Published on WSEAS Transaction on Sustainability and Development

Indoor air quality in waste treatment: environmental issue and biotechnology application for air pollution containment, a case study

ALESSANDRA BONOLI, SARA ZANNI
DICAM - Department of Civil, Chemical, Environmental and Material Engineering
Alma Mater Studiorum University of Bologna
via Terracini, 40131 Bologna
ITALY
alessandra.bonoli@unibo.it http://www.dicam.unibo.it/

Abstract: - A proper integrated management of municipal waste analyzes the entire life cycle of waste, from cradle to grave, i.e. the final stage of disposal or recycling, through which waste come back as a resource, as required by Waste European Directive. In this perspective, every possible impact factor should be taken into account and, therefore, air quality and odor control have to be addressed as crucial elements for sustainable waste management, as directly affecting quality of life of both workers and people living in the surroundings of waste treatment facilities. While the issue is generally regarded as a major concern in presence of incinerators (for air pollution control) and landfill (for odor, mainly), it is usually neglected when segregated dry waste treatment is involved, but it remains an element of concern for population and, therefore, public stakeholders. A modern segregated waste treatment plant, already compliant with regulations requirements regarding indoor air quality and human health, was taken as a case study to prove the effectiveness of a biotechnological treatment for air pollution and odor control. The system applied is based on stand-alone bio-oxidizers that provide internal air-mixing within the facility and capture particulates and gases by attracting them to a clean air zone generated by its action. In this paper, only the preliminary phase of application for the system is presented. It was preceded by a completion of analysis of air quality baseline, collected by a Wireless Sensor Network, which have been compared to the following five months of system activity, showing a consistent effectiveness in air pollutant containment and abatement. These results found confirmation in parallel independent laboratory analysis which showed comparable abatement trends. A comparison with a traditional biofiltration case study marked the great opportunity offered by the bioreactors' system implemented in an overall indoor air quality perspective.

Key-Words: - **Sustainable waste management system, Indoor Air Quality, Odor control, Immobilized Cell Bioreactors**

1 Introduction

The approach of the European Community with regard to waste management is based on the following principles:

- Prevention;
- Recycling and reuse;
- Final disposal and related monitoring.

Technologies related to disposal phase, as well as recycling, are to be understood in the wide framework of an integrated approach to all stages of waste management in order to ensure adequate protection of health and environment [1].

The integrated waste management systems are designed to organize waste streams, methods of collection, treatment and disposal, with the goal of achieving environmental benefits, economic optimization and social acceptability.

A proper integrated management of municipal waste analyzes the entire life cycle of waste, from cradle, corresponding to the time when a product becomes a waste, to the grave, i.e. the final stage of disposal or recycling, through which waste ceases to be such and come back as a resource. It is, therefore, clear, on the basis of the Waste European Directive that recovery technologies must be encouraged, in particular by encouraging selective collection of municipal wastes. In fact, the collection phase plays a major role in the integrated waste management system, as it allows to promote recycling operation necessary in order to substantially reduce pollution, energy and raw materials consumption, together with waste production in a cost-effectiveness, efficiency and environmental protection perspective [1]. In order to match European requirement, then, an integrated approach to environmental impact related to waste management must be implemented, taking into account every possible impact factor during the entire life cycle. As suggested by many authors, waste treatment facilities, from landfill to incineration, may be associated with emissions of air pollutant, negatively affecting air quality in the surrounding areas [2].

Even if municipal waste sorting and crushing plants carry a minor to negligible risk in terms of threat to public health, generating an amount of contaminants (both gases and particles) lower by orders of magnitude when compared to, for example, incinerators, they nevertheless may represent a source of disturbing odor and air quality-related operational risk for employees, as air contaminants can be a major source of respiratory diseases.

Traditional air pollution control and prevention technologies include physico-chemical methods such as adsorption on activated carbon, thermal as well as catalytic oxidation. The effectiveness of these technologies is strongly related to the ability to provide the right working conditions (e.g. high oxidation temperatures or controlled air flux rates and large reaction surfaces for adsorbent bed), and, therefore, operational costs tend to grow together with required performances. Furthermore, these technologies may lead to several by-products which, being pollutants, appears as concerning as the ones removed (e.g. exhausted adsorbent bed and incineration ashes, both heavy and fly ashes, which have to be disposed as dangerous wastes in EU Countries) [3] and present few to none application opportunity on diffusive sources of airborne pollutants (e.g. landfills or Biological Mechanical Treatment plants). Therefore, there is a need for alternative technologies for air pollution control that have the potential of replacing physico-chemical treatment technologies, stimulating the development of several solutions.

The removal of odors from air into wastewater and waste treatment plants is often effected through biological means in unit operations like biofilters, biotrickling filters and bioscrubbers, which can be generically referred as organic perfusion column [4].

In Europe, together with chemical deodorization, biofiltration is by now a well known and widely used technology for control of odors, air pollutants and volatile organic compounds (VOC - often related to disturbing odor issues) from different sources in industrial and public service sectors [5], but it remains difficult to apply, especially in urban area, because of the wide surfaces required and possible lowering in performance due to climate condition. Into a biofilter, in fact, a contaminated air flux is ducted to pass through a biologically enriched layer of a filter material (i.e. soil, wood chips, compost or mixed materials) where the pollutants are absorbed/adsorbed and biodegraded by the microbial population. Byproducts of microbial oxidation are primarily water, carbon dioxide, mineral salts, some volatile organic compounds and microbial biomass [6].

Microbial activity is regarded to be affected by moisture content, pH, nutrient limitation, temperature and microbiology of the biofilter medium [7], strongly relating the system performance to contour and working conditions.

2 Problem Formulation

It is well known that odor problems related to waste management system may originate from airborne or surface contaminants (i.e. bacteria and fungus growth, spores, chemical fumes or digestion vapor), so that a genuine health concern accompanies odors, even when intermittent or deriving from segregated waste treatment facilities, where organic fraction should be absent. Therefore, odor control remains one of the most significant challenges for waste treatment facilities today, even if materials come from segregated collection.

Since disturbing odor are usually caused by compounds with low odor thresholds, off-gas concentrations will often be in the low ppmv range [5], making their abatement rather difficult or very expensive, both under an economical and environmental perspective. Air treatment, in fact, requires a great amount of energy, especially when dealing with piped air. In addition to this, air extraction and ducting (similar to Pump-and-Treat system used in soil and groundwater remediation field), which is the most common technique applied for air treatment, do not guarantee problem solution, since odor are often carried by fine and ultrafine particulate, as well as by gases.

As the efficiency of odor and air pollutants treatment system in waste treatment facilities is widely regarded as unlikely to be sufficient for some volatile organics, more reliable tools are needed, in addition to commonly used technologies or in their replacement, in order to reduce such recalcitrant contaminants [8].

A modern segregated waste treatment plant was taken as a case study to prove the effectiveness of a biotechnological treatment working on motion of contaminant for concentration gradient and not through ventilation, providing a sustainable alternative to traditional air treatment techniques.

The waste treatment plant selected for the trial will be treated for 15 months with Immobilized cell Bioreactors, commercially known as AIRcel system, for the containment of odor problems alleged by the neighborhood and microbiological hazards possibly carried on wastes. Both issues are closely linked to the type of work performed within the facility, even thought former air quality checks have shown that the plant is compliant to regulations for healthcare in workplaces. The company involved into the test has shown, however, interested in establishing a new standard of environmental quality within their facilities in order to prevent health and environmental risks both for workers and population living in nearby areas.

The effectiveness of the experimental application in terms of reduction of airborne contamination (gaseous, odorous and microbiological) shall be evaluated by monitoring performed by an accredited third party laboratory, a continuous wireless monitoring station and evaluation of the attitudes of people about the trend of odor emissions from the plant.

The preliminary phase of application for the system, presented into this paper, was preceded by a completion of analysis of air quality baseline: the control units (commercially known as U-Monitor) have been, in fact, installed the previous week the bioreactors system was set. The definition of the baseline was carried out during one week (July 14 to 20), excluding the first 3 days of installation (11-13 July), which showed high concentration values so abnormal compared to following days, and considered, conservatively, not significant for the construction of a term of comparison. The baseline is, therefore, been detected in a period of decreasing activity, up to the stop, of the plant for summer break.

2.1 Performance test

A precisely scheduled monitoring plan has been developed, as to cover the whole experimental period, i.e. 15 months after its inception, during which a continuous monitoring system will be kept operational and lab analysis, such as column air test for gases and odor and Petri plates count through Surface Air System sampling, will be repeated on a seasonal basis as a complement and countercheck. In order to reproduce as faithfully as possible the boundary conditions, the production cycle will be reconstitute, from time to time, very similar to the baseline.

During the technical inspections, spot measurements were made of Volatile Organic Compounds by PID (handheld photoionizer) which, although not bearing an absolute probative value, had completed the perceptual impressions collected. This kind of portable device, in fact, is a broad band detector, calibrated on using isobutylene, and other compounds may produce a response depending on concentration. Being not selective (it may virtually ionize every compound with an ionization energy less than or equal to the lamp output) and sampling on an instant basis, this monitoring method has not been taken into account as a reliable performance test for the system.

In order to have continuous feedback on the effectiveness of the bioreactor system installed, two monitoring stations have been places in different location of the treatment facility (supply station and secondary shredder), equipped with a set of sensors that can detect a variety of contaminants, as well as explained in the next section.

2.1.1 Monitoring System

The monitoring system consists of a Wireless Sensor Network (WSN), designed to collect air quality data in the environments where the bioreactors are installed, and a software platform that is the control center, processing and visualization of the data collected.

The objective of the monitoring devices is to detect the presence of harmful gases and fine dust into the environment and, optionally, some environmental parameters, such as temperature and humidity.

The monitoring devices, physically realizing the WSN, are characterized by:

• sensors for the detection of

- temperature
- humidity
- environmental contaminants (mainly toluene ($C_6H_5CH_3$), hydrogen sulfide (H_2S), ethanol (CH_3CH_2OH), ammonia (NH_3)
- solvent gases (mainly alcohol, solvents, hydrocarbons, VOC)

• particle counters PM1 and PM2.5
• built-in WiFi module for wireless and real time communication of data
• time of collection of environmental data set to 15 minutes.

2.1.2 Baseline definition

The definition of the baseline of comparison is critical for evaluating the performance of the system. This baseline has, in fact, to include a sufficient number of days to constitute a proper statistical basis for the calculation of an average that can be representative of the period and the activity of the plant. The combination of the trial with the decrease in physiological activity of the plant for the summer necessitated a proper assessment of this aspect, but it was regarded, nevertheless, as a great opportunity to relate operational phases of the facility to air pollutant concentration, during this preliminary study.

Since the very first days of application of the monitoring system showed a significant gap in high concentration of all sensors, they have been discarded and the more representative trend displayed in the following week was assumed as baseline value.

AVG values	Air Contaminant	Solvent Gas	Dust (1-2,5 micron)
Feeder	84 ppm	65 ppm	2341 part/dm3
Secondary Shredder	52 ppm	63 ppm	1820 part/dm3
Whole Facility	68 ppm	64 ppm	2080 part/dm3

Table 1. Baseline values

Evaluation of the data collected so far by the U-Monitor can not ignore the contextual consideration of production trends, as the baseline definition period and the installation of the bioreactors system took place during summer, when waste treatment proceeds in a cycle far different from the standard. At the same time, summer months, in the previous year, proved to be a critical period for disturbing odor emission, probably related to longer rest of residual material into storage tanks and anaerobic conditions establishing into them, giving space to sulfur compounds to develop and spread out.

3 Problem Solution

The air treatment system proposed to try to improve air quality standards into the waste treatment facility is constituted by stand-alone Immobilized cell Bioreactor, carefully sized and placed in order to empower the system effect and overlap influence area of the single units. No exhaust air pipeline has been installed, since the AIRcel system works on indoor containment of contaminants, preventing issue typically related with air ducting, such as high energy consumption for ventilation and air conditioning and difficulties in capturing pollutant which may be more affected from electrical surface field rather than air motion, because so fine that specific surface is overwhelming compared to mass and volume.

3.1 Technology applied

The system is based on stand-alone bio-oxidizers that provide internal air-mixing within the facility and capture particulates and gases by attracting them to a clean air zone generated by its action.

The bioreactors, in analogy to biofilters technology [4], consist of three phases in close contact: a solid phase, which is the bioreactor itself, a liquid phase, i.e. water, and a gas phase, that is air to be treated. As in common biofilters, a physical support for biomass growing is offered by a solid medium, but, in this case, a plastic patented bioreactor is provided with optimized configuration in order not only to become growing support for biomass, but even to enhance its degrading activity.

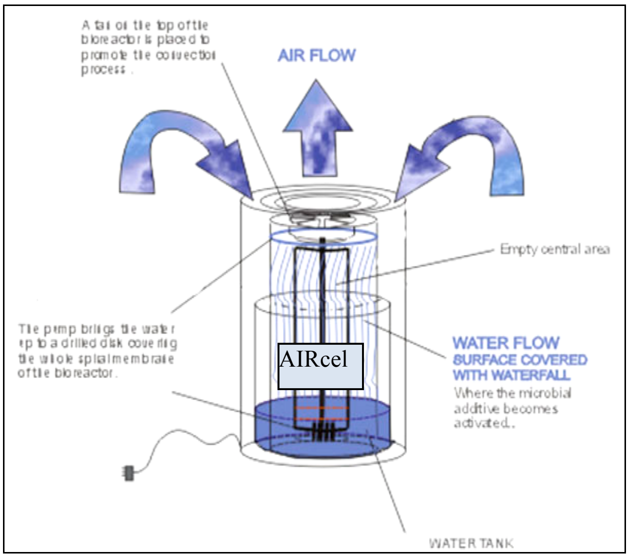

Fig. 1 - Simplified outline of an AIRcel bioreactor (provided by U-Earth Biotechnologies s.r.l.)

The leading mechanism is the biological digestion of the hazardous materials attracted. These miniaturized treatment plants, in fact, utilize bio-oxidation to destroy gases, volatile organic compounds (VOCs), odors, and remove particulates though bio-hygienics principles, i.e. the natural phenomena used to control IAQ, electrical as well as biological [18], thus airborne contaminants are first captured and subsequently digested biologically.

Many authors stated the effectiveness of specific bacteria strains in degrading different contaminants [4], such as Chemoheterotrophic bacteria to promote Organic Carbon oxydation (from VOC to CO_2 and H_2O), Nitrifying bacteria for nitrification (from NH_4^+ to nitrite and nitrate), Sulfur oxydising bacteria to achieve Sulfide oxydation (from H_2S to S^0 and sulfate) (all in aerobic environment) and Denitrifying bacteria, to promote Denitrification (from nitrate to gaseous nitrogen) in anaerobic conditions. Nevertheless, since the biomass representing the core of the AIRcel technology is a proprietary formulation, in which the claim is that no genetically manipulated microorganism, it appears to be a quite composite bacteria and enzymes consortium The biomass proposed is, infact, able to attack and digest compounds different in nature, degradation process, contour conditions requirements and inhibitors, final products and reaction by-products.

Intimate gas-liquid mixing with electrically grounded water from the reservoir tank additionally grounds the clean air zone, attracting and capturing pollutants. Contaminants, along with the odors that they generate, are attracted to this clean air zone by concentration gradients (pollution moves from high to low concentration, both with mass and electrical charge), where the charged particles are removed by electrical grounding and the organic compounds are oxidized [9][10][11].

This can be accounted as a sustainable technology, particularly when compared to standard air treatment systems, since it does not require elevated temperatures (as post-burners) or pressures (as membrane filters) or excess energy (as any ventilation system) to operate.

In the waste treatment facility offered as case study, n.8 AIRcel of the bigger size have been placed: n.6 inside the building and around the potential source of contamination (input waste material storage, treatment line and final product storage tanks); n.2 just outside, in order to cover the main exit of final product and guard the external border of the two storage tanks, accounted to act as major source of odor contamination. A simplified sketch of the treatment plant and system implemented is provided below, with the aim of showing the expected area of influence of the eight bioreactors.

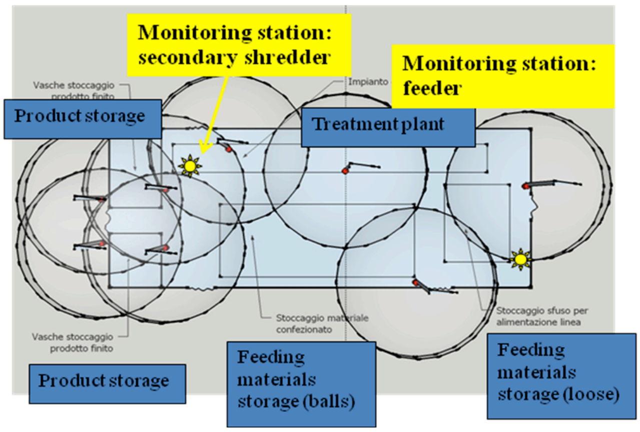

Fig. 2 - Outline of the system into the treatment facility

3.2 Results and discussion

The evaluation of the data collected by monitoring system has been divided between gaseous contaminants and particulate matter, which present different behaviors both in chemical and physical terms.

In order to provide an effective comparison between the contaminant concentration found during the first five months of the trial and what obtained as a baseline, some graphs are displayed in the following pages. In particular, results returned by the sensors "Air Contaminant" and "Solvent Gas" are reported first, as more closely related to the odor quality of the environment.

3.1.1 Gaseous contaminants

It is immediately evident how the system has responded to the initial saturation condition with expected developments of airborne pollutant concentration, the interpretation of which can not, however, be abstracted from the evaluation of operational condition of the waste treatment plant:

• initial increase in the concentration of the contaminants monitored, although the peak contained 80% of the baseline value (Fig. 3), corresponded with the delivery of particularly smelly waste material. The highlighted peak is evident for both contaminant clusters detected. This event has come to engage on the phase of desaturation of the system that could not be still able to immediately treat the emergency;

• subsequent decrease of the concentrations of airborne contaminants, with a similar trend found by two different sensors and in the two positions of detection;

• secondary peak concentration (highlighted in violet in Fig. 3) detected during the second week of operation, appears as correspondent to the working phase of the system on the contamination immobilized on surfaces. This event, which tends to momentarily increase the concentration of pollutants in the indoor environment, has occurred concurrently with a maintenance issues on the machines;

• concentrations after the peaks are subsequently dropped, despite the recovery in the plant full capacity at the beginning of September: during the first 120 days of operation of the plant at full capacity, the airborne contamination continued its downward trend now that the system reached a state of equilibrium that allows the containment of pollutant events within a very short time;

• the next four peaks (highlighted in Fig. 3 and 4 in red) detected by the sensor "Air Contaminant" at the Feeder and have been related to maintenance work on the bioreactors, which required the stop of the air treatment system;

• in Fig. 4 and 5, a black arrow indicates a secondary peak in concentration detected by the Solvent Gas sensor, presumably due to the delivery of particularly smelly material;

• the concentrations found in the last weeks of full operational performance of the bioreactors' system, were maintained within 15% of baseline values, with a consequent reduction greater than 85% detected by both sensors, but Week 46 and 50-51 experienced major failure of the technology and, consequently, higher peak of contaminants concentration have been detected. In Par. 3.4 an attempted correlation between system's failures and secondary concentration's peaks was made, with the aim to proceed in the next months of the trial period with an deeper analysis of the phenomena.

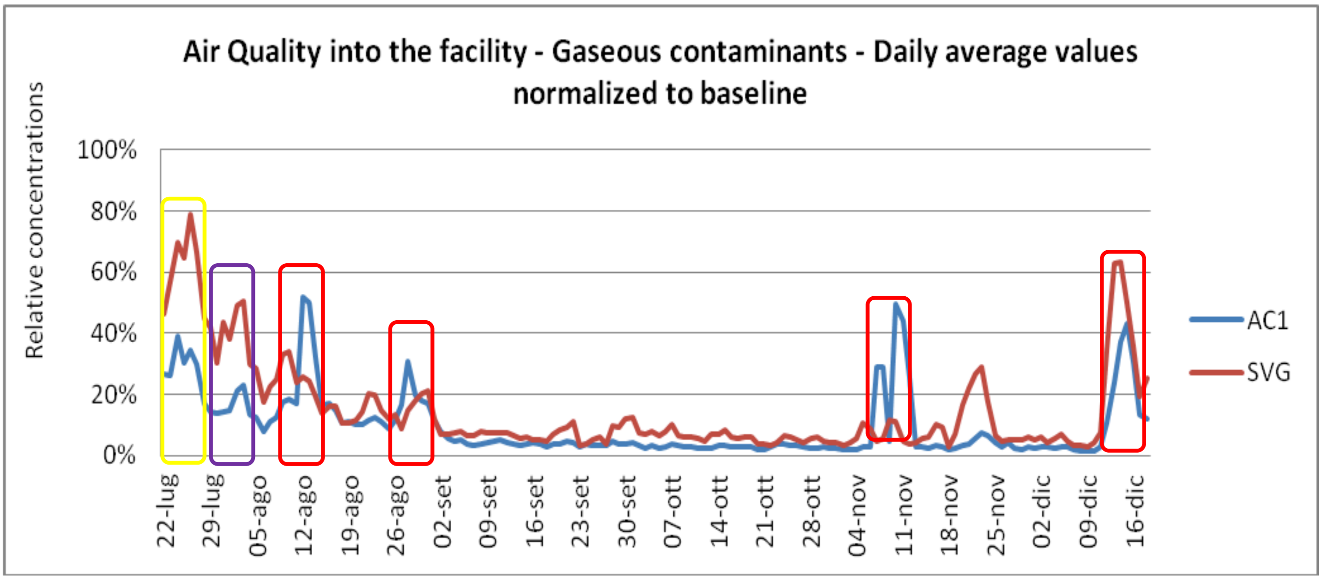

Fig. 3 - Daily avg values referred to baseline value, gaseous contaminants

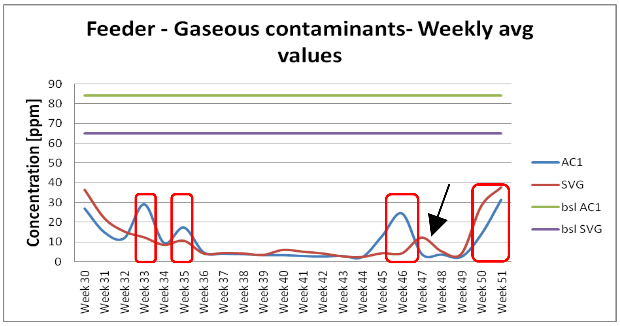

Fig. 4 - Weekly avg values, gaseous contaminant at the feeder section

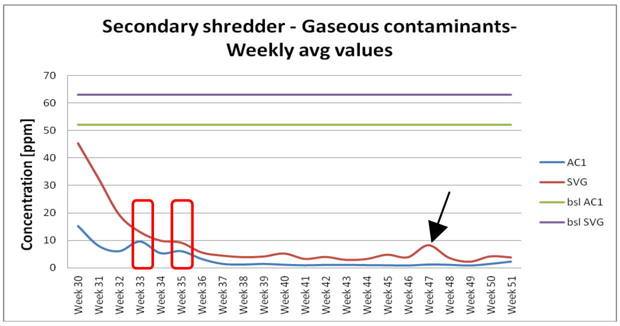

Fig. 5 - Weekly avg values, gaseous contaminant at the secondary shredder section

Relating concentration peaks detected by sensors with indication of intense or disturbing odor event recorded by workers (note that no odor events has been reported by people living in the surrounding area), it can be considered that they proved to be related to gaseous concentration peaks detected at the feeder section, while no correspondence were detected with secondary shredder activity.

The peaks of gaseous contamination appear to be wider (so, longer lasting) and with a higher absolute value during the frst weeks of Bioreactors system application (July and August). During September, on the contrary, the peaks of contaminants are tighter (i.e. "shorter" in time) and reach an absolute value greatly reduced (6-8 times) than in previous months.

This trend shows that, following a first period of de-saturation (July and August) in which a large amount of contaminants (high peak values) travels slowly to the AIRcell system (broad peaks), after nearly two months of operation (from September on to December), contaminants move in small clouds (peak values slightly higher) that are attracted quickly toward AIRcell (narrow peaks) and do not spread into the surrounding environment.

The absence of abnormal measurements on device Secondary Shredder attest that the AIRcell can capture and remove contaminants that generate odors, preventing its spread to areas far from the source.

3.1.2 Particulate matter

The contamination related to particulate matter, perceived as "fine dust" characterizing the indoor air, has been detected in parallel with the gaseous contaminants already presented. In order to give a consistent interpretation of the results a few considerations are needed:

- The particulate contamination is necessarily influenced by the activity of the plant, since it is generated by the operations of opening the waste balls and consequent shredding of the waste for final sorting, alternated to moment spent cleaning of the conveyor belts, which, therefore, must be emptied and production line stopped. For this reason, the evaluation of the performance should be carried out in parallel with production notes provided by the Company and, in particular, it is necessary to divide the consideration of two different periods:
  1. summer, characterized by partial and intermittent activity of the plant, with delivery of materials, waste treatment and maintenance works when needed (July, 22nd-August, 30th), as demonstrated by the different baseline values encountered (higher for feeder section, rather than secondary shredder area);
  2. autumn, with recovery of full time production of the plant (September, 1st - December, 18th);
- particulates tend to move in the air in eddies and clouds with a different degree of concentration, rather than distribute evenly in the environment;
- the two areas where monitoring stations have been installed are characterized by very different work load of suspended particulate matter: while the burden on the feeder section is related to input of the vehicles and the opening of the "bales" of waste delivered, the secondary shredder undergoes waves of contamination from two possible sources:
  1. the proper shredding activity
  2. the cleaning of the conveyor belts by means of compressed air, carried out at time intervals dictated by the conditions of the same belts.

These issues explain a trend of concentrations quite different from what revealed on gaseous contaminants and it is crucial to consider separately the two monitoring stations.

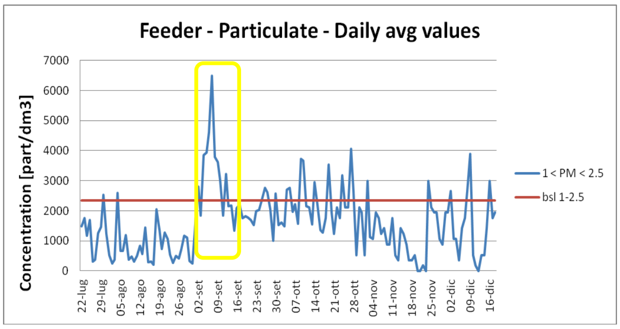

Fig. 6 - Daily avg values, particulate matter at the feeder section

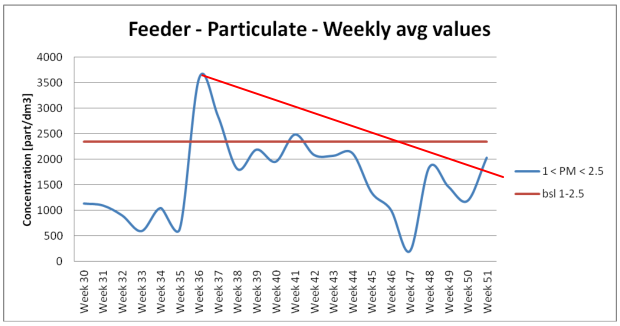

Fig. 7 - Weekly avg values, particulate matter at the feeder section

The first five weeks of AIRcel system activity are characterized by a reduction of particulate contamination in correspondence to the feeder section of the plant, as shown by weekly average values, which are below 40% of the baseline. Since the levels of operation of the plant have been kept low and close to the total rest in the period of the definition of the baseline and in the subsequent weeks, it can be stated that the system contained the contamination present in the plant during those weeks.

The only peaks that exceed the baseline value are so explainable:

- 07/29/2014 peak: maintenance of AIRcel units after two days of alarm due to a high load of dust which covered the air outlet, evidenced by the remarks quoted in the production notes. At the same time, the plant has been running for two shifts on July, 24th and 25th and one again on 28th;
- 08/05/2014 peak: maintenance of AIRcel units in the days immediately preceding it.

In correspondence of waste treatment plant coming back fully operational on September 1st, a peak concentration of particulate matter has been detected (marked in yellow in Fig. 6-8-10), due to the re-suspension of material trapped in machinery remained steady for weeks and the increase in the pollution load carried by the shredding of waste. During the following weeks, the peaks tend to decrease, returning to fluctuate around the baseline values at the feeder section. This corresponds to a satisfactory result in containment of dust contamination, since particulate concentrations are back to a diminishing trend, albeit in full operation of the plant (which implies trucks coming in and out of the building to discharge waste materials and bulldozer moving it from storage to feeder section), towards values that characterized a period of progressive switching off of the same and the peaks are progressively decreasing (red line in Fig. 7).

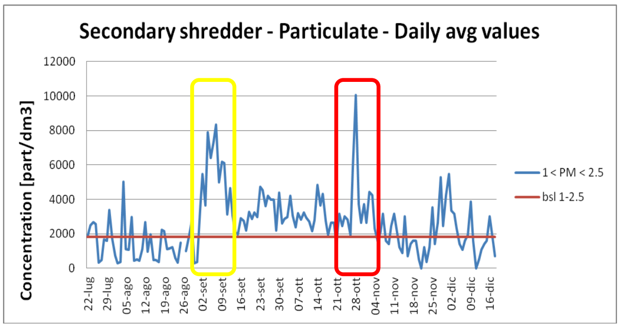

Fig. 8 - Daily avg values, particulate matter at the secondary shredder section

The area of the secondary shredder is evidently of more complex management (note that the facility is an open space, with no sects deviding operating sectors), due to the very nature of the processing, which tends to re-suspend periodically dust and particulate matter (even those deposited on the surfaces by gravity). Since the baseline has been defined in a period of partial processing inside the plant, values lower than the ones detected at the feeder section were provided for the same period; in contrast, the resumption of activities has meant that the peak concentrations are higher in this area, although chronologically corresponding to those already tested at the feeder (even during the shutdown, i.e. July 29th and August 5th).

The direct dependence from the operating schedule, or cleaning activities, is reflected in the performance of the most jagged peaks of concentration in daily average concentration (Fig.8). An evident peak was detected during and immediately after the maintainance work performed in late October (in red in Fig. 8 and 9). Over the forthcoming months, it will be determined the degree of correlation between these peaks and the cleaning of conveyor belts, in collaboration with the company, which is required to keep track of cleaning activities, as has been done for the production.

The line drawn in green color in Fig.9 shows how the concentration peaks are progressively decreasing, to demonstrate containment performed by the system even in conditions of full operation of the plant.

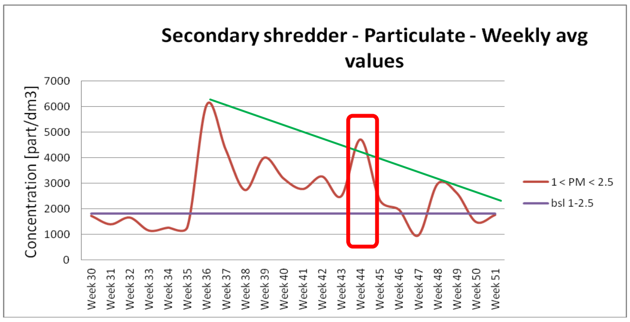

Fig. 9 - Weekly avg values, particulate matter at the secondary shredder section

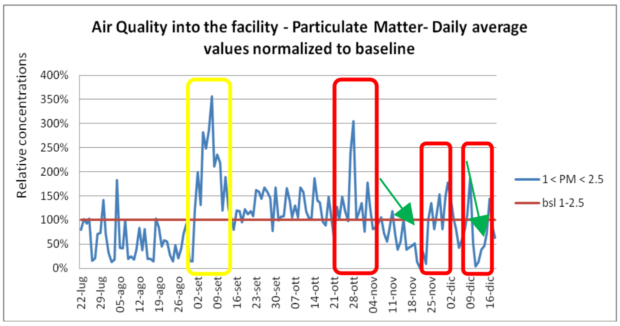

Fig. 10 - Daily avg values referred to baseline value, particulate matter

The concentration's trend at the two sections are, obviously, reflected by the overall air quality inside the facility (Fig. 10, with the re-starting of plant activity marked in yellow and major maintenance works in red), but, thanks to this elaboration, it becomes more evident how the maintenance and cleaning operation on the bioreactors affected positively the system's performance, providing a sensible decrease in particulate concentration (highlighted with green arrows following the steep of the decreasing trend).

3.3 Comparison with lab analytical data

As stated by many authors, the detection of relations between olfactory odors units and concentration of gaseous indicators in the air presents several criticality, such due to the high number of odor producer compounds as to different olfactory effects generated in presence of antagonist or synergic elements[12].

In this case a combined use of olfactory methods and traditional chemical analyses has been applied to indicator compounds, procedure generally regarded as a useful mean of evaluation of odor impact on territory in the proximity of solid waste treatment or storage plants. The evaluation of odor effect with physical-chemical analysis, which appears as the most strict approach when compared to olfactometry, presents, nevertheless, several elements of concern in the monitoring planning phase, since even a single source of emissions could easily be carrier of multiple odor-promoter compounds. This concern is, obviously, enhanced when the possible source of air contamination is as heterogeneous as municipal solid wastes (even if derived by segregated collection, as material object of the present study).

The general approach to odor detection is commonly related to: a) concentration compared to odor detection threshold; b) intensity; c) physical-chemical characteristics d) hedonistic tone; e) quality. Trying to determine a direct correlation between odorimetric units and gaseous concentration of compounds identified as odor indicators could be both complicated and misleading, due to the number of odor producer compounds as well as to different olfactory effects generated in presence of antagonist or synergic elements [12].

The odorimetric unit (1 O.U./m^3) is defined accordingly to the standard CEN TC 264, as "The amount of odorant that dispersed in 1 cubic meter of neutral air causes a sensation odor" and is considered as a measure of the concentration of odor [13].

On the basis of Liu et al., odors from biostabilization processing of municipal solid waste after Biological Mechanical Treatment (BMT) have been analyzed by Gas chromatography–mass spectrometry (GC–MS) analysis and results showed that, among the total volatile organic compounds (VOCs), the main components of the produced gas were benzene, toluene, ethylbenzene and xylene (BTEX) along with other alkanes, alkenes, terpenes, and sulphur compounds [14]. Methyl-mercaptan and dimethyl-sulphide are also often regarded as characterizing parameter of odour emissions by guideline for solid waste treatment and storage plants [15].

In the present study, a static sampling method has been applied, in order to obtain a more accurate outcome: the sample is, in fact, collected in a bag and analyzed within 30 hours; this sampling is used to odoriferous sources with concentrations varying in time due to wide reaction surfaces involved, as lagoons, tanks and landfill [13]. The instrumentation used for the sampling consists of a sample probe, distribution tube, a particulate filter upstream to the detecting system, a hood designed to provide turbulent airflow. The sample is collected only after the passage of a volume equal to 3 times shell volume into Nalophan™ bags with PTFE pipes, following the UNI EN 13725:2004 standard procedure.

Accordingly to international standards, for wide emitting surfaces or indoor environments, more than one sampling point are to be selected: for the present study, seven collection points have been identified (n.1 inside the waste treatment facility, n.4 outside the passage doors and n.2 on the roof of the building, one at the chimney of the extraction duct and one after the traditional air treatment system)

As stated by many authors and, in particular, on the basis of conclusions of Shaharuddin et al. [19], meteorological parameters present great influence on airborne particulate behavior. Thus, meteorological data have been recorded during sampling collection, in order to correctly evaluate the results: this allowed a detailed analysis of the two baseline campaigns which led to the conclusion that only one presented the necessary weather, pressure, temperature and wind conditions to be accounted as representative of the average local conditions during summertime.

Different analytical methods have been applied, accordingly to international standards, for different contaminants to be found into the air column:

- Hydrogen sulphide - EPA method 15
- Aliphatic amines - Nalophan bag+CG-MS
- Mercaptans - Nalophan bag +CG-FPD
- Hydrocarbons and aldeydes - EPA TO 15 1999 mod. (Nalophan)

Among compounds tested, aliphatic amines and mercaptans remained below the detection limit value in all the sampling campaign, while a significant abatement has been recorded for total hydrocarbons and odor, as showed in Table 2.

Sampling	**Odors [O.U.]**	**Total Hydrocarbons [ppm]**
07/03/2014	918	2036
10/30/2014	412	685
Abatement performance	55%	66%

Table 2. Gaseous contaminants and odor abatement performance

Due to the peculiar working principle of the system proposed, a direct comparison with removal efficiency provided by benchmark technologies could be either difficult or misleading. This system, as discussed before, works on indoor air, treating it inside the facility, while all other systems applied on odor and emission from MSW treatment plant operate on extracted and ducted air. Nevertheless, a comparison with results provided by Liu et al. [14], is presented in Table 3. In Liu's experiment, a compost biofilter was established in Shangai's BMT pretreatment and composting processes used for MSW disposal and its performance checked. The biofilter showed higher removal efficiency for alkanes with smaller molecular weights, compared to the higher molecular weight ones. As marked in the following table, performance obtained is comparable, but, considering that biofilters treat extracted air, a correction factor related to extraction fan and ducting efficiency should be applied in order to evaluate the overall performance of the system in direct comparison with AIRcel's technology.

Compound	**Aircel technology removal efficiency**	**Liu et al. [14] removal efficiency**
Pentane	81%	87,4%
Hexane	96%	85,8%
Octane	36%	91%
Decane	75%	10%
AVG	72%	69%

Table 3. Alkanes abatement performance in comparison with results provided by Liu et al. [14]

In parallel with gaseous contaminant detection, microbial contaminant counts have been performed during the same monitoring campaigns.

A STRAINBUSTER 60 sampler has been used in association with Petri plates. Samples have been taken at human height (1,5 m from the ground), as requested by international standards, in three different monitoring points inside the waste treatment facility, since the outdoor environment is not expected to be affected by microbial contaminant concentration inside, unlike what happens for gaseous and odor producer compounds.
Several microbial strains have been monitored, some of which resulted undetectable even in the baseline definition phase (i.e. *Fecal Streptococcus,Pseudomonas aeruginosa, Staphylococcus aureus* and *Salmonella spp)*, but total count per temperature interval and some strains experienced sensible variations during the testing period, as reported in Table 4.

Microbial indicator	**Variation from baseline**
total bacteria count at 22°C	9% (-6%)
total bacteria count at 36°C	-38%
total coliform bacteria	-98%
total mycetic count	60% (-43%)
fecal coliform bacteria	-98%
enterobacteria	-99%
Overall abatement performance	-48%

Table 4. Microbial contaminants abatement performance compared to baseline

Target potentially harmful bacteria (colifrms, fecal coliforms and enterobacteria) showed a decreasing in number of colonies above 98%, while the total count at 36°C (a mixed indicator, not specifically identifying harmful bacteria) diminished of about 38%. The total bacteria count at 22°C appears not sensibly affected by the system application, but is less significant in human health protection perspective than the 36°C count. The countertrend data seems to be the Fungi count, since it shows an increasing of about 60%, compared to baseline. Nevertheless, this data can be explained by comparing it to the first baseline attempt monitoring, discarded for meteorological reason: climate conditions (i.e. low pressure, rainy day), in fact, where probably more similar from the first attempt baseline to the final monitoring time (late October) and this appears to affect the development of Fungal colonies overwhelming the system ability to treat them.

3.4 Overall considerations

To complete the evaluation of the data collected, perceptual aspects has been taken into consideration, being directly related to the conditions of odorous contamination and, in addition to correlations made in the previous paragraph, impressions of the facility's staff and complaints from the local residents have been recorded and it is inferred what follows:
1. since the summer, reported as critical for odor conditions for the surroundings in previous years, no alert for malodorous emissions has been reported. It can be considered as a preliminary, but crucial achievement of containment of airborne contamination. The summer period, in fact, is a critical time for the odor emissions on the one hand for weather and climate reasons (high temperature, in fact, promotes anaerobic digestion of residual waste), and secondly, due to the slowing down, until the total stop, of the plant activity. This operating mode favors the establishment of anaerobic conditions within the storage tanks of the residual material and, consequently, the development of anoxic sulfur compounds (eg hydrogen sulphide) with low odor threshold and, therefore, potentially disturbing in smell;
2. the staff notes that the smell is still present within the facility, related to the input of particularly odorous material and its processing, but at the same time, it tends to not propagate outside. This configuration corresponds to the action of the containment principle established by AIRcel system around the source of contamination and it is reflected in measurements provided by portable photoionization detector (PID), which detected
2.1 fluctuating values of volatile organic compounds within the plant, related to the nature of snapshot surveys the device performs, which appear to be less effective in open environment;
2.2 a decrease of the same values at the chimney, where the flow of air conveyed by local extractor makes the measurements more constant in time and, then, reliable, as far as possible: this data confirms the impressions of the staff and corresponds to the expected behavior of the contaminants, which are

attracted by AIRcel more effectively than traditional aspiration.

An overall evaluation of the system performance can not ignore the influence of units malfunctions and difficulties in adapting such system to the peculiar environment of a segregated waste treatment plant. As noticed into results presentation section, a sensible influence on system's performance is exerted by maintenance conditions of the bioreactors. In occurrence of major failure of the machines, in fact, a decreased performance is offered by the whole system, proving its efficiency in contaminants capturing and removal while in full functionality. In Table 5, malfunctions of bioreactors units are reported, together with an estimated system's functionality left, in order to try and find a correlation between these occurrences and secondary concentration peaks in sensors' readings. The residual functionality is just an estimation, since no remote control of the bioreactors is provided so far and it is consequently impossible to guess how long the malfunction is lasted. This is particularly evident when considering the 13% of system functionality found during the early October maintenance work, which is, in fact, coupled with just a slight increase in contaminants concentrations, probably due to the short malfunction time. On the other hand, a 50% of residual functionality in earl December has led to a strong increase in gaseous contaminants (from a value lower than 10% of the baseline to about 50%). At the same time the more recent maintenance works are evidently related to dramatic abatement compared both to former contamination condition and baseline values: this suggests an optimal cleaning schedule for the bioreactors of about 4-6 weeks, when applied in waste treatment facilities.

Maintenance date	Units under malfunction alert	System functionality left
07/29-31/2014	n.5	38%
08/4-6/2014	n.3	63%
08/27-28/2014	n.2	75%
10/03/2014	n.7	13%
10/22/2014	n.1	88%
12/09/2014	n.4	50%

Table 5. Malfunctions log and residual functionality of the system

3.5 Outlook of the work

By the end of the testing period, several outcomes are expected:

1. Recognizing correlation between lab test and wireless monitoring system results, in particular aimed to find a possible correlation between particulate sensor readings and microbial count performed through impact sampler.
2. Identifying a link between particulate matter peaks at the secondary shredder section and conveyor's belt cleaning operations, in order to make them predictable.
3. Establishing an equilibrium state for the bioreactors system, with a stable containment of air pollution and predictable performance.
4. Defining a new state-of-the-art both for the AIRcel system, with a predictable sizing-related performance for this industrial sector, and for indoor air quality standards into modern segregated waste treatment plant.

4 Conclusion

The effectiveness of a biotechnological air treatment system (AIRcel) on improving air quality inside a modern and regulation compliant waste treatment facility is under investigation by the means of a fifteen months test period, during which different monitoring methods are applied in order to delineate the more comprehensive performance trial possible. The Immobilized Cell Bioreactor's system's working principle relies on motion of contaminant for concentration gradient and not through ventilation, providing a sustainable alternative to traditional air treatment techniques, both for the reduced energy consumption and lower potentially disturbing emissions. This would be a sensible improvement towards environmental, economic and social sustainability, since waste treatment facilities are widely associated with emissions of air pollutant, negatively affecting air quality in the surrounding areas

The baseline has been detected in a period of decreasing activity, up to the total stop of the plant for summer break, element which influenced application results in two ways:

1. providing a rest period for the crushing, and therefore, withdrawal of waste material, which tended to increase gaseous contaminants values due to anaerobic conditions established into the storage tanks;
2. showing a lower concentration of particulate matter due to shredder's stop, destined to be overwhelmed by working conditions, which, actually returned concentration peaks.

The gaseous contamination has been effectively treated with an immediate response to the intensification of work and events maintenance on the system, reaching a higher value decreased by 85% compared to baseline during the last weeks of full functionality of the system.

The particulate contamination is clearly influenced by the processing conditions of the waste treatment system, both from a chronological point of view: it is clearly recognizable, in fact, the time of resumption of full operational schedule, whose concentration peaks are gradually decreasing, and topographical, since the data at the secondary shredder are higher than the one detected at the feeder section, while during the definition of the baseline (when processing of waste material has almost stopped), an opposite behavior was found. The concentrations trend is, nevertheless, decreasing and fluctuating below the baseline values, showing a strong dependence on the machines' cleaning and maintenance conditions.

Both gaseous contaminants and particulate matter appear to be effectively captured and treated by the system, as demonstrated by stress test conditions provided by several units' malfunctions occurred during the trial period, during which the detected concentrations experienced peaks strictly related to system's failure and decreasing trends consequent to the maintenance works. The optimal cleaning schedule for the system is identified in 4-6 weeks, confirming the strong dependence of the performance from the recovery ability of the water system (in hospital environment application, in fact, the experienced optimal cleaning schedule was 10-12 weeks) related to the load of contaminants to be treated.

The peaks of smell recorded inside the facility are reflected in the surveys carried out.

The smell impressions gathered by the staff and the absence of complaints from the residents around the plant confirmed a reduction of odor emissions at their source, limiting the fugitive contaminants, despite the working conditions of the venting inside the facility have not changed.

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