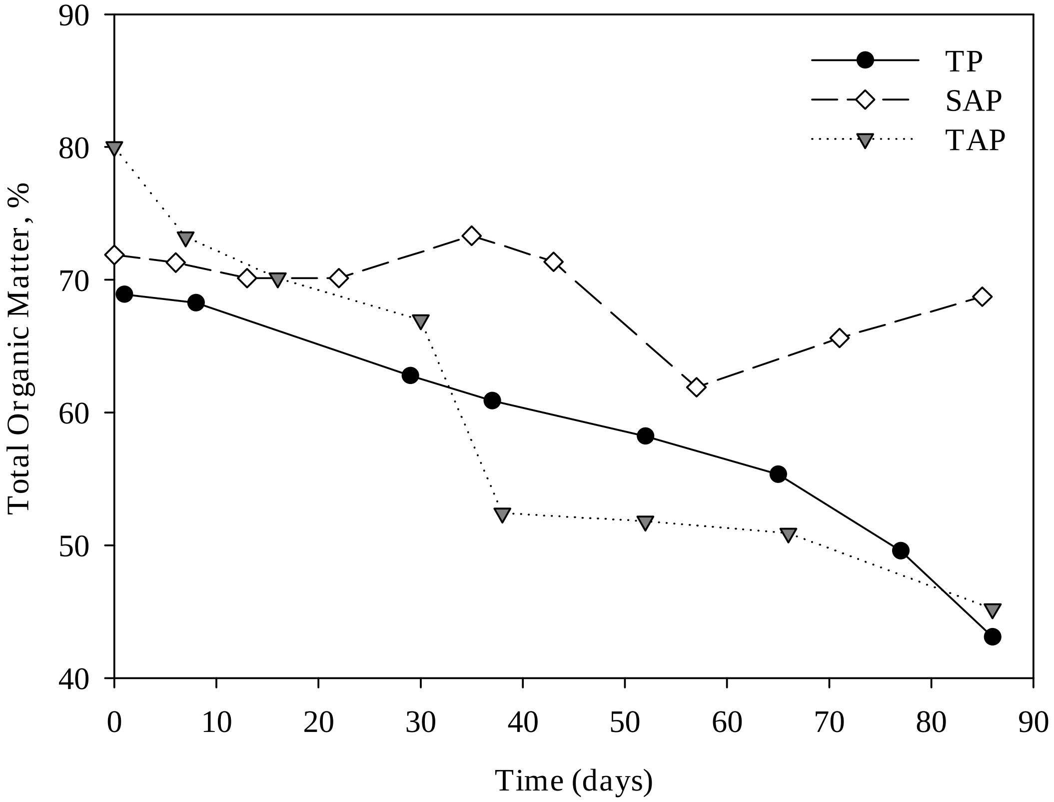

TP
SAP
TAP
Total Organic Matter, %
90
80
70
60
50
40
0
10
20
30
40
50
60
70
80
90
Time (days)

Fig. 5.

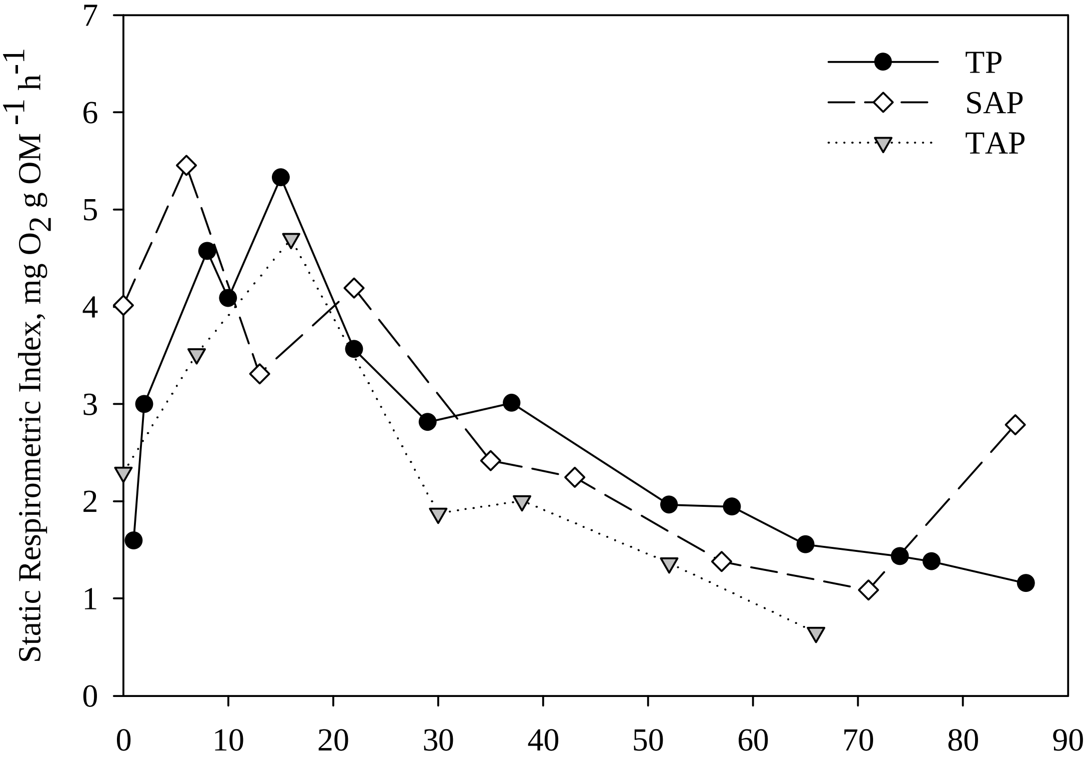
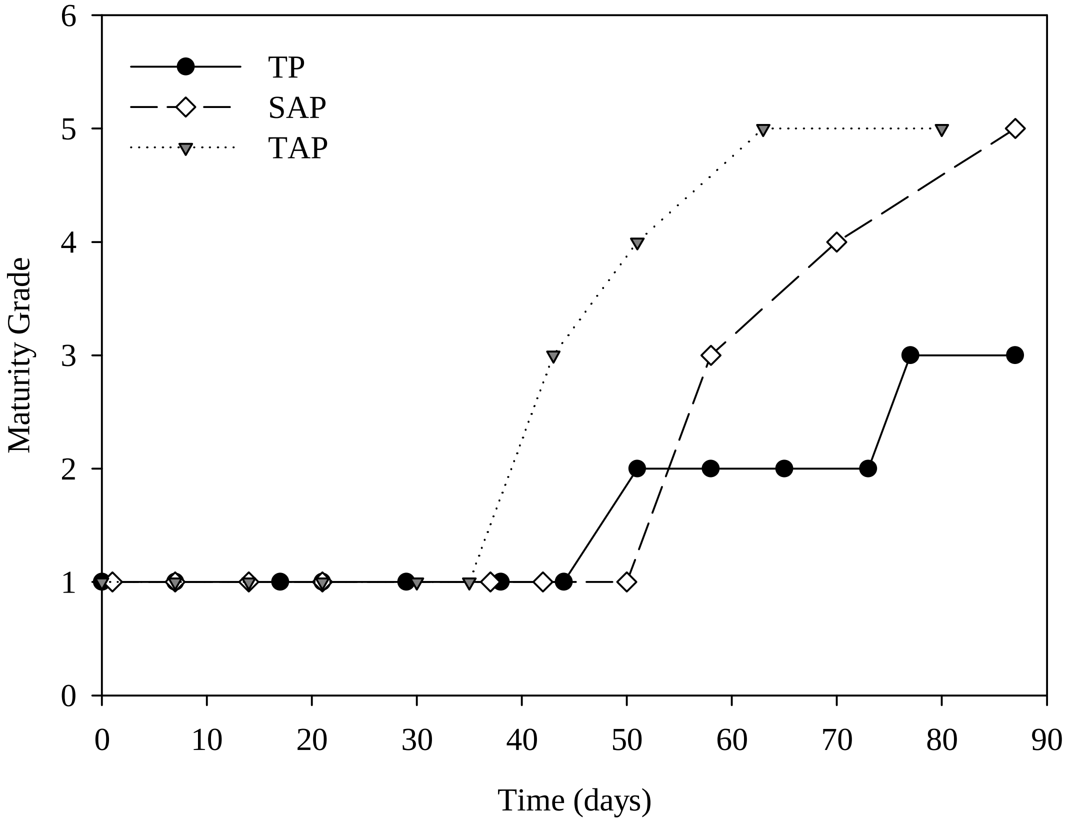

TP
SAP
TAP
Static Respirometric Index, mg O2 g OM -1 h-1
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
70
80
90

Fig. 6.


TP
SAP
TAP
Maturity Grade
Time (days)
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
90