LIFE Project Number

<**LIFE05 TCY/MA/000141**>

FULL PROJECT TITLE

# ‘Design and Application of an Innovative Composting Unit for the Effective Treatment of Sludge and other Biodegradable Organic Waste in Morocco, MOROCOMP’

**Task 6:**

**Development of guidelines and specifications covering the sludge composting process - Characterization and use of compost as soil improver**

**Deliverable 18A**

## Report on the optimum operating conditions for the composting unit

**July 2008**

## 1. Introduction

The bioreactor accelerates the decomposition and stabilization of organic waste. The composting bioreactor is an in-vessel unit in which the biochemical processes, which involve organisms or biochemically active substances derived from such organisms, are carried out. The design of a bioreactor is quite a complex engineering task. Under optimum conditions the micro-organisms or cells will reproduce at an outstanding rate. The in-vessel's environmental conditions like gases (i.e., air, oxygen, nitrogen, carbon dioxide), temperature, pH and oxygen content levels, and agitation speed need to be closely monitored and controlled [1,2,3,4]. The determination of the optimal course of composting is assessed through the means of experiments. Therefore the selection of the experimental set-up is of crucial importance in the process of composting optimization. Each experimental set-up is linked to a particular application and has its limitations. It is useful to optimize the parameters which have to be adjusted during substrate pre-treatment and composting, with the exception of particle size and temperature, and to reduce the number of variants which have to be investigated in greater detail in experiments. As all regulation possibilities such as aeration, hydration, agitation can be simulated with the technical scale set-up, their complex cooperation can be taken into consideration. Encouraging composting variants can be tested, compared and optimized [5,6,7,8,9].

This report aims to optimize sludge composting and co-composting processes using various waste streams and to optimise the operation of the system.

To determine the optimal course of composting four different composting trials have been performed using a variety of waste such as primary sludge from the UWWTP of El Jadida city in Morocco, secondary sludge from food industry, sugar beet leaves, straw residues, sheep and cow manures in various ratios and under different operational conditions. Composting trials have also been performed using effective additives such as zeolite and perlite for the treatment of the aforementioned waste in order to promote composting without getting involved in the biodegradation process. The selection of the experimental set-up was determined according to the feedstock material and its characteristics while at the end of each trial valuable feedback was obtained for the

optimization of the next composting trials. The temperature, moisture and oxygen content of the substrate was closely monitored on a daily bases during composting while for the evaluation of the processes complete physicochemical analyses have been performed (i) to the raw material that was used as feedstock to the in-vessel composting bioreactor (ii) to the leachates generated during composting (iii) to the substrate throughout the duration of the composting processes and finally (iv) to the derived product resulting from each composting trial.
Deliverable 13 of the MOROCOMP project presented in detail the factors affecting the composting process, the methodology and experimental procedures, the methods for sampling and analysis, the results obtained and their evaluation and the evaluation of the produced composts.

The present work will show the obtained controlled operational parameters for the optimisation of the composting process for each trial but prior to this a brief overview of the composting trials and their composition is presented.

**Composting trials and their composition**

Table 1 presents the composting trials (four in total) and their composition of the feeding material used for each run. For the 1$^{st}$ trial, primary sludge was used with sugar beet leaves (the ratio being approximately 1:1). No secondary sludge was available in the area of El Jadida, while sugar beet leaves are found in excessive amounts since sugar beet along with wheat are the primary cultivations that are being practiced in Doukkala region. For the 2$^{nd}$ trial primary sludge, sheep manure, sugar beet leaves and straw have been used. These materials are characterized as BOW. All the above organic waste is found in abundance in the area. For the 3$^{rd}$ trial, primary sludge and cow manure were used as organic waste and zeolite as an additive. The role of additives is to assist the composting process without partcipating in the biodegradation process. They usually increase the void volume of substrate and thus better aeration and hydration is achieved. For the 4$^{th}$ trial, secondary sludge from a private food industry and perlite as additive were used. The above combinations are mainly based on the different waste streams that are found in abundance in the area.

**Table 1: The physicochemical characteristics and the quantity of the raw material used in each composting trial**

| | 1st Trial | | 2nd Trial | | | | 3rd Trial | | | 4th Trial |
|---|---|---|---|---|---|---|---|---|---|---|
| Parameter | Primary sludge [700kg] | Sugar beet leaves [650kg] | Primary sludge [520kg] | Sheep Manure [250kg] | Sugar beet leaves [490kg] | Straw [50kg] | Primary sludge [700kg] | Cow Manure [180kg] | Sugar beet leaves [450kg] | Secondary sludge [1500kg] |
| Dry Solids (%) | 27.8 | 51.65 | 32.16 | 84.37 | 53.74 | 90.27 | 31.3 | 92.56 | 52.10 | 21.45 |
| pH | 6.8 | 7.1 | 6.3 | 8.5 | 7.2 | 7.1 | 6.5 | 9.2 | 7.1 | 5.7 |
| Total C (% d.s) | 10.5 | 59.94 | 11.03 | 47.71 | 58.60 | 59.08 | 12.6 | 45.43 | 61.50 | 46.32 |
| Total N (% d.s) | 1.76 | 3.52 | 1.91 | 2.83 | 3.43 | 0.94 | 1.65 | 2.65 | 3.48 | 5.74 |
| C/N ratio | 5.97 | 17.03 | 5.77 | 16.86 | 17.08 | 62.85 | 7.64 | 17.14 | 17.67 | 8.07 |
| Total P as $P_2O_5$ (% d.s) | 1.300 | 0.240 | 1.3942 | 0.9310 | 0.2470 | 0.1721 | 1.0715 | 0.5620 | 0.2605 | 3.68 |
| K as $K_2O$ (% d.s) | 0.691 | 3.524 | 0.9670 | 4.2683 | 3.4673 | 1.9890 | 0.8540 | 3.7545 | 3.5878 | 0.46 |
| Ca as CaO (% of d.s) | 4.873 | 3.387 | 4.5235 | 6.8071 | 3.4418 | 1.1122 | 4.2507 | 6.9176 | 3.6205 | 4.13 |
| Mg as MgO (% of d.s) | 2.339 | 1.381 | 2.2073 | 1.7388 | 1.5807 | 0.5666 | 2.0860 | 1.2601 | 1.5463 | 0.82 |
| Cd (mg/Kg d.s) | 0.986 | 0.113 | 0.8218 | 0.5937 | 0.1590 | 0.1305 | 1.1731 | 0.7858 | 0.1022 | 0.4820 |
| Cr (mg/Kg d.s) | 18.410 | 0.828 | 25.2105 | 10.4570 | 0.5719 | 0.6012 | 21.6286 | 13.8386 | 0.8056 | 12.9371 |
| Cu (mg/Kg d.s) | 141.471 | 7.924 | 135.2713 | 17.3205 | 12.2520 | 6.6361 | 175.3108 | 24.65726 | 13.414 | 98.3961 |
| Ni (mg/Kg d.s) | 24.305 | 0.895 | 26.9106 | 11.1481 | 0.9365 | 1.0037 | 31.4635 | 16.0901 | 1.3201 | 9.7721 |
| Pb (mg/Kg d.s) | 81.094 | 0.504 | 63.3828 | 2.8133 | 0.3043 | 0.3260 | 91.6719 | 2.17552 | 0.3830 | 21.9202 |
| Zn (mg/Kg d.s) | 237.894 | 48.916 | 251.8231 | 34.8637 | 31.9314 | 23.909 | 225.5545 | 45.4673 | 36.5834 | 593.7208 |

## 2. Composting process control

Composting process control involves all the actions that had been planned and carried out with respect to the operational conditions of the in-vessel bioreactor.

### 2.1 Programming the plc of the in-vessel bioreactor

The operation of the agitation, hydration and aeration systems is being performed by the PLC (Programming Logic Controller) automatic control system. These operations can also be performed manually.

- Programming the frequency and duration of the substrate's <u>agitation</u>:

The electric monitor can operate X times per day for a duration of Y minutes per hour. The maximum set values are Xmax = 12 times/day and Ymax = 15 minutes while the minimum ones are Xmin = 0 times/day and Ymin = 0 minutes.

- Programming the frequency and duration of the substrate's <u>aeration</u>:

The ventilator system can operate X times per day for a duration of Y minutes per hour. The maximum set values are Xmax = 24 times/day and Ymax = 10 minutes while the minimum ones are Xmin = 0 times/day and Ymin = 0 minutes.

- Programming the frequency and duration of the substrate's <u>hydration</u>:

The hydration system can operate X times per day for a duration of Y minutes per hour. The maximum set values are Xmax = 2 times/day and Ymax = 15 minutes while the minimum ones are Xmin = 0 times/day and Ymin = 0 minutes

The specifications of each composting trial are given below:

- <u>1st trial:</u>

The operation of the agitation, hydration and aeration systems was performed by the PLC automatic control system. These operations can also be performed manually. The programming of each operation during the 1$^{st}$ composting trial is given below:

✓ Programming the frequency and duration of the substrate's agitation:

The motor was set to operate 3 times per day (every 8 hours) for 5 minutes each time for the agitation of the substrate.

✓ Programming the frequency and duration of the substrate's aeration:

The fan was programmed to operate 3 times per day (every 8 hours) for 5 minutes each time for the aeration of the substrate.

- ✓ Programming the frequency and duration of the substrate's hydration:

The hydration system operated manually during the 1st composting trial although it could be programmed to operate automatically. The substrate was subjected to hydration whenever it was considered appropriate according to its moisture content that had been recorded from the daily measurements. The duration of the hydration operation as well as the water flow were also adjusted according to the moisture content of the substrate that had been recorded from the daily measurements

- <u>2nd trial</u>

The operation of the agitation, hydration and aeration systems was performed by the PLC automatic control system. These operations can also be performed manually. The programming of each operation during the 2nd composting trial is given below:

- ✓ Programming the frequency and duration of the substrate's agitation:

The motor was programmed to operate 4 times per day (every 6 hours) for 5 minutes each time for the agitation of the substrate.

- ✓ Programming the frequency and duration of the substrate's aeration:

The fan was programmed to operate 4 times per day (every 6 hours) for 5 minutes each time.

- ✓ Programming the frequency and duration of the substrate's hydration:

The hydration system operated manually during the 2nd composting trial although it could be programmed to operate automatically. The substrate was subjected to hydration whenever it was considered appropriate according to its moisture content that had been recorded from the daily measurements. The duration of the hydration operation as well as the water flow were also adjusted according to the moisture content of the substrate that had been recorded from the daily measurements

- <u>3rd trial</u>

The operation of the agitation, hydration and aeration systems was performed by the PLC automatic control system. These operations can also be performed manually. The programming of each operation during the 3rd composting trial is given below:

- ✓ Programming the frequency and duration of the substrate's agitation:

For the first 10 days of the process the motor was set to operate 4 times per day (every 6 hours) for 5 minutes each time. For the next 7 days the motor was programmed to operate 3 times per day (every 8 hours) for 5 minutes each time and for the rest days of the process it operated 2 times per day (every 12 hours) for 5 minutes each time.

- ✓ Programming the frequency and duration of the substrate's aeration:

For the first 10 days of the process the fan was set to operate 4 times per day (every 6 hours) for 5 minutes each time. For the next 7 days the fan was programmed to operate 3 times per day (every 8 hours) for 5 minutes each time and for the rest days of the process it operated 2 times per day (every 12 hours) for 5 minutes each time.

- ✓ Programming the frequency and duration of the substrate's hydration:

The hydration system operated manually during the 3rd composting trial although it could be programmed to operate automatically. The substrate was subjected to hydration whenever it was considered appropriate according to its moisture content that had been recorded from the daily measurements. The duration of the hydration operation as well as the water flow were also adjusted according to the moisture content of the substrate that had been recorded from the daily measurements

- <u>4th trial</u>

The operation of the agitation, hydration and aeration systems was performed by the PLC automatic control system. These operations can also be performed manually. The programming of each operation during the 4th composting trial is given below:

- ✓ Programming the frequency and duration of the substrate's agitation:

For the first 8 days of the process the motor was set to operate 4 times per day (every 6 hours) for 5 minutes each time. For the next 7 days the motor was programmed to operate 3 times per day (every 8 hours) for 3 minutes each time and for the rest days of the process it operated 2 times per day (every 12 hours) for 2 minutes each time.

- ✓ Programming the frequency and duration of the substrate's aeration:

For the first 8 days of the process the fan was set to operate 4 times per day (every 6 hours) for 5 minutes each time. For the next 7 days the fan was programmed to operate 3 times per day (every 8 hours) for 3 minutes each time and for the rest days of the process it operated 2 times per day (every 12 hours) for 2 minutes each time.

- ✓ Programming the frequency and duration of the substrate's hydration:

The hydration system operated manually during the 4th composting trial although it could be programmed to operate automatically. The substrate was subjected to hydration whenever it was considered appropriate according to its moisture content that had been recorded from the daily measurements. The duration of the hydration operation as well as the water flow were also adjusted according to the moisture content of the substrate that had been recorded from the daily measurements

**2.2 Measurement and control of the temperature of the substrate**

Temperature is a very important factor that promotes the accelerated decomposition of organic material and for the development of optimum composting conditions. The temperature in composting process effects significantly the microbial communities and mass reduction of the substrate. Jing-Chun Tang, Atsushi Shibata, Qixing Zhou and Arata Katayama [10] suggest that mesophilic composting is more effective for mass reduction in cattle manure composting than thermophilic composting since the duration of the mesophilic phase is longer and thus the decomposition activity higher.

Heat exchange is needed to maintain the bioprocess at a constant temperature. Biological activity is a major source of heat, therefore in most cases water is added to control the temperature level in the bioreactors were the microbiological activity takes place. In our case the heat exchange in the bioreactor is achieved through the air suction system which sucks air from the bioreactor's interior and sends the gases to the bio-filter while at the same time fresh air is introduced into the substrate.

The temperature of the substrate was being measured at regular time intervals throughout the composting duration. For these measurements a microchip was used (DATA LOGGERS MODEL 100 2K). The device was installed in the interior of the bioreactor and was collected at the end of each composting trial and after the collection and removal of the end product. The recorded temperature values were obtained, using the software of the device. For comparison reasons and for the better understanding of the temperature profile during the composting processes, additional temperature measurements of the substrate have been performed using a portable thermometer. These temperature values were recorded once per day at the same point inside the bioreactor.

The specifications of each operation are given below:

- <u>1st trial</u>

In the process of composting, microorganisms break down organic matter and produce carbon dioxide, water, heat, and humus, the relatively stable organic end product. Under optimal conditions, composting proceeds through three phases which may have considerable overlap based on temperature gradients and differential temperature effects on microorganisms. These are 1) the mesophilic, or moderate-temperature phase, which lasts for a couple of days, 2) the thermophilic, or high-temperature phase, which can last from a few days to several weeks, and finally, 3) the cooling and maturation phase which results to the stabilisation of compost. Figure 1 presents the temperature evolution during the 1st composting trial. The temperature values are the mean values obtained from the temperature data loggers and the temperature probe.

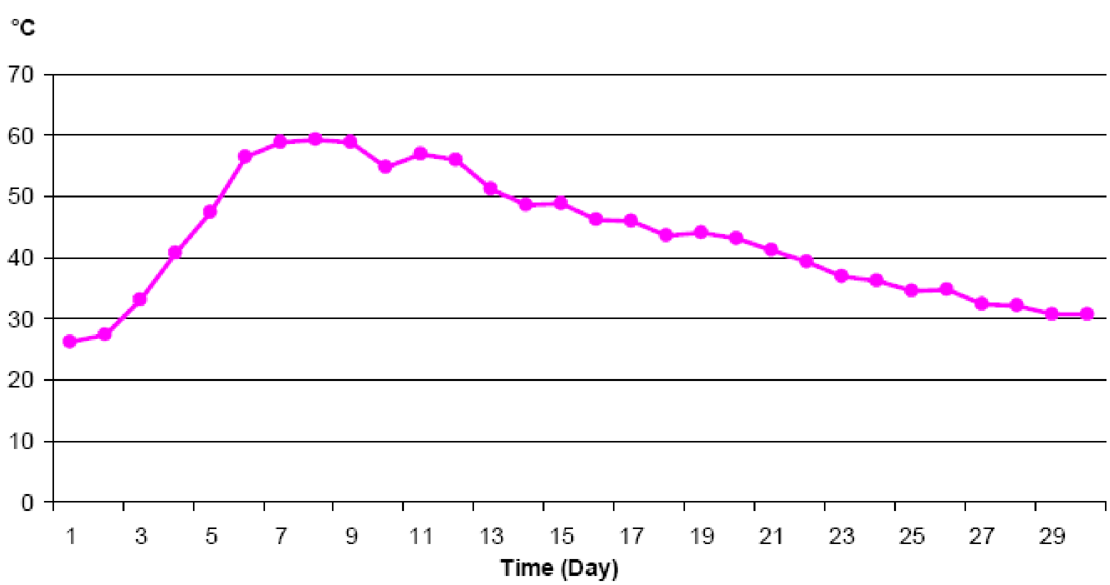

**Figure 1: Temperature profile during the 1$^{st}$ composting trial**

Temperature measurements during the 1$_{st}$ composting trial showed that the substrate passed from an initial mesophylic phase (<40°C) to a thermophylic stage approximately on the 4$_{th}$ day. The initial decomposition of the organic matter is carried out by mesophilic microorganisms, which rapidly break down the soluble, readily degradable compounds which are present in the primary sludge compounds. Microorganism activity releases large amounts of energy in the form of heat. This heat accumulates due to the self-insulating qualities of the compost material and causes the temperature to rise rapidly. As the temperature was rising above about 40°C, the mesophilic microorganisms become less competitive and were being replaced by others that are thermophilic, or heat-loving. Compared with the initial mesophilic phase, the degradation rates were higher during the thermophilic phase as it is shown by the elevated temperatures and the increased microbial activity compared to the mesophilic phase. During the thermophilic phase the maximum temperature was achieved on the 8$^{th}$ day which was approximately 60°C while elevated temperatures ranging from 55°C to 60°C remained in the mixture for 7 continuous days (6$^{th}$ to 12$^{th}$ day) which is sufficient time for the sterilisation of the substrate from potential pathogenic microorganisms. Only after all substrate, capable of promoting microbial activity, had been used up did the temperature begin to fall to reach a second mesophylic phase while the maturation process took place during this last stage of the process.

- 2$^{nd}$ trial

Figure 2 shows the temperature evolution during the 2$^{nd}$ composting trial.

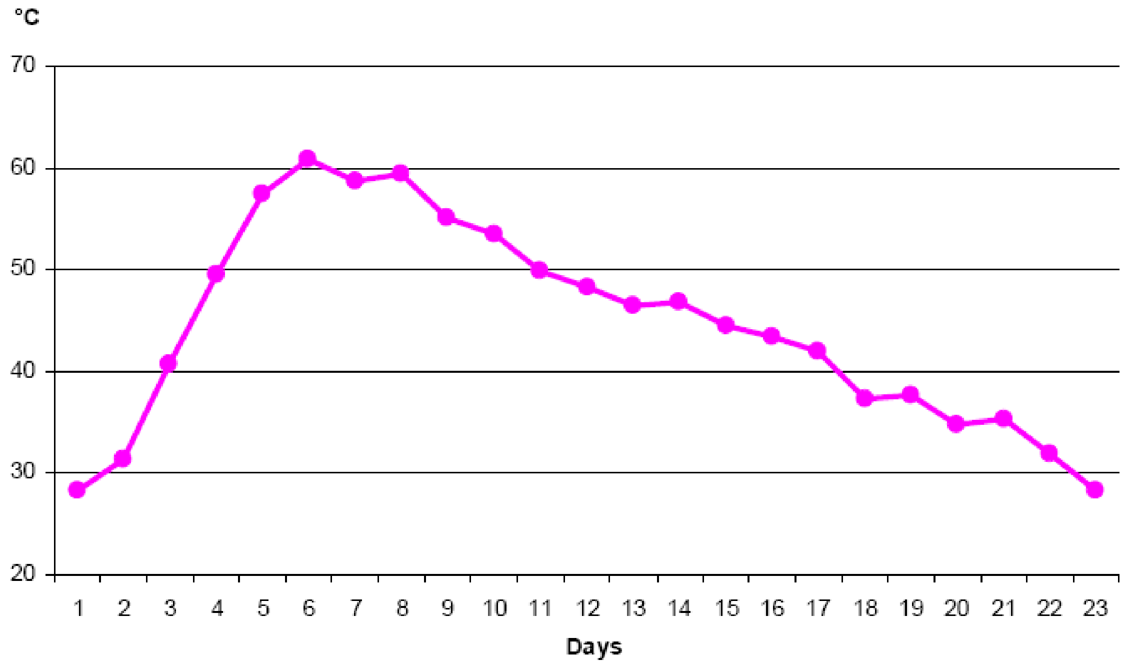


**Figure 2 Temperature profile during the 2nd composting trial**

According to Figure 2 the substrate passed from an initial mesophylic phase (<40°C) to a thermophylic stage after the 3rd day of the initiation of the composting process. Due to the early decomposition of the soluble, readily degradable compounds which are present mainly at the primary sludge compounds, large amounts of heat were released and caused the temperature to rise rapidly and reached to a maximum of 60.9°C on the 6th day. Elevated temperatures (>50°C) were maintained in the bioreactor for eight continuous days (4th to 11th day) which is sufficient time for the sterilisation of the substrate from potential pathogenic microorganisms that exist in the composting material. Only after all substrate, capable of promoting microbial activity, had been used up did the temperature begin to fall to reach a second mesophylic phase on the 17th day of the process while the maturation process took place during this last stage of composting.

- <u>3rd trial</u>

Figure 3 presents the temperature evolution in the 3rd composting trial as has been recorded.

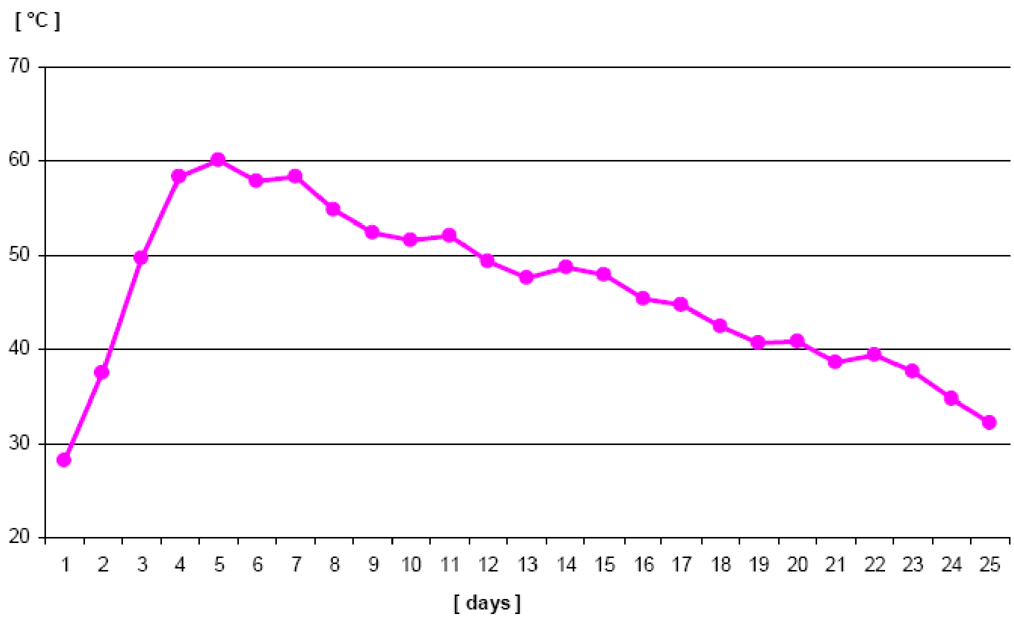


**Figure 3: Temperature profile during the 3rd composting trial**

According to Figure 3 the substrate passed from an initial mesophylic phase (<40°C) to a thermophylic stage after the 2nd day of the initiation of the composting process. The rate of processing in a biochemical system is directly proportional to the increase of temperature. Microbial activity during the 3rd composting process released large amounts of heat which accumulated due to the initial fast decomposition of the soluble, readily degradable compounds (present mainly at the primary sludge compounds and cow manure) and due to the self-insulating qualities of the compost material the temperature rose rapidly and to reached to a maximum of 60.1°C on the 5th day. Elevated temperatures (>50°C) are maintained within the bioreactor for 9 continuous days (3rd to 11th day) which is sufficient time for the sterilisation of the substrate from potential pathogenic microorganisms that exist in the composting material. Only after all substrate, capable of promoting microbial activity, had been used up did the temperature begin to fall to reach a second mesophylic phase on the 21st day of the process while the maturation process took place during this last stage of composting.

- <u>4th trial</u>

Figure 4 presents the temperature evolution in the 4$^{th}$ composting trial as has been recorded.

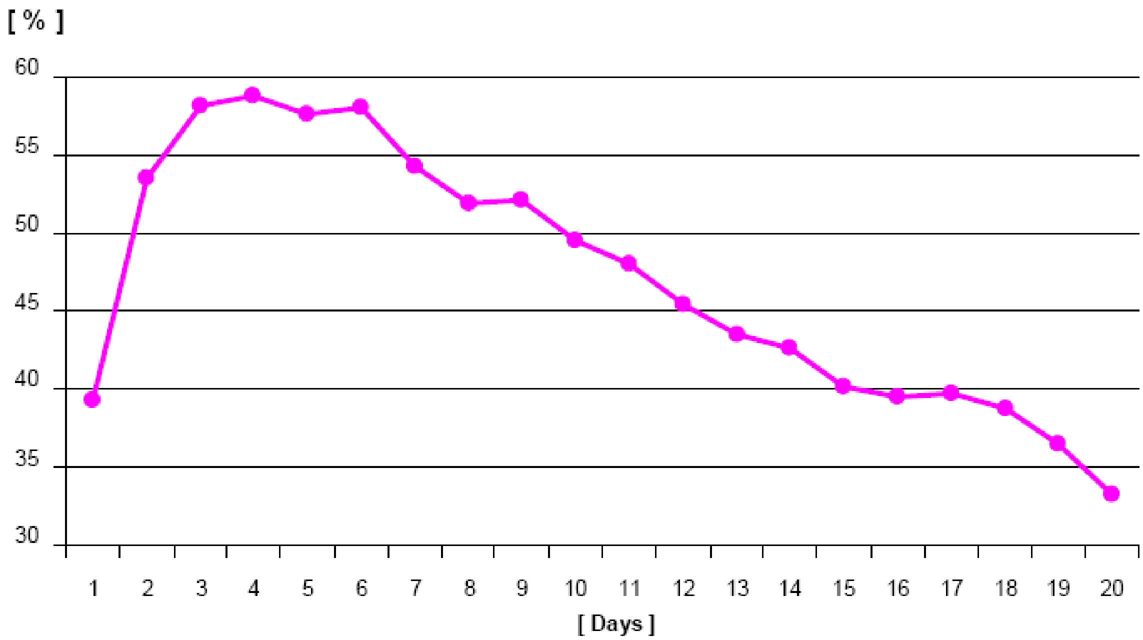


**Figure 4: Temperature profile during the 4th composting trial**

According to Figure 4 the substrate passed from an initial mesophylic phase (<40°C) to a thermophylic stage after the 1$_{st}$ day of the initiation of the composting process. Due to the initial fast decomposition of the soluble, readily degradable compounds present at the secondary sludge and due to the self-insulating qualities of the compost material the temperature of the substrate rose rapidly and reach to a maximum of 58.8°C on the 4$_{th}$ day. Elevated temperatures (>50°C) were maintained within the bioreactor for 8 continuous days (2$^{nd}$ to 9$^{th}$ day) which is sufficient time for the sanitization of biosolids from potential pathogenic microorganisms that exist in the composting material. Only after all substrate, capable of promoting microbial activity, had been used up did the temperature begin to fall to reach a second mesophylic phase on the 15$^{th}$ day of the process while the maturation process took place during this last stage of composting.

### 2.3 Measuring and control the moisture of the substrate

Moisture content is the single most important factor that promotes the accelerated decomposition. The bioreactor technology relies on maintaining optimal moisture content near field capacity (approximately 35 to 65%) and adds water when it is necessary to maintain that percentage [1,7,11]. The moisture content of compost varies depending on the porosity of the reactor feed, free air space, aeration-oxygen, temperature, and other related physical factors.. Moisture is essential for all living organisms since it supports their metabolic processes while water is the medium for the chemical reactions, transportation of nutrients and allows the microorganisms to move about. Most microorganisms are very sensitive to this factor in their environment. When the moisture content of an actively composting mixture falls between 35% and 40% of the total weight, decomposition rates decelerate significantly as microbes are less able to carry out their metabolic activities; below 30% they essentially stop. On the other hand, moisture level higher than 60% can quickly lead to anaerobic conditions and foul-smelling as water fills the pore spaces of the organic mixture impeding oxygen diffusion through the composting material. This leaves no room for air, a condition that is not favorable for aerobic microorganisms. For most compost mixtures, 55% to 60% is the recommended upper limit for moisture content while the optimum value is between 40 to 65% of the total weight of the composting material.

The moisture level was being recorded once per day for the duration of the composting process. Six same weighted and representative samples were being selected daily from inside the bioreactor. The final sample was formed after stirring and mixing the six samples together to form a homogeneous material. From the homogeneous material six separate samples were selected weighted and dried at 105°C for 12hrs. The dried samples were then placed inside a desiccator for cooling and weighting. The moisture content was evaluated from the average value of the six separate samples. The specifications of each operation are given below:

- 1$^{st}$ trial

Figure 5 presents the moisture evolution during the 1$^{st}$ composting trial.

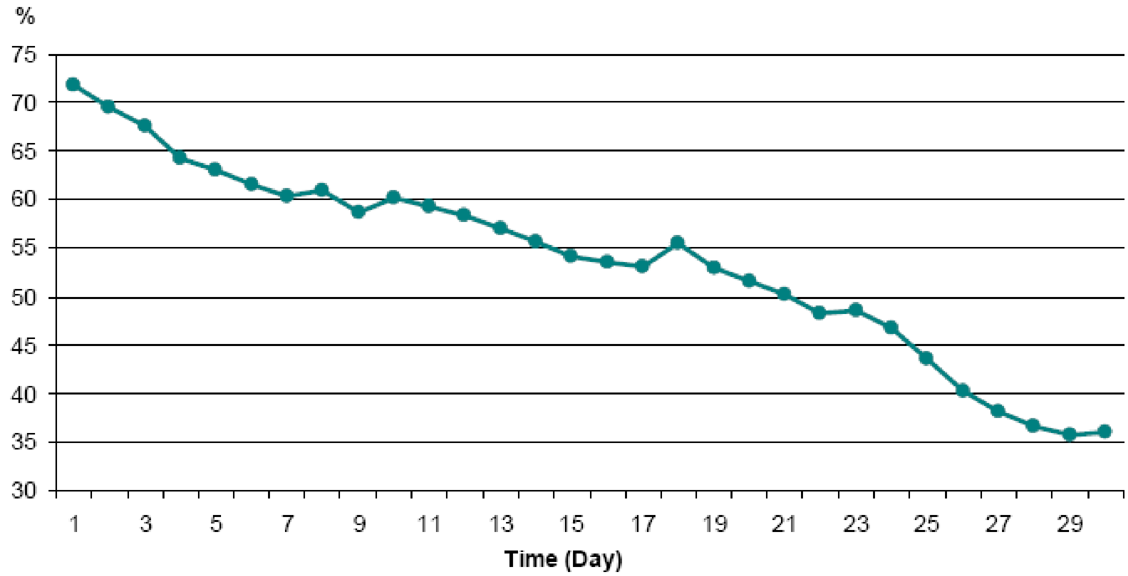


**Figure 5: Moisture content profile during the 1st composting trial**

From the results obtained for the 1st composting trial, the initial substrate appeared to have increased moisture content (71.8%) which was steadily reduced due to the initial decomposition of the readily degradable organic matter carried out by mesophilic microorganisms. After the 8th day of the process the moisture content had fallen less than 60%. This level of moisture content in conjunction to sufficient agitation and oxygen supply of the substrate enhanced the metabolic activities of microbes and led rapidly to higher temperature values. Elevated temperature values (thermophilic phase) reduced even more the moisture content due to water evaporation which at the end of the composting process, on the 30th day, was at 36.1%. Low water level reduces the intensive microbiological activity. Also at the same time reduces the transportation costs of compost, so it is required to have low water content when the compost is mature. It is worth mentioning that spontaneous water content increases were recorded during the composting process on the 8th, 10th, 18th and 23rd day due to the hydration of the substrate in order to maintain moisture at desirable levels.

- <u>2nd trial</u>

Figure 6 shows the moisture content evolution during the 2nd composting trial.

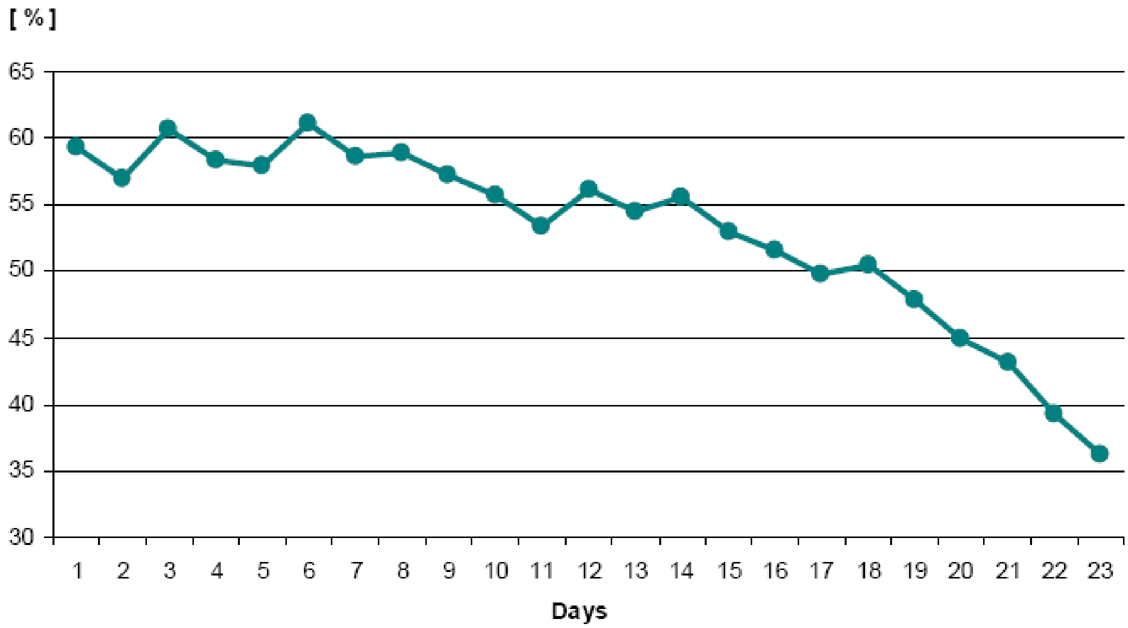


**Figure 6: Moisture content profile during the 2nd composting trial**

According to Figure 6, the initial mixture of the 2nd composting trial had a moisture level of 59.3%. The moisture content was sustained at optimal levels around 50 to 60% for the first 18th days of the process due to the hydration of the substrate and its sufficient agitation and aeration. At the final stage of composting the water quantity was gradually decreased reaching at 36.2% at the final day of the process on the 23rd day.

- <u>3rd trial</u>

Figure 7 presents the moisture evolution in the 3rd composting trial as has been recorded.

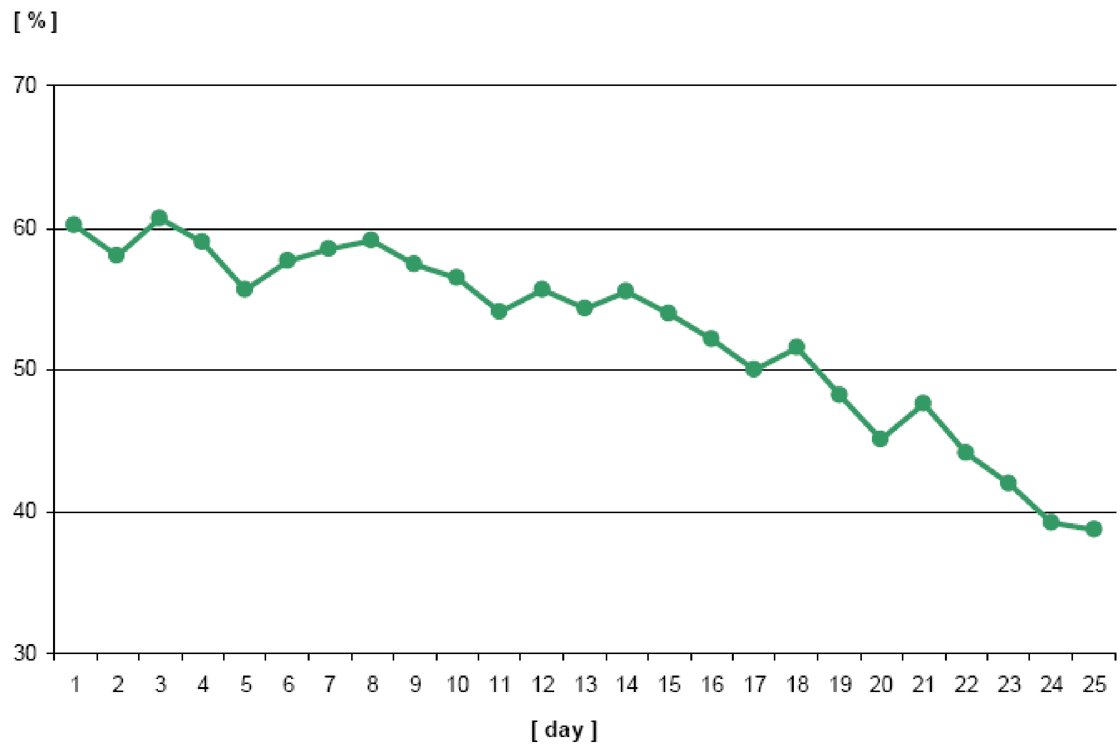


**Figure 7: Moisture content profile during the 3rd composting trial**

From the results obtained, the initial substrate had a moisture content of 60.2% which is within the optimal range as stated above. The presence of readily degradable organic matter in conjunction to sufficient substrate's agitation and oxygen supply enhanced the metabolic activities microbes and caused the temperature to rise, leading to moisture content reduction as composting was developing. The moisture content was sustained at optimal levels around 40% to 60% throughout the duration of the 3rd composting trial due to the manual hydration of the substrate and its sufficient agitation and aeration. At the final stage of composting the water quantity was decreased reaching 38.8% at the final day of the process.

- <u>4th trial</u>

Figure 8 presents the moisture evolution in the 4th composting trial as has been recorded.

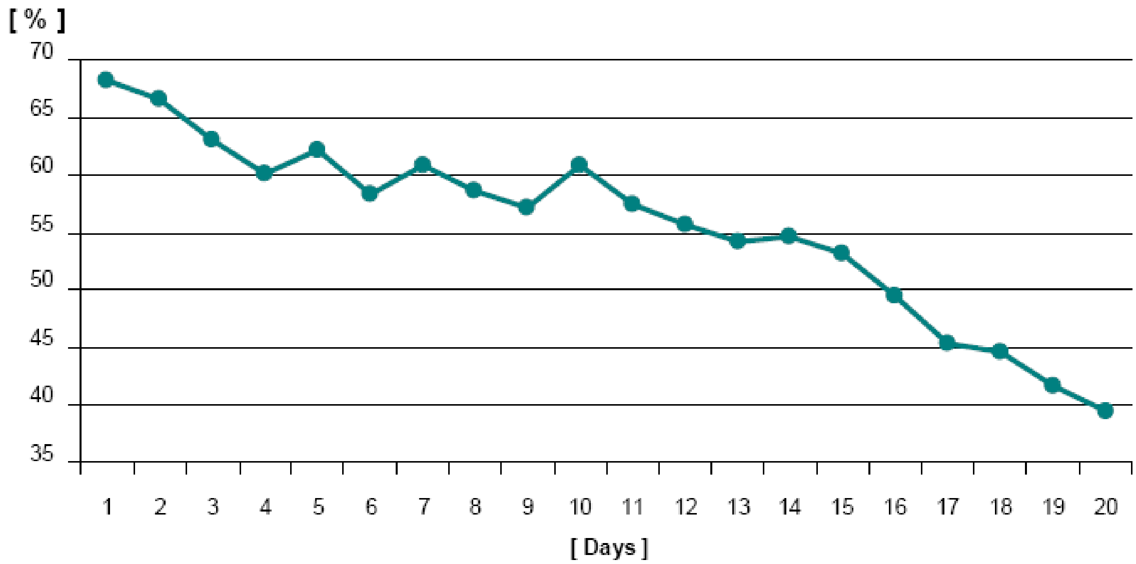


**Figure 8: Moisture content profile during the 4th composting trial**

According to Figure 8 the initial substrate had a moisture content of 68.2% since secondary sludge that was used as primary raw material did not undergo dewatering. The presence of readily degradable organic matter present in sludge, in conjunction to sufficient substrate's agitation and oxygen supply enhanced the metabolic activities of microbes and caused the temperature to rise rapidly leading to moisture content reduction at the initial stage of the process. The moisture content was sustained at high levels for the majority of the composting process due to the manual hydration of the substrate. The water quantity in the substrate kept decreasing throughout the duration of the trial reaching at 39.5% at the final day of the process on the 20th day.

### 2.4 Measuring the oxygen content of the substrate

Air is injected into the waste mass to promote aerobic activity and accelerate waste stabilization. Optimal oxygen transfer is needed to give satisfactory results in terms of process control, quality of end-product, low energy consumption, and hygienization of compost. Rafaela Cáceres, Xavier Flotats and Oriol Marfà [12] state that the different aeration strategies have a clear effect on the evolution of pH, electrical conductivity (EC), nitrate-N, ammonia-N and bicarbonate content. They also state that nitrification is favored under good aeration conditions, probably due to the greater availability of ammonia-N that is transformed into nitrate-N. Optimal oxygen transfer is perhaps the most difficult task to accomplish. Oxygen transfer is enhanced through agitation, which is needed to mix nutrients and to keep the substrate homogeneous. There are however limitations to the speed of agitation, due to the high power consumption (that's proportional to the cube of the speed) and the damage to organisms (excessive tip speed). In our case air is injected into the waste mass, using a fan system. Ventilation was controlled in order to maintain the $O_2$ level in the internal atmosphere of the composting mass between 15 and 20% [13].

The oxygen level was being recorded once per day for the duration of the composting process. The measurements were being recorded using a portable oxygen meter (model OA 2) and setting the device at the same point inside the bioreactor. The specifications of each operation are given below:

- 1$^{st}$ trial

The in-vessel composting system was designed to operate in aerobic conditions during which the decomposition of the organic matter takes place in the presence of oxygen. Oxygen is an essential ingredient for successful composting since microorganisms oxidize carbon for energy emitting carbon dioxide. Therefore the ventilation of the substrate is a very basic parameter of the composting process since it concerns bio-oxidation processes of the organic substrate. Aeration has multiple functions (i) it provides sufficient oxygen to the compost mixture, (ii) it controls the systems temperature and (iii) it removes moisture as well as $CO_2$ and other gases resulting in a more efficient compost process. The air supply contributes significantly to lowering the substrate's moisture, since the moisture of sludge is high. Moisture content, temperature and aeration (oxygen supply) of compost are linked together since microbial activity and thus elevated temperatures require a certain level of moisture content without the compost material being too wet and heavy so that free air space will be sufficient between the particles for air to diffuse into it. Although composting process takes place even in low oxygen content (5%), oxygen concentrations greater than 10% are considered optimal for maintaining aerobic conditions and thus sustaining aerobic microbial activity

[14]. Figure 9 presents the oxygen evolution during the 1st composting trial. oxygen evolution during the 1st composting trial.

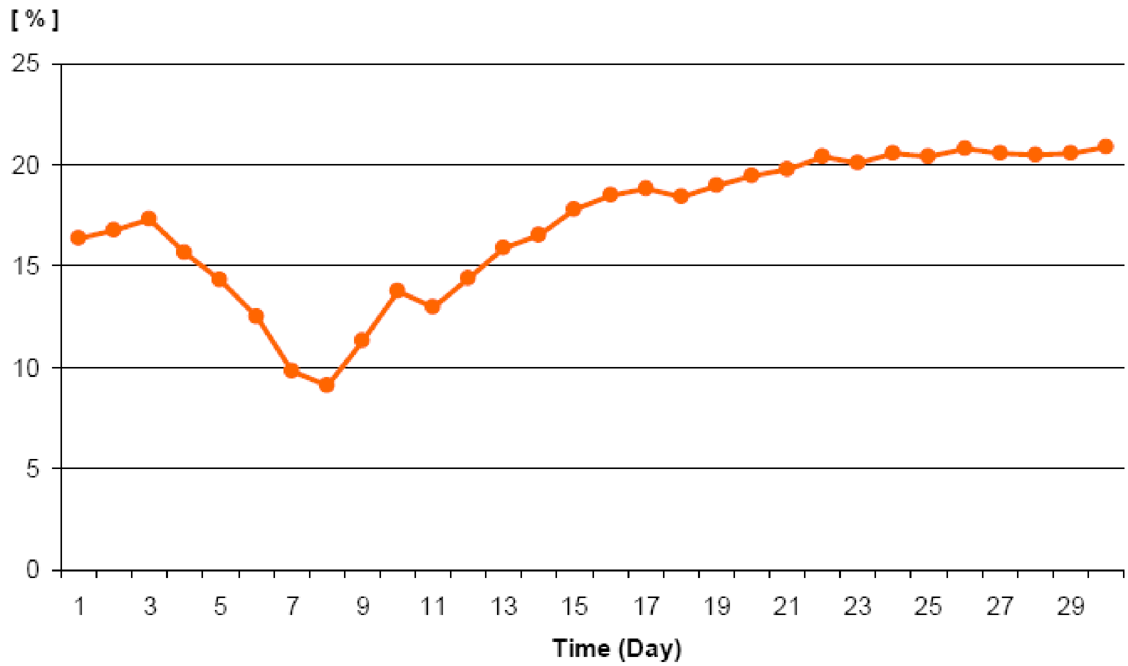


**Figure 9: Oxygen profile during the 1st composting trial**

According to Figure 9 the oxygen concentration of the substrate was maintained greater than 10% for the majority of the 1st composting trial duration. Furthermore an incremental tendency of oxygen concentration was achieved throughout the process indicating that the agitation and aeration of the substrate was sufficient in promoting aerobic conditions in the bioreactor. The lowest oxygen values just below 10% were observed during the thermophilic phase of composting due to the high oxygen demand for the oxidation of the available organic matter. In addition, at the latest stage of the process, the level of oxygen increased and exceeded the 20% on the 22nd day indicative of the low rate of organic matter decomposition since the oxygen nearly reached the atmospheric oxygen level. It must also be mentioned that the steep decrease of oxygen content on the 8th day of the process was due to the suspension of the agitation system operation which was caused by a malfunction to the bioreactor's motor which was restored immediately as explained below.

- <u>2nd trial</u>

Figure 10 presents the moisture evolution during the 2nd composting trial.

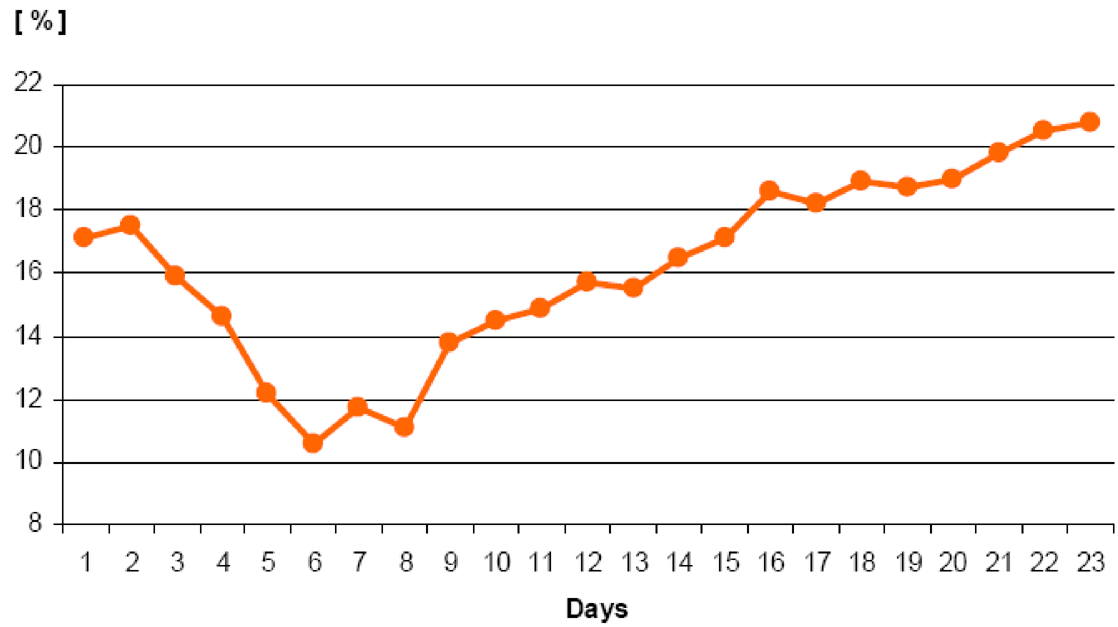


**Figure 10: Oxygen profile during the 2nd composting trial**

According to Figure 10 the oxygen concentration of the substrate was maintained higher than 10% throughout the duration of the 2nd composting trial. The lowest oxygen concentration values were recorded during the thermophilic composting phase due to the high microbial activity of aerobic micro-organisms which consume oxygen for the decomposition of the organic matter. The increased oxygen level and the incremental tendency of oxygen concentration during composting indicate that the agitation and thus the aeration of the substrate were sufficient in promoting aerobic conditions in the bioreactor. At the latest stage of the composting process the level of oxygen exceeded the 20% indicative of the low rate of organic matter decomposition since the concentration of oxygen nearly reached that of the atmosphere (21%).

- <u>3rd trial</u>

Figure 11 presents the moisture evolution during the 3rd composting trial.

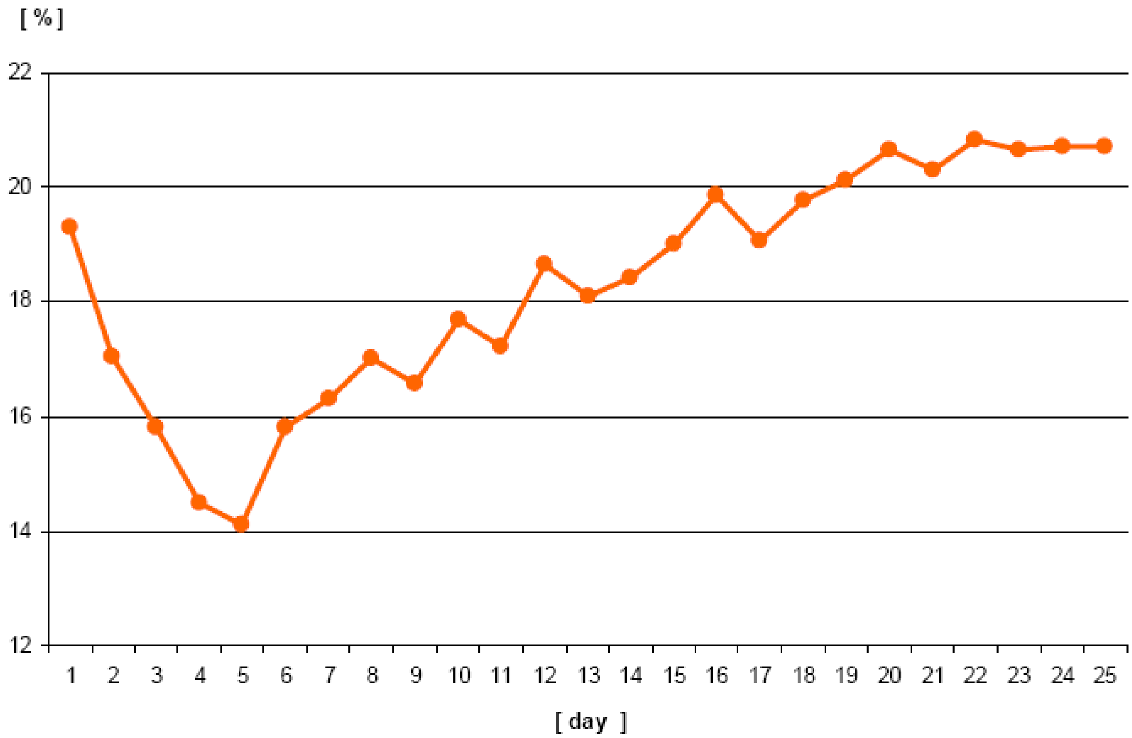


**Figure 11: Oxygen profile during the 3rd composting trial**

According to Figure 11 the oxygen concentration of the substrate was maintained higher than 14.0% throughout the duration of the 3rd composting trial. The lowest oxygen concentration values were recorded during elevated temperatures (3rd to 11th day) due to the high microbial activity of aerobic micro-organisms which consume oxygen for the decomposition of the organic matter. The increased oxygen level and the incremental tendency of oxygen concentration during composting indicate that the agitation and thus the aeration of the substrate were sufficient in promoting aerobic conditions in the bioreactor. At the latest stage of the composting process (19th day onwards) the level of oxygen maintained higher then 20.0% indicative of the low rate of organic matter decomposition since the concentration of oxygen nearly reached that of the atmosphere (21%).

- 4th trial

The readily degradable components of the raw materials are metabolised during the initial period of composting. Therefore the production of heat and the need for oxygen are greatest at the early stages and then steadily decrease. Without a constant supply of oxygen, the process will slow down and if there is insufficient oxygen, the process can become anaerobic. As has been mentioned composting process takes place even in low oxygen content (5%) however, oxygen concentrations greater than 10% are consider optimal for maintaining aerobic conditions and thus sustaining aerobic microbial activity. Figure 12 presents the moisture evolution during the 4th composting trial.

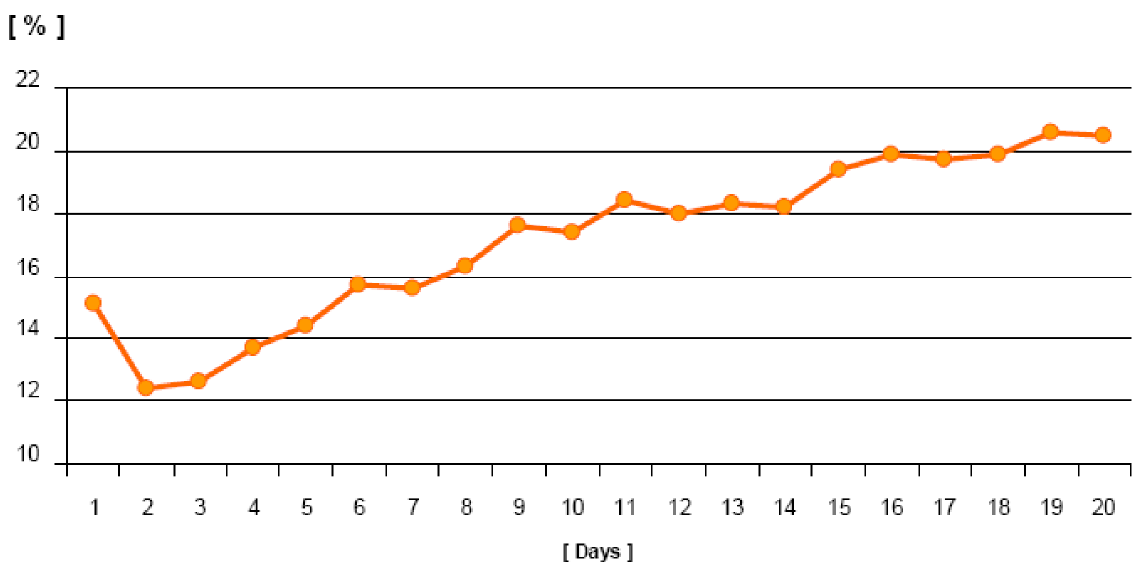


**Figure 12: Oxygen profile during the 4$^{th}$ composting trial**

According to Figure 12 the oxygen concentration of the substrate was maintained at high levels (>12.0%) throughout the duration of the 4$^{th}$ composting trial. The lowest oxygen concentration values were recorded during the thermophilic composting phase due to the high microbial activity of aerobic micro-organisms which consume oxygen for the decomposition of the organic matter. The increased oxygen level and the incremental tendency of oxygen concentration during composting indicate that the agitation, aeration and hydration of the substrate were sufficient in promoting aerobic conditions in the bioreactor. From the 14th day onwards the substrate passed to a second mesophilic phase in which the rate of oxygen demand was reduced whereas the oxygen content was maintained above 19% until the end of the process indicative of the low rate of the organic matter decomposition

## 2.5 Reprogramming the plc of the in-vessel bioreactor

The plc of the system was reprogrammed in case of suspending the in-vessel bioreactor operation due to potential malfunction. The reprogramming of the plc involved the adjustment of the agitation, hydration and aeration system settings that are performed by the PLC automatic control system.

The specifications of each operation are given below:

- <u>1$^{st}$ trial</u>

The agitation system operation was out of order on the 8$^{th}$ day of the composting process since a malfunction occurred to the bioreactor's motor and all the operations of the automated control system were suspended. At that time the aeration of the substrate was handled manually from the control panel. After the problem had been restored the operation of the bioreactor was reprogrammed and restarted.

- <u>2$^{nd}$ trial</u>

The plc of the in-vessel bioreactor was not reprogrammed during the 2nd composting trial.

- <u>3$^{rd}$ trial</u>

The plc of the in-vessel bioreactor was not reprogrammed during the 3$^{rd}$ composting trial.

- <u>4$^{th}$ trial</u>

The plc of the in-vessel bioreactor was not reprogrammed during the 4$^{th}$ composting trial.

## 2.6 Retention time:

It is worth mentioning that the four trials have exhibited good performance as far as composting retention time is concerned following the cycles/stages that are expected for composting processes e.g. mesophilic (1$^{st}$ stage), termophilic, mesophilic (2$^{nd}$ stage), normal conditions. From the results it is shown that the main composting process is nearly over within 15 to 18 days with the exception of the 1$^{st}$ trial. The rest of the time is mainly for the completion of the composting and could be performed outside the bioreactor and thus optimizing its use. The 4$^{th}$ trial, which included the treatment of secondary sludge and additives, followed the shortest cycle. The retention time were: for the 2nd trial 23 days, for the 3rd trial 25 days and for the 4th trial 20 days.

### 2.7 Monitoring and maintenance during composting

Throughout the duration of the composting process, for each trial, the electromechanical equipment and the rest of the bioreactor components and infrastructure were being monitored daily in order to maintain their operational status. The regular maintenance of all the electromechanical equipment of the system was performed according to the suggestions of the manufactures. In addition daily cleaning of the floor and surface of the bioreactor was performed in order to obtain high hygiene level for the personnel.

### 2.8 Disruption and start up of the bioreactor operation

This section describes potential disruptions that had been occurred during the composting trials with respect to the operation of the in-vessel bioreactor.

- 1st trial

The disruption of the in-vessel bioreactor operation on the 8th day involved only the operation of the agitation system of the bioreactor and that of the hydration system. The operation of the ventilation system was controlled so that the gases emitted during the process were being removed through the bioreactor's air suction system which disperses gases through an air-pipe to the bio-filter area[1] in order to prevent undesirable odours within the building where the bioreactor is installed.

- 2nd trial

No disruptions of the bioreactor's operation occurred during the 2nd composting trial which lasted for 23 days.

- 3rd trial

[1] the bio-filter bed was filled with the end product resulted from the 1st composting trial

No disruptions of the bioreactor's operation occurred during the 3$^{rd}$ composting trial which lasted for 25 days.

- 4$^{th}$ trial

No disruptions of the bioreactor's operation occurred during the 4$^{th}$ composting trial which lasted for 20 days.

### 2.9 Restoration of malfunctions and maintenance of the bioreactor

This section involves the actions that had been initiated to restore potential malfunctions during the composting trials. The specifications of each operation are given below:

- 1$^{st}$ trial

During the 8$^{th}$ day of the composting process a malfunction occurred to the motor of the in-vessel bioreactor. The chain providing motion to the revolving axle was broken. The revolving axle comprises of stirring elements responsible for the agitation of the substrate. The malfunction was restored and the bioreactor started to operate again on the 9$^{th}$ day of the composting process.

- 2$^{nd}$ trial

No malfunctions occurred during the 2$^{nd}$ composting trial.

- 3$^{rd}$ trial

No malfunctions occurred during the 3$^{rd}$ composting trial

- 4$^{th}$ trial

No malfunctions occurred during the 4$^{th}$ composting trial

## 3. Quality characteristics of the produced composts.

Table 2 shows the physicochemical characteristics of the composts according to which the quality of the produced compost was evaluated [14-17]. The carbon to nitrogen ratios (C:N) of the produced composts reflect to a good quality compost since they acquire ratios lower than 12 which is considered as a very good value for finished composts. The nutrients content for all trials indicates that the macro-elements quantity of composts is sufficient for agricultural applications while the ammonium to nitrates ratios ranging from 0.09 to 0.24 are within the suggested limits of fully mature composts. The analysis on heavy metals shows that their concentration is quite low within the suggested EU limits and that only a low percentage ranging from 1.4% to 6.2% of the various metals is available in dissolved forms. Finally the elevated temperatures that occur in all four trials lead to the elimination of the pathogenic microorganisms that are present in the raw material prior to the initiation of composting processes.

**Table 2: Physicochemical characteristics of composts produced from each composting trial**

| Parameter | Compost 1 | Compost 2 | Compost 3 | Compost 4 |
|---|---|---|---|---|
| Dry Solids (% d.s) | 63.9 | 63.8 | 61.2 | 60.5 |
| pH | 7.31 | 7.28 | 7.03 | 7.3 |
| Total Carbon (%) | 28.84 | 33.84 | 23.80 | 31.29 |
| Total Nitrogen (%) | 2.86 | 2.85 | 2.43 | 5.12 |
| C/N Ratio | 10.08 | 11.87 | 9.79 | 6.11 |
| $NO_{-3}$ - N ( mg/Kg d.w ) | 1286.48 | 998.43 | 388.12 | 3257.00 |
| $NH_{+4}$ - N ( mg/Kg d.w) | 302.62 | 207.73 | 38.65 | 304.10 |
| Total P as $P_2O_5$ (% d.s) | 0.7584 | 0.9264 | 0.79322 | 4.22515 |
| K as $K_2O$ (% d.s) | 3.0118 | 3.9505 | 3.21070 | 0.53814 |
| Ca as CaO (% d.s) | 4.7107 | 5.4785 | 5.74819 | 4.71073 |
| Mg as MgO (% d.s) | 2.1266 | 2.0931 | 2.02320 | 0.93060 |
| Cd (mg/Kg d.s) | 0.4739 | 0.59735 | 0.72949 | 0.54460 |
| Cr (mg/Kg d.s) | 8.1537 | 11.19308 | 13.51757 | 13.00632 |
| Cu (mg/Kg d.s) | 64.2264 | 54.17476 | 82.47363 | 110.93610 |
| Ni (mg/Kg d.s) | 10.8509 | 11.96504 | 17.38393 | 10.05946 |
| Pb (mg/Kg d.s) | 34.0357 | 20.03207 | 38.15530 | 25.83016 |
| Zn (mg/Kg d.s) | 132.8445 | 109.24231 | 118.22976 | 730.18767 |

## 4. Concluding Remarks

An extensive presentation of the experimental work in relation to the optimum operating conditions for the composting unit has been given in the previous sections. In this section the results are summarized and conclusions are drawn.

In Table 1 the composting trials (four in total) and their composition of the feeding material used for each run was shown. For the 1st trial, primary sludge was used with sugar beet leaves (the ratio being approximately 1:1). No secondary sludge was available in the area of El Jadida, while sugar beet leaves are found in excessive amounts since sugar beet along with wheat are the primary cultivations that are being practiced in Doukkala region. For the 2nd trial primary sludge, sheep manure, sugar beet leaves and straw have been used. These materials are characterized as BOW. All the above organic waste is found in abundance in the area. For the 3rd trial, primary sludge and cow manure were used as organic waste and zeolite as an additive. The role of additives is to assist the composting process without partcipating in the biodegradation process. They usually increase the void volume of substrate and thus better aeration and hydration is achieved. For the 4th trial, secondary sludge from a private food industry and perlite as additive was used. The above combinations are mainly based on the different waste streams that are found in abundance in the area.

The most important part of the work is to achieve the optimum operating conditions for the composting unit. Concluding remarks, for each of the controlled operating parameters, are given bellow:

- Programming the plc of the in-vessel bioreactor:

The operation of the agitation, hydration and aeration systems is being performed by the PLC (Programming Logic Controller) automatic control system.

- ✓ Programming the frequency and duration of the substrate's agitation:
  - *1st trial:* The motor was set to operate 3 times per day (every 8 hours) for 5 minutes each time for the agitation of the substrate.
  - *2nd trial:* The motor was programmed to operate 4 times per day (every 6 hours) for 5 minutes each time for the agitation of the substrate.
  - *3rd trial:* For the first 10 days of the process the motor was set to operate 4 times per day (every 6 hours) for 5 minutes each time. For the next 7 days the motor was programmed to operate 3 times per day (every 8 hours) for 5 minutes each time and for the rest days of the process it operated 2 times per day (every 12 hours) for 5 minutes each time.

- *4th trial:* For the first 8 days of the process the motor was set to operate 4 times per day (every 6 hours) for 5 minutes each time. For the next 7 days the motor was programmed to operate 3 times per day (every 8 hours) for 3 minutes each time and for the rest days of the process it operated 2 times per day (every 12 hours) for 2 minutes each time.

✓ Programming the frequency and duration of the substrate's aeration:

- *1st trial:* The fan was programmed to operate 3 times per day (every 8 hours) for 5 minutes each time for the aeration of the substrate.
- *2nd trial:* The fan was programmed to operate 4 times per day (every 6 hours) for 5 minutes each time.
- *3rd trial:* For the first 10 days of the process the fan was set to operate 4 times per day (every 6 hours) for 5 minutes each time. For the next 7 days the fan was programmed to operate 3 times per day (every 8 hours) for 5 minutes each time and for the rest days of the process it operated 2 times per day (every 12 hours) for 5 minutes each time.
- *4th trial:* For the first 8 days of the process the fan was set to operate 4 times per day (every 6 hours) for 5 minutes each time. For the next 7 days the fan was programmed to operate 3 times per day (every 8 hours) for 3 minutes each time and for the rest days of the process it operated 2 times per day (every 12 hours) for 2 minutes each time.

✓ Programming the frequency and duration of the substrate's hydration:

- The hydration system operated manually during the ***1st, 2nd, 3rd and 4th*** composting trials although it could be programmed to operate automatically. The substrate was subjected to hydration whenever it was considered appropriate according to its moisture content that had been recorded from the daily measurements. The duration of the hydration operation as well as the water flow were also adjusted according to the moisture content of the substrate that had been recorded from the daily measurements

- Reprogramming the plc of the in-vessel bioreactor:

The plc of the system was reprogrammed in case of suspending the in-vessel bioreactor operation due to potential malfunction. The reprogramming of the plc involved the adjustment of the agitation, hydration and aeration system settings that are performed by the PLC automatic control system.

- ✓ *1st trial:* The agitation system operation was out of order on the 8th day of the composting process since a malfunction occurred to the bioreactor's motor and all the operations of the automated control system were suspended. At that time the aeration of the substrate was handled manually from the control panel. After the problem had been restored the operation of the bioreactor was reprogrammed and restarted using the initial settings.
- ✓ *2nd trial, 3rd trial and 4th trial:* The plc of the in-vessel bioreactor was not reprogrammed during the composting.

The successful control of aeration, hydration and temperature were achieved by the control system that constitutes an essential component of the bioreactor.

- <u>Temperature:</u>

The temperature profiles of the composting processes developed very satisfactorily for all trials. Initially, a mesophilic temperature around 35°C was developed followed by the thermophilic area 50°C to 60°C, both indicating that the processes were being well developed. The moisture content initially varied significantly from trial to trial but during the process the moisture was controlled in order to be kept within the required values 50% to 60%.

- <u>Moisture:</u>

During the composting process moisture content, for all trials, maintained in optimal values, approximately 35 to 65%. The moisture content falls to lower values towards the end of the composting process.

- <u>Oxygen:</u>

For a successful composting process oxygen plays a very important role for the degradation and stabilization of the organic substrate under aerobic conditions. All trials were very successfully controlled by maintaining the oxygen content at high levels ensuring that adequate oxygen was being diffused within the mass of the substrate. For all trials the values were much above the 15% oxygen content for the much composting time.

- Retention time:

It is worth mentioning that the four trials have exhibited good performance as far as composting retention time is concerned following the cycles/stages that are expected for composting processes e.g. $1^{st}$ mesophilic stage, termophilic, $2^{nd}$ mesophilic statge, normal conditions. From the results it is shown that the main composting process is nearly over within 15 to 18 days with the exception of the $1^{st}$ trial. The rest of the time is mainly for the completion of the composting and could be performed outside the bioreactor and thus optimizing its use. The $4^{th}$ trial, which included the treatment of secondary sludge and additives, followed the shortest cycle. The retention time were: for the $2^{nd}$ trial 23 days, for the $3^{rd}$ trial 25 days and for the $4^{th}$ trial 20 days.

- Monitoring and maintenance during composting :

Throughout the duration of the composting process, for each trial, the electromechanical equipment and the rest of the bioreactor components and infrastructure were being monitored daily in order to maintain their operational status. The regular maintenance of all the electromechanical equipment of the system was performed according to the suggestions of the manufactures. In addition daily cleaning of the floor and surface of the bioreactor was performed in order to obtain high hygiene level for the personnel.

- Disruption and start up of the bioreactor operation :
  - ✓ *$1^{st}$ trial:* The disruption of the in-vessel bioreactor operation on the $8_{th}$ day involved only the operation of the agitation system of the bioreactor and that of the hydration system. The operation of the ventilation system was controlled so that the gases emitted during the process were being removed through the bioreactor's air suction system which disperses gases through an air-pipe to the bio-filter area in order to prevent undesirable odours within the building where the bioreactor is installed.
  - ✓ *$2^{nd}$ trial, $3^{rd}$ trial and $4^{th}$ trial:* No disruptions of the bioreactor's operation occured.

- Restoration of malfunctions and maintenance of the bioreactor
  - ✓ *$1^{st}$ trial:* During the $8_{th}$ day of the composting process a malfunction occurred to the motor of the in-vessel bioreactor. The chain providing motion to the revolving axle was broken. The revolving axle comprises of stirring elements responsible for the

agitation of the substrate. The malfunction was restored and the bioreactor started to operate again on the 9th day of the composting process.

- ✓ *2nd trial, 3rd trial and 4th trial:* No malfunctions occurred during the composting trials.

Important part of the work is to achieve a good quality compost for the different trials and the different BOWs and additives used.

- pH values, near neutral, indicate that the composting process is towards the end.
- The C:N ratios obtained reflect to a good quality compost that acquire ratios lower than 12 which is considered as a very good value for finished composts.
- The relatively high content of nutrients (NPK) for all trials indicate that the compost produced can be used for agricultural purposes while the ammonium to nitrates ratios ranging from 0.09 to 0.24 are within the suggested limits of fully mature composts.

Composting, using sewage sludge and other green wastes as feedstock material is one of the fields where the research has been focused during the last years and the experience that our research team has obtained, in the control and the optimisation of the composting process in various mixture of sewage sludge with different green waste and additives, is significant and useful. However there is not yet a European normative that controls the characteristics and the permitted uses and applications of biosolids. EU has set priorities in the waste management and the optimisation of the composting process and the monitoring of the control parameters of the process that we purpose for the in-vessel composting system are in accordance to these priorities.

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