UNIVERSITA' DEGLI STUDI DI PADOVA

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MSc in Environmental Engineering

Master Thesis
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Experimental evaluation of Final Storage Quality threshold values for a semi-aerobic landfill

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Part 1

Theoretical Introduction

1 Introduction and Goals

“After closure, municipal solid waste landfills must be managed and controlled to avoid adverse effects on human health and the environment. Aftercare (or post closure care) can be brought to an end when the authorities consider the landfill no longer pose a threat to human health and environment.” (Laner et al., 2012).

This sentence explains shortly the aftercare concept and its need in a complete and correct waste management program with, always, the main purpose to defend human health and environment. Applying this concept is really complicate because the environmental topic is quite new, old landfills are not built by considering this problem, remediation is complicate and expensive, wastes and technologies are often different each other, etc. Aftercare concept comes from sustainability concept, that prescribes to take care of the present actions, in the present generation time, in order to not impact in the future. This means that the landfills must be safe in less than half century and so some engineering measures must be studied and taken to guarantee this target. Moreover, the European legislation and the liners efficiency asks for a complete stabilization in 30 years maximum (EU, 1999). One of the main problems is defining when and how the safeness situation is reached and the aftercare can be finished, because of the big range of situations and possible treatments that can be adopt. Research conducted to define termination criteria, brings to three main kind of approach: limit values, risk assessment, performance-based methods (Laner et al., 2012). Between the first and the second family, there is the Final Storage Quality approach that consists in evaluate some indexes and threshold values to be reached, generally valid for all MSW landfills, and a risk assessment to be more site-specific (Cossu et al., 2007). This approach is easy to apply and gives immediately the values on which designs the landfill since the beginning and so the possibility to adopt the better solutions for the specific waste in the specific place. The definition of the FSQ indexes and values is still debated and the present work is a contribute that starts form the indexes purposed by Cossu et al. in 2007; it tries to evaluate the threshold values for a semi-aerobic landfill using a lysimeter test and a comparison with other similar tests.

The final goal of this thesis is the evaluation of FSQ threshold numerical values valid for a semi-aerobic landfill, considering also some other aerated tests for comparison of results.

The first part of the thesis is a theoretical and technical overview. Sustainability and aftercare concepts are introduced together with the European law related to these concepts. The second part consists in a scientific article where the test and its elaboration are explained and analyzed to evaluate the FSQ threshold values. The third part are the annexes where more complete and detailed tables and plots are reported with all the analytical procedures.

2 Theoretical Approach

2.1 Sustainability Concept

Sustainability is a concept that must be applied to every human activity that can have an impact on the environment for future generations; landfills are surely part of this category.

The first definition is the one given in 1987 by the World Commission on Environment and Development (WCED), in the Our Common Future Report (formally named Brundtland Report because the president of this commission was the Norwegian Premier Gro Harlem Brundtland). The following sentence is considered the Sustainability first definition:

“The development must meet the needs of the present without compromising the ability of future generations to meet their own needs.” (UN, 1987)

This is a first way to explain a concept that will be revised and refined in the following years. The word Sustainability is not presented in the report, but it is created later on this principle. The definition is anthropogenic because it does not consider nature or ecosystems, but only human needs; now the evolution of the concept generally considers environment in its wider meaning. The real innovation of this concept is the inter-generational equity that brings to the necessity to consider the future effect of the present actions, that before was limited to some years only. This concept is expressed in two words:

- **Needs**, in particular, the essential needs of the world's poor, to which overriding priority should be given.
- **Limitations,** imposed by the state of technology and social organization on the environment's ability to meet present and future needs.

In the following years, some other definitions are provided by international associations, the most famous is the one accepted by Word Conservation Union (IUCN), United Nations Environmental Program (UNEP), World Wildlife Found (WWF), and many others:

“Sustainable development means improving the quality of life of humans, while living within the carrying capacity of supporting ecosystems”.

This definition includes the nature needs, not only human ones, it contains the word sustainable and it introduces the concept of carrying capacity. This concept is a tool to evaluate how many resources the present world can replace in a time and, so, how many of these resources the humanity can use without compromising the environment.

Modern concept of sustainability can be described as a three-legged stool (Figure 1.1) in which sustainability is the seat and the legs are environment, society and economy. The three legs must be equal to well sustain the seat: according to this metaphor, the society, the economy and the environment must have the same importance to be sustainable.

Figure 1.1: Three legged stool, The three legs (environment, society and economy) must have the same importance to be sustainable.

According to the level of application of the sustainability, it can be divided in 2 approaches:

- Strong sustainability: it is right loyal to definition and does not foresee any exception.
- Week sustainability: it wants to achieve sustainable conditions but it considers time for change and exceptions to its applicability.

Landfills that follow the sustainability concept are structures where waste must not be dangerous for the future generations, and so, it must be stabilized in one-generation time (about 30 years). This requires the use of technology for fast treat and extracts all the mobile-dangerous compounds in the generation time, to let it be in safeness once this period is finished.

2.2 Aftercare Termination

Aftercare is defined as the period between the end of the landfill filling (stop waste delivery and top cover placement) and the end of monitoring and managing the in situ treatments. This is a quite new concept, because, until 30 years ago, the landfills were not engineered structures so, once filled, they were close with a soil film and leave without care. The more recent engineered landfills (named traditional landfills) have some tools to avoid environmental pollution, visual and odor impacts and biogas emissions. Once close, they are only monitored until the potential emissions falls down under an acceptable level; often the biogas is extracted for energy recover and leachate is brought to treatment. Sometimes, the covers are so effective that inhibit the water circulation that is fundamental for liquid extraction and for biological processes, necessary to compounds degradation. This structure is not built to proper treat waste in order to reduce the emission potential but only to contain the pollution, that remains present and will be released once the containment system fails (mummification and release processes). The new landfilling strategy must consider not only the site building, the environmental protection and the waste disposal, but also aftercare: a predetermined period of in situ treatments to be sure that the refuse will be stable at the end of the period and the landfill can be leave without problems. These treatments can be, as instance, flushing, leachate recirculation, aeration and/or a studied mix of these technologies site and waste specific. This kind of landfill can be named Sustainable, because it tries to respect the sustainability concept: a landfill can be considered sustainable if emissions do not significantly modify the quality of surrounding environmental compartments: air, water, soil (Cossu et al., 2007). This definition is accepted even in other works (Hjelmar and Hansen, 2005; Heyer et al, 2004).

Different landfill types with different aftercare length are visible in Figure 1.2 below. Emissions will initially increase for some years because of the continuous input of waste, but when the landfill is close, aftercare starts and the emissions can only decrease thanks to stabilization and extraction. The traditional landfills emission can continue for much more than thirty years, the green one is the sustainable landfill that is the maximum evolution allow by the present law.

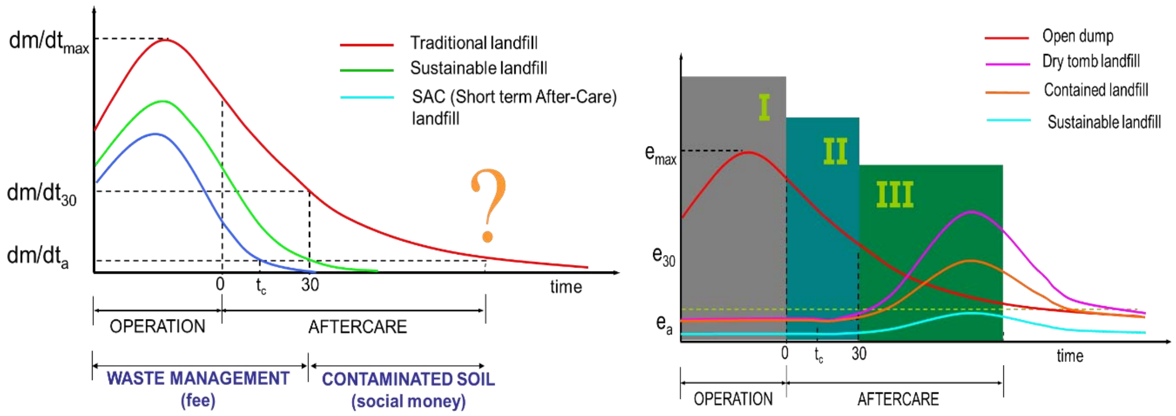

Figure 1.2: Difference between traditional (red), sustainable (green) and short-term aftercare landfill (blu) regarding the aftercare length. On the right the emission potential versus time is print, after 30 years a possible breaking of barriers is foreseen, so it is necessary that emission potential is low before that time, for sustainable landfilling.

Another problem bond to the aftercare termination is the possible uncontrolled emissions. After 30 years, the barrier system will start to have lacks and some emissions can be uncontrolled. If after this period, the emission potential is still high the landfill will start to pollute environment even after decades of its closure (dry tomb and contained landfill case). Paradoxically an open dump, which emits tons of pollutants in the first years, after 30 years will be clean enough (red case in Figure 1.2). The sustainable landfill has the barriers to guarantee the safeness for environment the first decades, the generation time, and the emission potential will be that low that if the barriers fails suddenly after that period, there will be no problems.

2.3 European and Italian Legislation

The European Union produces directives regarding waste since the declaration of Dublin in 1990, where the concepts for guarantee a good public waste management are summed:

- “Avoidance”: prevention of waste production.
- Development of clean technologies and clean products.
- Development of technologies to decrease the waste toxicity.
- “Polluters pays”: the manufacturer is responsible for its product.
- In waste management the first priority is reuse, recycle and material recover.
- Energetic recover, trough incineration too.

- Use of landfilling limited to necessary.

These concepts are the basis on which every European Directive is made and they bring to develop a more sustainable waste management that can generally be summed in the following Figure 1.3.

Figure 1.3: Pyramidal policy for waste management in Europe. First avoidance, second material recover, third energy recover, fourth landfilling.

On the top, there is the “Avoidance”, that means trying to prevent the waste production at source and/or finding more sustainable and clean technologies that produce less or less impacting wastes. The second place, in order of importance, deals with the material recover or recycle, that aims to separate some waste categories that can be treated and converted in new resources. Energy recover is at the third place: this includes all the technologies for producing energy from waste, from incineration to anaerobic digestion and others. In last position, landfilling regards the waste that cannot be treated or used anymore and its fate is close the material cycle being buried. It is fundamental the concept of the pyramid, every passage has a certain priority, but every passage is necessary for a correct waste management system.

The Directive 1999/31/CE, named “Landfill Directive”, regulate all the landfill management. The main points are:

- Three kinds of landfills: for Hazardous Waste, for non Hazardous Waste, for Inert waste. MSW landfills are in the second category. This division is made to better manage and regulate the waste disposal, according with the kind of waste dangerousness and pollution potential.

- Supply Technical normative and guidelines for each one of the categories.

- Develop procedures for all activity.
- Discipline the post closure phase (Aftercare).
- Define the criteria for waste acceptability in a specific landfill.

The 1999/31/CE dictates that aftercare should continue for at least 30 years after closure of the landfill (EU, 1999) without more precise guidelines of inner waste conditions or possible emissions (Cossu et al., 2007).

In Italy, the first law regarding waste management is the D.P.R 915/1982, that was only a first general approach to the topic. A more complete and useful law is the D.Lgs. n°22 1997, named “Decreto Ronchi”, that applies in Italy all the European directives written before. In this regulation, there was not rules for landfill management or construction. The landfills are object of the D.Lgs. n°36 2003 that adopted the European Directive 1999/31/CE. If for landfills the 36/2003 is still valid, for waste, remediation of contaminated sites, environmental authorization and almost all other environmental topics the D.Lgs n°152 2006 named “Testo Unico Ambientale” is issued. The 152/2006 is fundamental for the landfilling too because it influence heavily the incoming waste and the general waste management strategy, even if it does not regard site construction or management.

2.4 State of the Art

There is not a unique solution to the problem of aftercare end. European Union and some other non-European countries try to give an answer approaching the problem in different ways (Laner et al., 2012).

- Specified time termination. The aftercare terminates automatically after a predetermined time. A fixed time methodology is very positive for simplicity (planning, bureaucracy, policy, etc.) but if the landfill is dangerous even after the predetermined time, the responsible will no more be the owner but the society.
- Perpetual care. The owner responsibility will never end as time goes by, but only by achieving a safe situation. This approach will avoid responsibility or costs for society but becomes complicate for the owner (planning, funding, policy, etc.) and, maybe, money will be spend to protect against insignificant risks.

- Termination when specific endpoints are reached. Authorities must fix some parameters for leachate, gas, solids and settlement, when the landfill reach them the aftercare will end. The approach is quite simple, time required can be evaluate and so planning and financial problems can be avoid, the owner is push to reach the endpoint as soon as possible and the society will have no responsibility. The negative aspect is that the approach is not site-specific.

- Termination when stability is reached. This is an approach very similar to the previous one, with the same qualities and lacks, but the parameters are only bond to waste.

- Termination based on landfill performance. A model of landfill must be built and continuously uploaded with monitoring data to well predict the behaviour of processes inside, when the safe conditions are reached than the aftercare may end. This approach is surely the best in terms of efficiency but it will be expensive and very complicate, because it requires highly professional figures for the model building and management and for the authorities control too.

The legislation and the research often try a mix of these approaches to balance the merits and avoid the deficiency of each one. As an instance, European Union indicates the specific time termination of 30 y, (like sustainability concept suggest) but at the same time the aftercare will never ends if the landfill is not safe. Research is oriented in three kinds of procedures (Laner et al., 2012):

1. Target values to evaluate aftercare is a methodology derived from the specific endpoint one. Authorities must define all parameters, threshold values, times and conditions that must be respected by the landfill and the owner must design the structure in respect of these limits. The approach is simple, it does not require highly professional figures and the aftercare termination is a mathematical issue. The absence of site-specific criteria is often solved with the addition of a site-specific analysis as Risk Assessment (Cossu et al., 2007). Another problem is the right definition of these parameters that must be made by low, and only few countries implement such system until now (Laner et al., 2012).

2. Impact/risk assessment to evaluate aftercare is an approach that foresees the use of models to evaluate the parameters to be monitored and the threshold values to be reached. The assessment is similar to European and Italian approach to remediation of contaminated sites (D.Lgs 152/2006). Sensible target must be found and a maximum

risk is assigned to them to evaluate the maximum concentration of a pollutant they can be expose with. Knowing that concentration, a transport model is built backward from the targets to the source to find the maximum concentration at source. This last value is necessary to reach and declare aftercare end. The procedure needs a professional figure to be made and, once this parameter is evaluated, it becomes similar to the target values approach.

3. Performance based on methodology is derived from the performance based termination approach that is centred on a model in constant update with monitoring data, that governs the entire landfill. This model is able to predict the future emissions and the future risk, and so the aftercare termination. The main disadvantage of this approach is the constant necessity of highly professional figure and constant monitoring.

Whatever approach is chosen to determine aftercare, at least in European Union the sustainability concept is used and so the aftercare must be close in one-generation time. Moreover, the costs of maintenance and monitoring bring the owner to reach the safe condition in the shorter time as possible to declare aftercare end. For this reason, the acceleration of the stabilization becomes one fundamental topic in waste management in the last decades. In order to reach the conditions for terminate aftercare, it is necessary increasing the degradation-extraction of pollutants for overthrow the emission potential as faster as possible. For the purpose many technologies have been developed:

1. Pretreatments applied to waste before disposal in landfill. The purpose of pretreatments is preparing the waste to the following treatments or decreasing the emission potential off situ where is easier to do.

    - Mechanical treatments generally consist in sorting of unwanted or recyclable matter, shredding, milling, compacting, etc. These processes are useful for disposing the least waste as possible, saving volume, increasing specific surface for chemical-biological activity. Generally, a mechanical pretreatment is always made before landfilling.

    - Aeration pretreatment is used especially in case of high content of organic substances. This pretreatment will rapidly decrease the readily biodegradable compounds, avoiding all the problems that degradation in landfill has.

    - Thermal pretreatments are a big family of technologies like incineration, gasification, pyrolysis, etc. They can aims to volume reduction, thermal stabilization, recover energy, divide long chains of hydrocarbons, etc. Incineration is the most common one and has the double effect of recover energy and decrease critically the volume even to 1/10 of initial one. This effect is particularly appreciate in countries with low space for landfilling.

2. In situ treatments: technologies applied during normal landfilling activities-aftercare and design before construction. The planning of these treatments must be made before construction, because many landfill's systems are designed according to them.

    - Flushing is increasing the normal water supply of a landfill. The positive effect is the L/S ratio increase that allows to extract more soluble pollutants in lower time (Valencia et al., 2009). The negative effect is lower air circulation in case of semi-aerobic landfill and its uselessness for the carbon extraction (Ritzkowsky and Stegmann, 2013). Generally increase leachate production is not applied, because of the costs of leachate treatments and because the Italian legislation does not prescribe that, even if it is a good practice.

    - Leachate recirculation is the reintroduction of a percentage of leachate in the upper part of the landfill with apposite pipes. It is used for liquid supply in arid zones, even if a leachate has not the extraction capacity of fresh water, and it is better used for redistribution of nutrients and moisture, for enhance the biological activity.

    - Semi-aerobic landfills are landfills with natural convection of air guarantee by large open pipes in the bottom. The traditional landfills are anaerobic, the oxygen presence allows to better degradation of more compounds in lower time and without producing methane gas or persistent odors. In this landfills, generally the aeration is heterogeneous, so there are always anoxic or anaerobic zones remaining.

3. Remediation treatments: technologies designed and applied during aftercare in response to a situation that will not guarantee the overthrow of emission potential. This technologies are designed in response to a specific situation that will never be solved with in situ normal technologies.

- Aeration is one of the most used technology in all traditional anaerobic landfills that still produce high quantity of biodegradable compounds and ammonia. It consists in drill pipes into landfill body by which insufflates and extracts air, changing the reaction kinetics and degrading compounds that anaerobic conditions cannot.

- Landfill mining consists of excavation of the waste and its treatment off situ.

A good practice for waste management is designed the entire cycle of treatments considering the synergic effects that one technology can be on the others, the characteristics of initial waste, the final quality that is necessary to achieve and the site specific conditions. Landfilling is a highly uncertain topic because all the uncontrolled situations possible, a good initial planning and a design that considers this problems and the possibility to change the treatments during the activity, is the best way to build a landfill. All these technologies have a mutual effect, one can enhance another, or block it, and these aspects must be considered in planning phase. Often all the three family of treatments are at the same time present in a landfill. Pretreatments are necessary to reduce initial pollutants concentration, in situ treatments for manage landfill, remediation treatments to deal with situation out of planning.

2.5 FSQ Approach

The “Final Storage” term was coined in middle eighties by the Swiss working group on landfills and it is used for indicate the old waste deposited in landfills (Cossu et al., 2007). “Final Storage Quality” refers to the quality reached by emissions and waste when all active control measures can be safely removed (Cossu et al., 2007). FSQ is an approach for aftercare termination determination based on a combination of a minimum set of general target values (to be met and tabled), together with specific target values respecting the local site conditions (find with a Risk Assesment) (Cossu et al., 2007).

A focal point of this procedure is in the indexes, with relative threshold values, that can describe the state of landfill and emissions for all the operative conditions (technologies, wastes, climate, etc.) and for all the possible pollutants. These indexes must be easy to analyze and technologically available in all Italy without too much costs.

The purposed indexes, used in this work, are (Cossu et al., 2007):

Biogas

- Total gas production (Nm3/d) or Areal biogas production (Nm3/d /m2): it is useful to verify the stability degree because, if reactions are low, the biogas production will be low or zero. If the production is zero, the gaseous emissions are zero and so the concentration of the species inside is not very important. It is difficult to evaluate properly, the best methodology is measuring the flux in the biogas catching system and evaluating the losses with a model. The areal one is evaluable with static or dynamic chambers, but this measure can be affected by chimney effect that brings gas where easy to escape creating "hot-spots" (Cossu et al., 1997).

- CO2, CH4, O2 concentrations (% total): they are fundamental to verify the state of waste and the reactions occurring. If CO2 and CH4 are 40% and 60% respectively, an anaerobic digestion is present, does not matter the age of waste: if the conditions are anaerobic, the relative percentages of these gas are always the same and the age can be determined only with production rate. If oxygen is present, even in low concentration, a semi-aerobic reaction happens. The absence of CH4 means a really well aerated situation, its presence in low concentration means that in a generally semi-aerobic landfill, there are anaerobic zones.

Leachate

- COD (mgO2/l): Chemical Oxygen Demand measures all the organic substance present in sample, biodegradable or not. This parameter can remain high even after many years because humic inside the sample. TKN is N-NH4+ plus the organic carbon so is a value always higher than the second one. Generally the ammonia presence in leachate is the great part of the TKN so often is analyze only N-NH4 even for have a measure of TKN. N-NOx (mgN/l): nitrogen oxide is mainly composed by NO2 or NO3, especially the last one. This compounds are products of nitrification process that happens in high presence of oxygen, and so in semi-aerobic landfills.and fulvic acids in landfill and must be manage carefully because does not indicate the age of waste (Cossu et al., 2007).

- BOD5 (mgO2/l): Biological Oxygen Demand measures the biodegradation of the biological substance. This test can be affected by nitrification, toxics presence and nutrients scarcity.

- BOD5/COD ratio is a good tool for estimating the age and the state of a landfill. All concentration measures are affected by the dilution of the sample that can change very much from place to place and with the climate. This ratio is not affected by these problems and it gives a pure number that generally varies from 0.5-0.6 for fresh waste to 0.1-0.0 for old one. A very old landfill can have a biodegradation capacity near zero but still emit great quantities of COD as lignine or fulvic or humic acids. The interpretation of this index can help to find nutrient scarcity or toxics. Generally the BOD5/COD ratio can be consider a good index for the stability of a landfill (Cossu et al., 2012).

- TOC (mgC/l): Total Organic Carbon gives the organic carbon emission, degradable or not. This parameter is useful as COD alternative or for the mass balance of carbon in the landfill.

- TKN or N-NH4+ (mgN/l): Total Kjeldhal Nitrogen and Ammonia measures respectively all nitrogen present in sample and ammonia nitrogen, giving the concentration of nitrogen

Solid samples of waste

- IR4 (mgO2/gTS): respiration index is the quantity of oxygen consumed during aerobic biodegradation in 4 days. This test is make with SAPROMAT equipment and is an index of residual degradation capacity.

- B21 (Nl/KgTS): Fermentation index measure the biogas produced by the anaerobic biodegradation of the sample in 21 days. This index also indicates the residual degradation capacity.

- TOC (mgC/KgTS or %): Total Organic Carbon can be also analyzed in solids and is useful for the carbon mass balance determination.

- Eluate characterization is make with the same analytical procedure of leachate. Eluate extraction can be made with a leaching test that brings a solid sample to the L/S of 10, than the eluate is filter and analyze. Eluate characterization can show the maximum extractable concentration of all compounds from the sample.

The values of these indexes must be under a certain threshold value fixed before. The procedure to evaluate FSQ is shown in the following Figure 1.4 and it is chronologically divided in steps: first, the emission analysis, than the solid ones.

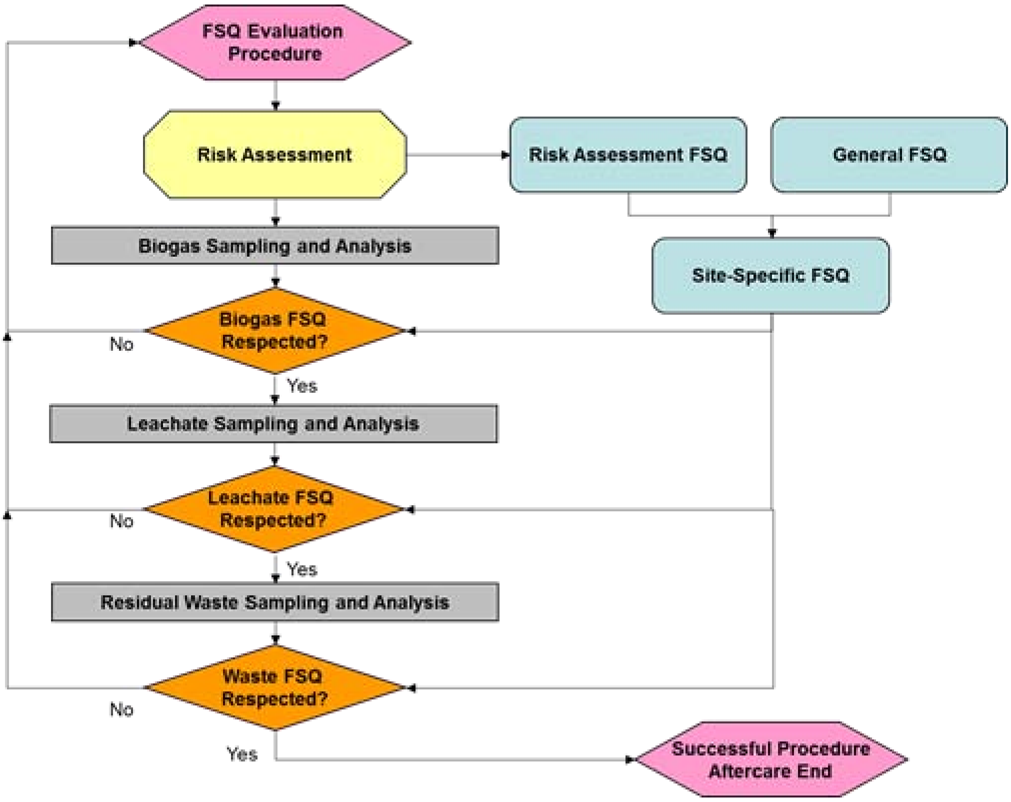

Figure 1.4: FSQ methodology, modified from the original (Cossu et al., 2007) for move up the Risk Assessment. The procedure must start when the aftercare can be terminate and finish with the authorization to aftercare end. If the FSQ are not respected than the procedure became a loop until the success.

The diagram is iterative: the first step is the Risk Assessment for the evaluation of specific FSQ for the landfill, the second is sampling and analysis of biogas, the third is leachate analysis and the last step is drill for soil samples. If a step is successful, it is possible to proceed with the following one, elsewhere not. The evaluation procedure starts with biogas analysis because it is commonly verified that its production and impact are less persistent than other emission sources (Horig et al., 1999). The second step is the leachate emissions analysis that is frequently collected and analysed for its disposal and treatment. Solids analysis are made at the end of the procedure because the sample collection and analysis are more difficult and expensive, the heterogeneity of waste requires a complex characterization campaign and the indexes considered are used as control of previous results. The Risk Assessment is performed before these analysis and it is useful to modify the general threshold values if is necessary to protect some sensible targets (Cossu et al., 2007).

3 Technical approach

3.1 Lysimeter and test cells for simulate landfills

The life of a landfill and its emission potential depend on many factors like water and air infiltration, type of waste, technology applied and many others. The final goal of the aftercare is reducing the stabilization time under the sustainable level of thirty years, but, generally, a landfill will be a potential polluter for more than this time. Moreover, a landfill is generally very big, and very heterogeneous both for waste inserted in, for age of filling and for the morphology. For these reasons, making direct measurement of a phenomena in real scale is difficult and inaccurate; some landfill simulators are necessary to reduce time and increase the parameters control. These simulators can be columns or lysimeters, depending on the dimensions and to the degree of control applicable.

Columns are small reactors (Figure 1.5 A), generally made of glass or plastic, which can contain some kilos of waste (10-50 Kg). Their dimensions allow the placement inside a building where water, temperature and air supply can be easily and carefully control, the emissions are cached, even the gaseous ones. Change management and operate on this kind of reactors is very fast. The main disadvantage of columns is that they cannot consider the heterogeneity of waste; this problem is solved by having more columns in a test campaign. These reactors allow very fast test thanks to the ideal conditions in which they operate and to the possibility to increase the liquid solid ratio very much in a short time.

Lysimeters are reactors like the columnar ones but bigger (Figure 1.5 B), they can contain more than 500 kg of waste. This increase of dimensions is useful to simulate all the phenomena due to the waste heterogeneity, like the preferential ways for the water flow, the different concentration of compounds inside the waste body, the presence of zones with different reaction types, the efficiency of the various treatments with the deepness, etc. The bigger dimensions decrease the efficiency of parameters control and the velocity of the tests. Generally they are heavily influenced by external temperature, changes have slower effects and they are more influenced to clogging of valves.

To compare the results of this laboratory tests with the real scale landfills can be reduced the timescale following a proportion or can be use other comparative scales. One of the most used is the liquid-solid ratio (L/S l/Kg) that consist in evaluate the cumulate leachate emissions for every time and substitute this values to the timescale. The accuracy of this method is due to the strict bond between all reaction and all emission processes with water circulation, except in the aerobic case where it is only sufficient the water presence (Ritzkowski and Stegmann, 2013). Despite this, the direct comparison between lab tests and field data must be always managed with caution and experience. In case of aeration, the lag-factor between lab and field performance depends mainly on the differences between the calculated (lab) and the real (field) aeration rate, the deviating aeration efficiency, the L/S ratio evaluation, the temperature and moisture differences and the higher heterogeneity of landfill (Hrad et al., 2013).

Figure 1.5: A: Columnar tests, these columns are in the ICEA department in “Voltabarozzo” Padova University. The left one are old foundry soils, the other two are fresh over-sieve >60 mm waste just putted in. These columns are high one meter, gas valves for leachate under the bottom and systems for water and air controlled circulation, can be completely filled of water and can be cover with a thermic blanket for set a temperature. Their capacity vary from 5 to 50 Kg depending on density. Gravel are dispose on the bottom and on the top of the sample to enhance the circulation of fluids. B: Lysimeter test, this reactor is in the ICEA department in “Voltabarozzo” Padova University too. This equipment is the same used in this thesis, the image is take in 2005 during the first phase of anaerobic treatment. The description of the is in the following chapter.

3.2 Lysimeter Equipement

The Padua lysimeter (Figure 1.6) is a reactor of height 3,1 m, with a square base of 80 cm length and a total volume of 2 m3. The faces are partially build of steel and partially in transparent Plexiglas, in all of them are located seven valves for monitoring biogas quality and quantity. In the right wall, there are three plastic tubes of 50 mm diameter with valves for the temperature measurement and the sampling of solids (Figure 1.6). In the main Plexiglas face, there is a HDPE pipe of 300mm diameter with holes; this tube is partially outside the reactor and partially inside the gravel layer (average size of 30 mm) that occupies the base of the reactor, over which there is the waste (Figure 1.7). The pipe function is to guarantee the natural aeration and to simulate a semi-aerobic landfill; in order to simulate a different type of landfill (as an anaerobic one) there is the possibility to close the hole with nylon. Over the gravel drainage layer, there is a geogrid to clearly separate gravel from waste and avoid the clogging of gravel. Under the drainage layer, on the bottom of the reactor, there are seven valves for the leachate extraction (Figure 1.7 A). The roof of reactor is close with a Plexiglas cap that avoids unwanted water and air infiltration (Figure 1.6 A). Forced air insufflations are guaranteed by a steel pipe in the middle of reactor (not used in this test). Water injection is made with a four-ways tubes to ensure a good distribution of water and try to reduce the preferential distribution of fluids. The thermal insulation is provided by an external polystyrene cover with a heat conductivity factor of 0,034 W/m°C that guarantees also a good protection to weathering (Piovesan, 2007) (Figure 6 B); this cover is absent in the last years (Figure 1.6 A).

Figure 1.6: Lysimeter of the ICEA department in “Voltabarozzo” Padova University. A: reactor in 2013 in “Voltabarozzo” structure. B: reactor in 2005 in “Via Loredan structure, ICEA department”. The reactor is the same but was transferred in 2007 from one structure to another.

Figure 1.7: Lysimeter of the ICEA department in “Voltabarozzo” Padova University. A: Particular of the leachate collection system under the bottom of the reactor and of the canisters used for the collection. B: Frontal view of the equipment with the leachate collection system and the natural aeration HDPE tube.

Unfortunately, some of these systems are unavailable after many years of weathering without maintenance, as instance forced aeration system and water distributing system (Figure 1.6). The HDPE aeration pipe and the drainage layer are not clogged; the water infiltration and the uncontrolled leaching are esteemed very poor. The temperature inside the reactor can be much higher compared to the outside one, because of the constant explosion to solar radiation and because of the metal walls (Figure 1.6 A).

3.3 Washing Test description

The thesis test conducted in the reactor is only the last phase of a more complex historical management regarding always the same waste since the 2005. The other phases are an anaerobic landfill simulation (Phase 1), two long aftercare semi-aerobic simulations (Phase 2 and 4), a flushing test (Phase 3) and a washing test (Phase 5, the last one). All these phases are better described in Part 2.

- Anaerobic test aims to simulate a traditional landfill where the oxygen in interstitial pores rapidly finishes and the anaerobic processes governs the reactor. In this situation, the water presence and circulation are fundamental to enhance the reactions and to redistribute the nutrients. Complete saturation (fill all interstitial pores with water) without water circulation will decrease the efficiency of the anaerobic reaction (Valencia et al., 2009). The gas composition will rise to 60% methane and 40% carbon dioxide, all free nitrogen present will escape. The kinetic is slower than aerobic one and many complex compounds like lignine, fulvic and humic acids, etc cannot be degraded in this conditions.

- Semi-aerobic aftercare test is the simulation of the period in which the filling and the main processes of a landfill are finished and the reactions go on without many controls required. Semi-aerobic is a condition by which the air circulation inside the reactor is guaranteed and so the constant oxygen presence allows the aerobic processes. These reactions have a fast kinetic and they can degrade much more compounds than anaerobic ones. Semi-aerobic stands for the imperfect aerobic conditions: the air circulation in waste body is affected by heterogeneity, lens of impermeable material, water bodies, etc that create some anoxic or anaerobic zone. The cause of this reactor cannot be defined perfectly aerobic but only semi-aerobic. In these simulations, the water is not provided but a certain moisture is always guaranteed by the uncontrolled infiltrations and the moisture in air that can enter through the aeration pipe. Aerobic reactions transforms biodegradable compounds in carbon dioxide and water, moreover the nitrogen in organic or ammonia form is nitrify to nitrates. The oxygen reduction is much faster than all other types so the efficiency of the biological process is quite high.

- Flushing test consists in the sudden increase of water injection in reactor with the double purpose to wash more soluble compounds and to enhance the possible reactions (Walker et al., 1997). This test is often performed with a recirculation for enhance the nutrient redistribution. To wash all the waste, excluding the effect of preferential flow ways of water, sometimes the reactor can be saturate but in this case, to guarantee always an active water circulation is necessary (Valencia et al., 2009).

- Washing test is a quick addition of great quantity of water that aims to extract the maximum compounds possible from the waste by leaching. The test is based on the idea that high-flushing rates produces a remarkable reduction of all concentrations in leachate (Cossu and Rossetti, 2003) (Cossu et al., 2003). The procedure is injection of fresh water corresponding to about 0,1 L/S ratio and recirculate it until leachate quantity and quality becomes stable. This recirculation is not to enhance biological processes, but to ensure the washing of all the reactor and water circulation that is necessary for pollutants solubilisation (Valencia et al., 2009). The reactor cannot be hydraulically saturated (completely filled of water), because of technical problems due to aeration pipes: this is the main reason for the low water input quantity. In any case, the aeration by natural convection (semi-aerobic conditions) is more effective with a lower flushing rate because high flushing reduces space for air in interstitial pores and because decreasing the temperature can enhance the convection process (Cossu and Rossetti, 2003). A first step will be necessary for refining the timescale of methodology according on how the lysimeter reacts to the test.

3.4 Mass Balance Approach

Mass balances are a useful tool for analyzing mobility-stability of compounds, their chemical or biological reactions, the oxidative states and their influence in other compounds presence. The balances that generally regard a landfill are mainly the Carbon and the Nitrogen ones because biodegradable organic substance and ammonia are the main two problematic polluters in leachate and because anaerobic conditions generate biogas that must be managed. Other secondary compounds presents in leachate are chlorine, sulfates and heavy metals: the first two can be found in great quantity but they can be washed to zero by water, heavy metals emissions are always quite low compared to the initial present in waste and often do not exceed the law limit emission (Manfredi and Christensen, 2009; Bigili et al., 2007).

The mass balance is based on the mass conservation formula:

$$Accumulation = input - output + production - consumption$$

Where: accumulation is what remains in landfill after the time dt, input is the waste income, output are the wanted or unwanted emission of leachate and biogas, production and consumption are the reaction happening inside waste body (Cossu et al., 2004).

$$\frac{dx}{dt}fix + \frac{dx}{dt}mob = \sum_i (Xsi * Qsi) - Xl * Qlc - Xl * Qlu - Xg * Qgc - Xg * Qgu - rV$$

The accumulation is in the left, the summary is the input considering all the different commodity-related source of the compound, the reaction term is the last one and all the subtractions are the emissions.

Where:

$\frac{dx}{dt} fix$	Is the accumulation in fixed form, no more mobile, that does not cause problems anymore. This is the term is wanted to be increase.
$\frac{dx}{dt} mob$	Is the accumulation in mobile form. This matter can still react or be emitted somehow.
$\sum_i (Xsi * Qsi)$	Is the total waste input that is the sum of the quantity of each merceologic category multiply by the compound content of each merceologic category.
$Xl * Qlr$	Is the mass of compound emitted in a controlled way by leaching: Qlr is the flux of leachate collected, Xl is the compound fraction in leachate.
$Xl * Qlu$	Is the mass of compound emitted in an uncontrolled way by leaching: Qlu is the flux of leachate that escape the collection and reach the environment outside the barriers, Xl is the compound fraction in leachate.
$Xg * Qgc$	Is the mass of compound emitted in a controlled way by gas: Qgc is the flux of biogas collected, Xg is the compound fraction in biogas.
$Xg * Qgu$	Is the mass of compound emitted in an uncontrolled way by gas: Qgu is the flux of biogas that escape the gas collection systems, Xg is the compound fraction in biogas.
rV	Is the reaction term, composed by the volume of reactor plus the kinetic constant. According with the compound characteristics and with the reaction conditions the kinetic constant can change very much.

The landfill goal is to avoid environmental pollution, before the stabilization of the waste. For this purpose it is necessary to rewrite the main equation transferring to left the uncontrolled emission to be avoided and to right all other terms.

$$Xl * Qlu + Xg * Qgu = \sum_i (Xsi * Qsi) - Xl * Qlc - Xg * Qgc - \frac{dx}{dt} fix - \frac{dx}{dt} mob - rV$$

According with this mathematical equation, in order to avoid the uncontrolled pollution it is necessary to avoid waste input (with minimization of waste, reuse, recycle), increase reactions (with increase kinetics, aerobic reactions, nutrient supply, recirculation of leachate), increase stable accumulation forms, increase leachate controlled emissions (allowing and facilitating water input in landfill) and increase gas controlled emissions (with a good collection pipes system).

The wanted mass balance for each pollutant is the one explained in Figure 1.8 with carbon. All the initial unstable, soluble and mobile compound is degraded and extracted under control to reach the final situation where the remaining compound is almost only stable. In this situation the landfill is safe, if this situation is reached in one-generation time the landfill is sustainable.

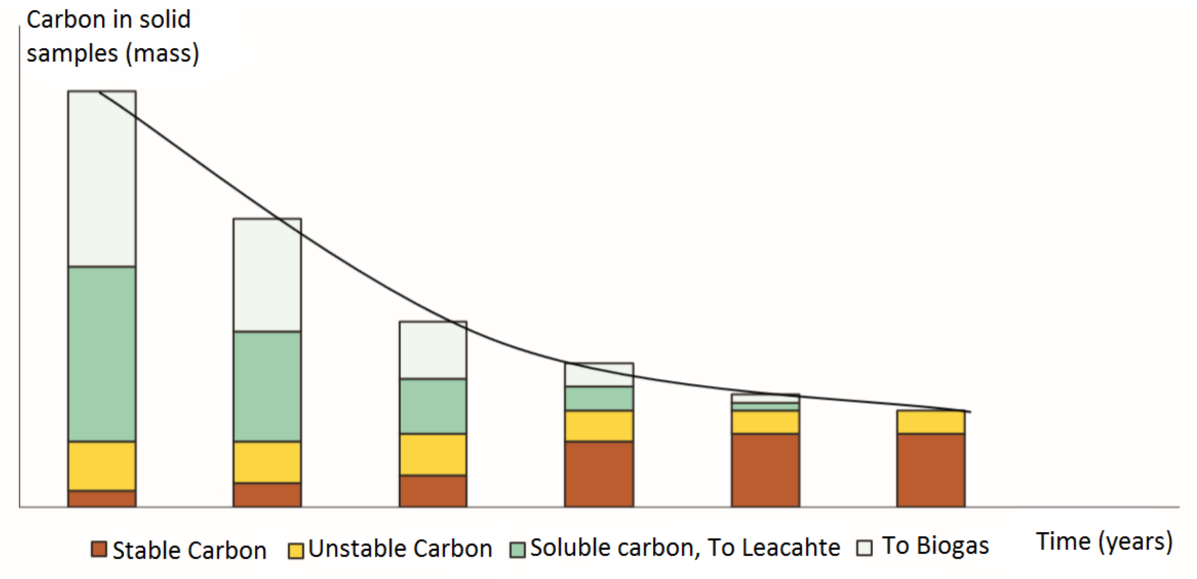

Figure 1.8: Speciation of carbon in a landfill (Piovesan, 2007). The carbon initially deliver in a landfill inside waste is mainly unstable degradable and/or soluble carbon that can generate leachate pollution, gas production and reactions. During years, the carbon will be partially extract and partially becomes a stable immobile form. At the end of this process it will be all stable compound that create no problems anymore (Carbon sink). The velocity of this process depends mainly on the site conditions and on the landfill management apply.

The sustainable landfill goal is the same of the normal engineered landfills but it must be achieved in a one-generation time, which means 30 years. This short time requires faster technologies for the stabilization and the encouragement of leaching controlled emissions to extract the maximum pollutants as possible.

The pollutants in a landfill can be thousands, form different families, with different effects. This abundance is due to the delivery to disposal of almost everything, potential hazardous objects too. Generally, the trace pollutants are not a problem because the mineral barriers will catch them and because they can be diluted in waste body. The real problem comes from the family of compounds present in great quantity. Because this abundance the easiest way to make balance is consider the elemental species: Carbon, Nitrogen, Chlorides, Sulphur (sulphates), and heavy metals mainly.

Carbon is the base of all organic compounds and it is the main polluter of a MSW landfill (Figure 8). Degradation of organic compounds generates almost all the landfill emission problems as pollution, odours, biogas and leachate. Organic carbon can be biodegradable (unstable) and unbiodegradable (stable) and they can be emitted both as leachate and gas. In anaerobic conditions (traditional landfills), biogas emission can be abundant for many years and compose more or less by 40% carbon dioxide and 60% methane; leachate emission is generally very rich of anaerobic digestion products. Aerobic digestion produces only carbon dioxide as gaseous emission and the leachate is less rich of degradable carbon because the kinetics are faster. Carbon is the most studied mass balance (Cossu et al., 2004).

Nitrogen is the other main landfill pollutant on quantity. It is generally present in landfills as ammonia and organic nitrogen bonded in organic matter. In anaerobic condition, its emission is only through leaching and it is quite slow; in fact, many landfills have levels of ammonia still high after decades. In aerobic condition, the situation can be more complicate because, if oxygen supply is sufficient, the nitrification process starts and converts the ammonia in nitrates. Nitrates are another source of pollution because they are soluble and can be extracted by leaching. In semi-aerobic landfills, there are often anoxic or anaerobic zones where the aeration is not efficient. In this zones, the denitrification of nitrates to free nitrogen gas happens. Totally in aerobic landfills the nitrogen emission can be in leachate (ammonia and/or nitrogen) and by gas (free nitrogen that does not cause pollution).

Chloride is a soluble compound that is often found in great concentration in landfill leachate. Its formation is due to plastics presence and other matter with Chlorine content. Sulphides come from the oxidation of sulphuric compounds, more abundant in aerobic conditions. Even this compound is often present in leachate, but its mass balance is quite difficult because of the great number of sulphur speciations and reactions possible.

Heavy metals can be found in great quantity in solid samples of waste but their leachate emissions are very poor. Their solubility depends mainly on pH (that must be under 6,5 to have a good solubilisation) and on humic substances presence (because they are generally bond to them) (Bigili et al., 2007; Manfredi and Christensen, 2009). If the pH is over 6.5 and the organic substance emission is poor, as in old landfills, the metals emission will be very low.

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Part 2

Scientific article

Abstract

Landfill aftercare completion is a target that must be achieve, for closing the waste management cycle. Final Storage Quality is one method for evaluate the site condition and establish if the landfill is environmentally safe or not. FSQ approach requires the definition of some indexes and threshold values that can describe the safe situation: once these values are respected, the landfill is safe and the aftercare can be terminate. The purpose of this work is evaluate the threshold values for a semi-aerobic landfill through a lysimeter washing test and comparison of results with other similar test, this comparison is made through the liquid/solid ratio as standardization parameter. The results show that the semi-aerobic conditions can rapidly stabilize biologically the organic carbon pollutants, even if the water supply is very low. For all other pollutants, the leaching is the only way to stabilize the waste and so an abundant water supply is necessary.

Summary

1. Introduction

The problem of landfills aftercare is a main topic in waste management and joins technical, political and economic aspects. The main issue is establishing aftercare termination and carrying out site-specific analysis to define appropriate landfill management options. There are several approaches to this problem (Laner et al., 2012): one of them is the FSQ approach, that considers the aftercare completion when some emission limit values are respected (biogas, leachate, solids, geotechnical stability) plus a risk assessment to be more site specific, if required (Cossu et al., 2007).

Aftercare phase can be considered finished when the emission potential is that low that the actual emissions do not harm the environment (Heyer et al., 2003; Cossu et al., 2007). This concept is strictly linked to the Final Storage Quality definition. The “Final Storage” term was coined in middle eighties by the Swiss working group on landfills and it is used in order to indicate the old waste deposited in landfills (Cossu et al., 2007). “Final Storage Quality” refers to the quality reached by emissions and waste when all active control measures can be safely removed (Cossu et al., 2007). According to this definition the aftercare may end when the waste reach the quality defined by FSQ criteria. These FSQ criteria are not universally defined yet, because the lack of reliable data and research. Moreover, little is known about the time to reach FSQ (Hjelmar and Hansen, 2005). To fix properly these indexes and their limit values, many long-term landfilling simulations have been carried on by different research groups and many field data have been collected. Anaerobic landfills with high L/S ratio are well studied and quite well known, less long-term studies are made on the new semi-aerobic landfills that requires a lower L/S ratio to stabilize carbon and nitrogen (Ritzkowski and Stegmann, 2013).

FSQ approach is very friendly with law because its simplicity. This is why the eventual achievement of FSQ is implicitly assumed in most landfill regulations, including the European directive 1999/31/CE (Laner et al., 2012; Hjelmar and Hansen, 2005). The methodology is grounded on the definition of some descriptive indexes and their threshold values, studied to guarantee both environmental and human safety and technical-economic feasibility. Indexes and values considered are alike each other because landfill emissions depends on the initial waste composition, that is comparable for all Europe, and because the basic design elements of modern engineered landfills are similar (Laner et al., 2012). The choice of these parameters must aim to characterize the emissions and the state of the landfill, with the least parameters as possible. Generally the research is focus on biogas quantity and quality (methane and carbon dioxide concentrations), leachate quality (carbon, nitrogen, chloride, sulphates and metals emissions), solid waste stability (Ir4, B21) and geotechnical stability (Laner et al., 2012; Cossu et al., 2007). Many research groups give some threshold values elaborated from field or test data. Most of these limits are fixed arbitrarily to guarantee environmental safeness but, in reality, require centuries to be reached (Manfredi and Christensen, 2009). Regarding the time required, the sustainability concept prescribes that they must not emit pollutants anymore in one-generation time, which means 30 years, that is equal to the minimum period for aftercare fixed by the European law (EU, 1999). Many methods have been considered for reduce the stabilization time: pretreatments, in situ treatments, remediation technologies. All this methods help to reach sustainability in shorter time but, as said before, the target values to be reached are not universally defined but only purpose (FSQ) (Cossu et al., 2007). For a good landfilling and aftercare management is necessary the knowledge of the targets to be reach, elsewhere the design of structures and treatments can be only a general estimation. For this purpose, the knowledge of these limits is a fundamental prerequisite for the design of treatments and not vice versa.

1.1 Goals

The present paper aims to evaluate the FSQ threshold values for gaseous and liquid emissions and for solid waste in case of semi-aerobic MSW landfill.

- A Lysimeter reactor is used for studying the status and the possible emissions of very old drained landfill with poor historical infiltration of water and presence of air in interstitial pores (Long aftercare of a semi-aerobic landfill). This reactor is heavily washed with water to increase rapidly the liquid-solid ratio and to evaluate the emission potential of the main polluters present in MSW landfill leachate. A historical research is made (Chapter 2.3) to evaluate the total emissions of the waste, considering all the tests made on lysimeter before. Analysis on residual waste are performed at the end of test to characterize the waste residues in reactor (Chapter 2.4).

- Results obtained are compared with other semi-aerobic tests in literature, using the liquid-solid ratio (Chapter 3). FSQ threshold values can be estimated from the L/S ratio at stability, the final concentration and the percentage of emission of all compounds respect to initial amount in Solid waste.

- Evaluated FSQ are compared with the ones purposed in literature or fixed by law (Chapter 3).

1.2 FSQ Methodology

FSQ is a threshold limits method to declare aftercare end, plus a risk assessment to be more site specific (Cossu et al., 2007). The design of the method is a step-by-step process that aims to evaluate, in order, biogas emissions, leachate emissions, solids composition and, finally, geotechnical stability. If the response of the first step is positive, follows the second; if steps are all positive, the landfill is no more a source of pollution and can be declared close (Figure 2.1). The evaluation of parameters starts from biogas and leachate because these emissions are well monitored and easiest to analyse (Horig et al., 1999). All these processes will be site specific because a risk assessment will identify the sensible targets and will correct the threshold values, if necessary.

The FSQ process is the one in Figure 2.1: the original idea is from (Cossu et al., 2007) that purpose this methodology. The present step-by-step schema is modify to move up the Risk Assessment, for the site-specific criteria determination, before the start of analytical procedure. The Procedure starts when the Final Storage Conditions are nearly reached, the Risk Assessment is immediately made to evaluate if the general FSQ threshold values need to be more precautionary because site specific particular conditions. After that biogas, leachate and residual waste are sampled and analysed to verify the FSQ criteria respect. If the procedure is successful, the aftercare may end.

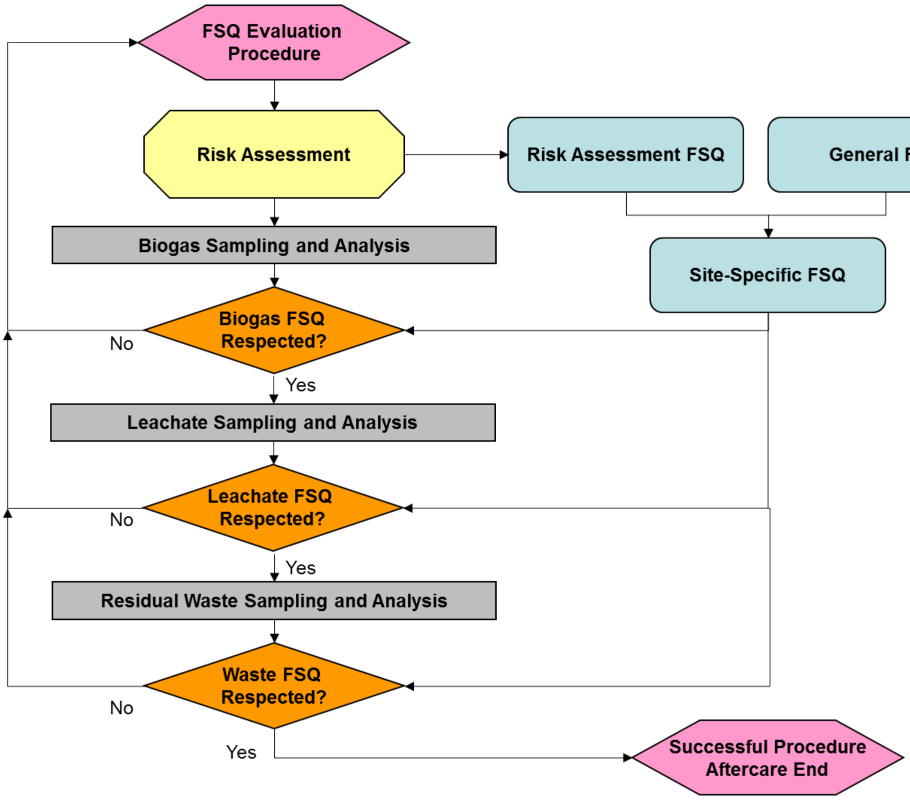

Figure 2.1: FSQ methodology, modified from the original (Cossu et al., 2007) for move up the Risk Assessment. The procedure must start when the aftercare can be terminate and finish with the authorization to aftercare end. If the FSQ are not respected than the procedure became a loop until the success.

The main difficulty, for the development of this method, is the correct determination of indexes and their threshold values. Theoretically, the FSQ values must be the same for all situations but the performances can be very different according with the technology choose: for this reason is necessary to proceed with the analysis of each kind of landfill separately. This work deals with the semi-aerobic type. Some other authors face the same problem with a threshold limit approach and the results are very comparable, especially in nitrogen and carbon emission parameters and values, less study focus on heavy metals or other pollutants (Laner et al., 2012).

The FSQ indexes considered are the ones purposed by Cossu et al. in 2007, with some additions that the semi-aerobic case requires or due to the recurring presence of some polluters (as instance nitrates):

- For Biogas: CH4 surface specific emission will be sufficient for verify presence of possible anaerobic zones that the metanotrophic landfill cover is not able to remediate: “hotspots”.

- For leachate: carbon and nitrogen components (COD, BOD5/COD ratio, TOC, ammonia, TKN) are considered with the addition of chloride, sulphates, nitrates and some heavy metals.
- For solids: a respirometric index (as instance IR4) is considered, eventually a leaching test.

2. Test Description and Results

2.1 Test Description

The lysimeter was filled with an amount of 750 kg of waste collected from a pre-treatment plant in Legnago (Verona) in May 2004. The waste incoming in the structure is jet source sorted for separate putrescible matter, plastic, paper, glass and metals. In the plant, the residual waste is sieved (60mm) and aerobically treated to stabilize the biodegradable fraction before landfilling. The 750 Kg of waste for the test have been taken immediately after the sieving and before the biological stabilization. The initial waste chemical characterization is reported in the Table 2.1, chapter 2.4.

The reactor has been managed for years with different tests, so that the waste life can be subdivided in five different phases, according with the treatment and the time:

- Phase 1, Anaerobic conditions with 10 l/w (litres per week) water injection (Padua average precipitation) for the first 180 days until reaching L/S ratio = 0,33 l/kg. Weekly analysis of leachate, temperature and biogas composition.
- Phase 2, semi-aerobic aftercare without water injection for 800 days. During the aerobic aftercare, the water circulation is null but some humidity and, also, some uncontrolled injection of rain can be present. Moreover, the leachate can escape uncontrolled if the inner level reach the aeration tube. No samples are take and no analysis are make.
- Phase 3, semi-aerobic flushing test with 28 l/w water injection (3 times Padua precipitation) for 2 months, until reaching 0,5 l/kg. (Cossu et al., 2007)
- Phase 4, semi-aerobic aftercare without water injection for 2100 days. During this phase, some uncontrolled inlet of rain can be present, as explain in Phase 2. No samples are taken and no analysis are made.

- Phase 5, washing test with 750 l of water (divided into 7 injections during for 3 months). The total amount of leachate was 540 l because the high evaporation during the summer in Italy and because the waste was very dry. Starting the phase 5, this uncontrolled water circulation is consider negligible because of the low possible infiltrations, because the inner water level was lower than the tube and because the trace of old liquid levels does not reach the tube too.

In particular, the Phase 5, object of this work, consists in:

- STEP 1: injection of 150 l of fresh water inside the reactor and monitor the leachate emissions quantity for some days (6-7). All leachate emitted must be recirculated and, every one or two recirculation, analysis of the pollutants concentration must be make in a sample taken from the homogeneous leachate (sampled just after exit). When leachate quantity and quality become stable, the step is finished, the final leachate amount is the one that will increase the L/S ratio. This process is useful for study the characteristics of reactor, its emissions, water leach-ability in waste with poor moisture for years, possible jumping effects of pollutants and how behaves the increase of concentration every recycle of the same water. The performed analysis are pH, conductibility, COD, TOC, TKN, ammonia, chlorines, sulphates and heavy metals (cadmium, chromo, copper, iron, manganese, nickel, lead, zinc). BOD5 is virtually zero after 3 years of aerobic degradation. First step (STEP 1) is structured to be long and with frequent analysis for refine the timescale of methodology according on how the lysimeter reacts to the test, from the second step, the process will become quicker.

- STEP 2-7: injection of about 100 l of fresh water inside the reactor, daily recirculation for 4 times, sampling and analysis on the second and the fourth recirculation. This washing methodology is developed according with results of the first step where the water injection exits almost completely in one day and the concentration of pollutants becomes stable after four recirculation. In this test the leachate recirculation is not made for enhance any process but to well wash all the waste and to have a significant sample for all liquid extracted. This step is repeated six times (STEP2-STEP 7), every one of these phases increases the L/S ratio of the reactor. STEP 8 is the analysis of the leachate emitted between the last washing (STEP7) and the reactor emptying, without injecting water.

- SOLIDS ANALYSIS: sample of solids are taken before the first washing step and after the last. Their analysis are fundamental for mass balance construction and for FSQ evaluation. Moreover, all the old stable waste extract from the reactor will be weight and characterize to evaluate all possible changes in all these years of reactions, flushing and washing. The performed analysis are total solids, volatile solids, ammonia, TKN, TOC and heavy metals (cadmium, chromo, copper, iron, manganese, nickel, lead, zinc), for the leachable part: PH, conductibility, COD, chlorines and sulphates.

The washing test aims to determine the threshold values for the FSQ parameters so it will be design for extract the maximum compounds possible from the waste by leaching. The test is based on the idea that high flushing rates produce a remarkable reduction of all concentrations in leachate (Cossu and Rossetti, 2003; Cossu et al., 2003). The procedure consists in injection of around 100 litres of fresh water per step (corresponding to about 0,1 l/Kg L/S ratio) and recirculation until leachate quantity and quality become stable. This recirculation is not made for enhance biological processes but for ensure the washing of all the reactor and ensure water circulation that is necessary for pollutants solubilisation (Valencia et al., 2009). The reactor cannot be hydraulically saturated because technical problems due to aeration pipes; this is the main reason for the low water input. In any case, the aeration by natural convection (semi-aerobic conditions) is more effective with a lower flushing rate, because high flushing reduces space for air in interstitial pores and decreases the temperature that can enhance the convection process (Cossu and Rossetti, 2003).

2.2 Test Apparatus and Analytical Methods

The experimental phase was carried out with a big landfill simulator (lysimeter) of approximately 2 m^3 of volume, equipped with water and a holed HDPE tube (600mm) on the bottom to enhance the air natural circulation (semi-aerobic conditions). Collection systems for leachate are in the bottom, biogas and temperature can be monitored from holes in the flanks and sampling points for residual waste are present at different heights. The lysimeter is useful for developing tests in a controlled environment, as column tests, but in large scale to better simulate landfill condition effect of waste heterogeneity, preferential ways for water circulation, nutrients and toxics heterogeneous distribution. The water injection is made in the upper part with the caution of distribute the liquid in all the waste body. The hydraulic saturation (complete filling of reactor with water) is impossible because the aeration tube will leachate out and because the air circulation will be no more guarantee elsewhere (Valencia et al., 2009). The reactor is open air so it is highly influenced by the external temperatures of Northern Italy.

Leachate samples are taken from the collection tanks under the lysimeter, by paying attention that the sample is representative for all the liquid extract. The residual waste samples collected before 2013 are residual waste tal-quale and the sample is made from the sampling tubes on the flanks of lysimeter. The residual waste collected September 2013 is taken from five different deepness and milled to increase the analytical reliability. The analytical methodologies used are all certified (Table 2.1). Leaching test is carried on for all residual waste sample following the UNI EN12457-2 standard, except for the absence of milling in the samples before 2013. The results show the effect of a 10 l/Kg L/S ratio increase, that is considerable as the maximum emission potential of the waste.

Table 2.1: Analytical standards for leachate and residual waste analysis.

Analytical standards for leachate	
pH	IRSA-CNR 29/2003, Vol1, n.2060
Conducibility	IRSA-CNR 29/2003, Vol1, n.2030
Total Organic Carbon (TOC)	IRSA-CNR 29/2003, Vol2, n.5040
Ammonia (NH3, titolazione)	IRSA-CNR 29/2003, Vol2, n.4030 C
Total Kjeldahl Nitrogen (TKN)	IRSA-CNR 29/2003, Vol2, n.5030
Nitrates (NO3-)	IRSA-CNR 29/2003, Vol2, n.4040 A1
Biological Oxygen Demand (BOD5)	IRSA-CNR 29/2003, Vol2, n.5120 B2
Chemical Oxygen Demand (COD)	IRSA-CNR 29/2003, Vol2, n.5130
Sulphates (SO4--)	IRSA-CNR 29/2003, Vol2, n.4140 B
Chlorine (Cl-)	IRSA-CNR 29/2003, Vol2, n.4090 A1
Metals	IRSA-CNR 29/2003, Vol1, n.3010 mod.+3020
Analytical standardss for residual waste	
Total Solids (TS)	IRSA-CNR Q. 64/84, Vol2, n.2
Total Volatile Solids (TVS)	IRSA-CNR Q. 64/84, Vol2, n.2
Total Organic Carbon (TOC)	UNI-EN 13137
Ammonia (NH3)	IRSA-CNR Q. 64/86, Vol3, n.7 mod.
Total Kjeldahl Nitrogen (TKN)	IRSA-CNR Q. 64/85, Vol3, n.6 mod.
Respirometric Index	ANPA 3/2001 n.12.1.2.3.

2.3 Leachate Data elaboration

The first washing (STEP 1 of Phase 5) starts the 20th May 2013 and finishes the 25th of June 2013. As pilot test, the clean water injected in the reactor is 150 l and after eight weekly recirculation and several analysis, the leachate outputs and pollutants concentrations become stable. Results show that are sufficient four daily recirculation to reach hydrological and concentration regularity (Figure 2.2).

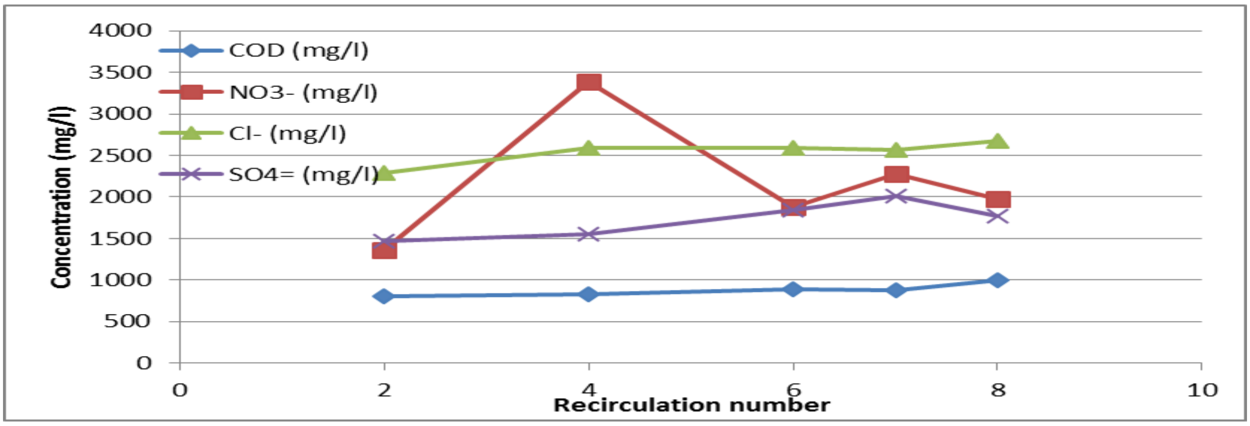

Figure 2.2: Step 1, Phase 5. Pilot test for Washing methodology, useful for optimize the following steps (2-7). In horizontal axe the number of recirculation of the same leachate, in vertical one the concentration of the main

The recirculation of all the extracted leachate, without water additions, increases only a little the extraction capacity of the fresh water initially injected, the 80-90% of compounds washed are dissolved in the first injection. Figure 2.2 shows this aspect: the first point is the leachate after two recirculations (Cl- as instance are 2250 mg/l), after four recirculations, the concentration is little higher (Cl- is 2500 mg/l), after 8 recirculations the results are the same. In this reactor, leachate recirculation has not the same extracting capacity of fresh water, the recirculation has the fundamental role of redistribute moisture and nutrients but is not so efficient for extract more pollutants with the same water. According with these results, only four recirculation will be necessary for the following steps (STEP2-STEP7), each one with only two samplings: the first to control the concentration regularity (after second recirculation) and the second to characterize the final extracted leachate (at the end of each step). The time between one recirculation and another is one day, because 80% of leachate exits in the first 2 hours and more than 95% in the first day.

Steps 1 to 8 concentration results are in the Figure 2.3 and show how the test has performed, cumulative massive emissions are in Figure 2.4.

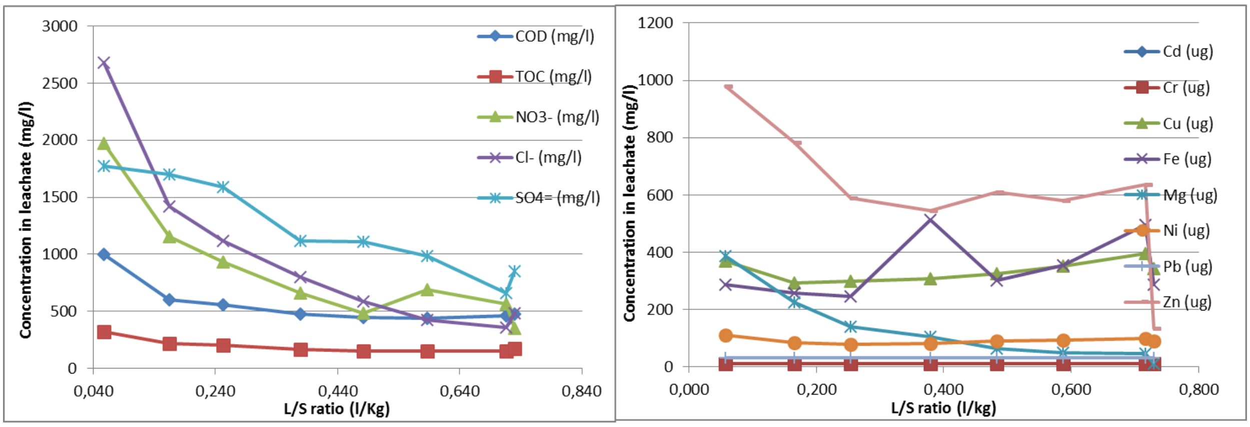

Figure 2.3: Step 1-8, Phase 5, Final concentration results for each step (mg/l) versus L/S ratio (l/Kg). A: COD, TOC, NO3, Cl-, SO4—concentrations, all decreasing constantly with increase of leachate extraction. B: Heavy metals concentrations, the behaviour is quite constant despite the increase of L/S ratio.

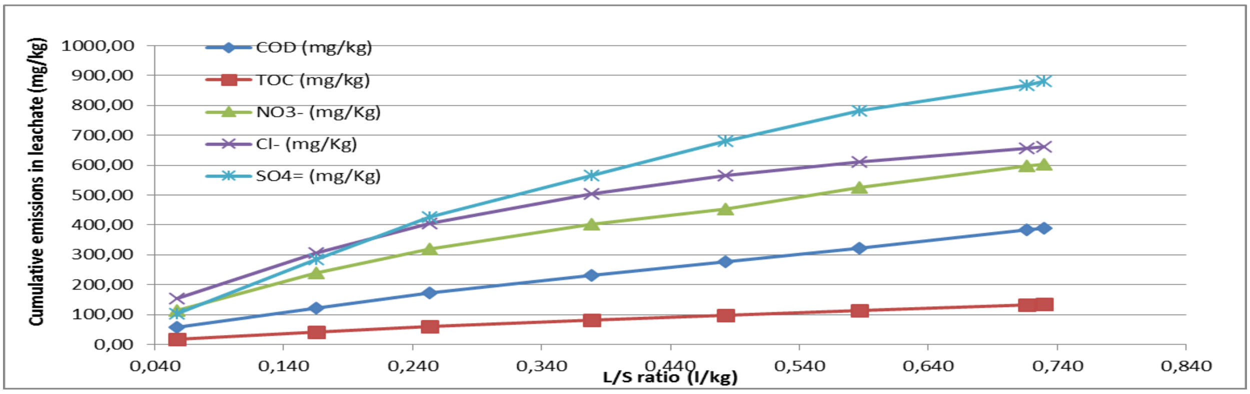

Figure 2.4: Step 1-8, Phase 5, Cumulative emissions in leachate (mg/Kg) versus test L/S ratio (l/Kg). The figure can show how each pollutant's mass extraction is in constant slow decrease. A behaviour characteristic of old stable wastes.

All concentrations trend in Figure 2.3 is decreasing slowly : carbon indexes (COD, TOC) are jet very stable because of the aerobic conditions, equally ammonia and TKN are undetectable because in aerobic conditions are converted into nitrates that are washed away (nitrification process). Chloride sulphates and metals presence in reactor decrease regularly with the washing. In the Figure 2.4 the cumulate extraction of contaminants is visible in mg per kilo of initial waste in reactor. The pictures show only leaching removal effect, no biological reactions can be observed because of the high stabilization degree of the waste.

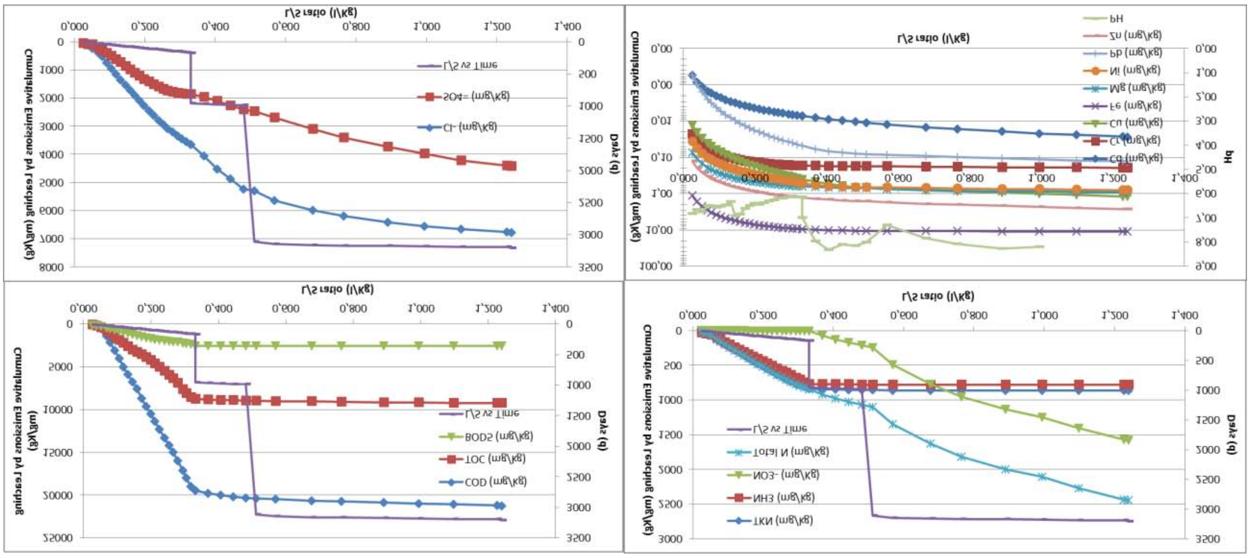

Figure 2.5: Phases 1-5, Cumulative Emissions Plots (mg/Kg) versus L/S ratio (l/Kg). A: Carbon indexes, B: Nitrogen indexes, C: chlorine and sulphates, D: Heavy metals in logarithmic scale. In A,B,C is plot the L/S ratio versus the time, in secondary vertical axe, to evidence the 2 aftercare simulation (300-1000 d, 1000 - 3000 d) where water injection was zero, in plot is a stair. In D is plot the pH in secondary vertical axe to evidence the dependence of heavy metal extraction respect to the pH.

Figure 2.5 reports the release amount of different compounds referred to the entire experimental period (phase 1-5). The L/S ratio is used as reference in place of time (horizontal axe), because water circulation governs the leachate emissions (Walker et al., 1997), but also air presence has a fundamental role in biodegradation in semi-aerobic conditions, even if the water circulation is absent (Ritzkowski and Stegmann, 2013). The L/S ratio is plot versus the time in right vertical axe to highlight the two periods without water circulation and to relate the L/S ratio to the time. The first aerobic aftercare creates a stair in the emission plots sensible to biological reactions; this phenomena is not observed in the second one, because the degradation processes are almost complete. The left vertical axe reports the emission in mg per Kg of initial waste.

COD, BOD and TOC are indexes that measure carbon emissions from leachate. They increase very much in the first anaerobic phase and suddenly fall off in the third one; this means that, in the aerobic phase, all the missing carbon has been emitted in CO2 form and that now the waste is biologically stable. The behaviour proofs that in aerobic conditions the water circulation is not fundamental but only a sufficient moisture presence in waste, for the organic carbon pollutants remediation (Ritzkowski and Stegmann, 2013). BOD5/COD ratio is a fundamental tool to describe the status of a landfill. COD index comprises also many non-biodegradable compounds, so it cannot be used as a stability index by itself. BOD measures the biodegradable carbon, but it can be affected by toxics presence or moisture-nutrients absence and other problems. Both of them are concentrations, which means that they depend on the water input. Joining the two parameters in a ratio BOD5/COD, the negative aspects of the single index are mitigate and so it is possible to make a good evaluation of the stability state of the leachate and of the landfill (Cossu et al., 2012). After 1000 days, the BOD5 is almost undetectable because of the long aeration period (the ideal conditions of the reactor that allows an abundant air circulation). This is visible in the Figure 2.5, where the BOD5 becomes suddenly constant and COD (500 mg/l) and TOC (200 mg/l) emissions become low and quite constant too. All the biodegradable carbon is converted in CO2 or in no more biodegradable compounds. Under full-scale conditions, a complete reduction of organic carbon (TOC or COD) would be unrealistic and not achievable in a reasonable time (Ritzkowsky and Stegmann 2013).

TKN, ammonia and nitrates (express in mg of nitrogen) are all indexes of nitrogen presence in waste. Nitrogen is initially present in form of ammonia and organic nitrogen, in anaerobic phase the emissions are only due to leach ability of these compounds. In the following aerobic phase, the nitrification process starts, enhanced by the oxygen presence, by which the ammonia is partially transformed in nitrates. A confirmation of this process is the presence of nitrates in leachate: nitrates are present only in aerobic phase and they are undetectable in anaerobic one. Nitrates can be converted in free nitrogen with the Denitrification process that requires anoxic conditions; in a semi-aerobic landfill, the presence of anoxic zones not reached by aeration is possible, but this test guarantees too much air circulation to consider this aspect. The long-term nitrogen emission in semi-aerobic environment can be only in form of nitrates, in presence of sufficient oxygenation like in this test, because TKN and ammonia concentrations are virtually zero. The sum of the nitrogen emission (organic N, ammonia and nitrates) is in Figure 2.5, plotted as Total N, and it has a behaviour quite constant, without evident stairs. This means that, despite the form in which nitrogen is present in reactor, nitrogen emission happens only by leaching, so water circulation is fundamental for nitrogen removal.

Chlorides does not react so the anaerobic or aerobic conditions does not affect their presence in leachate, the only think that can affect their leach ability is pH. This is confirmed by the Figure 2.5, where there are no sudden stairs in leachate emissions, because the concentrations depend only on the washing of these compounds. This means that the remediation of a semi-aerobic landfill must considered a sufficient flushing of water to remediate secondary pollutants and the nitrates (Raga and Cossu, 2013; Manfredi and Christensen, 2009).

Heavy metals are emitted in very low concentrations in leachate (Figure 2.3 and 2.5), even if their presence in initial waste is quite high, this because only a very small fraction of the total amount is leachable (Oygard et al., 2004). PH is considered to be the most significant parameter affecting metal concentration in landfill leachate because their dissolution is enhanced at low pH (4-6) but is blocked at high pH (8-13) by the sorptive capacity of soils and organic matter in waste. Generally young leachates have low pH and so leachate contains more metals that old ones or aerated ones, the pH increase rapidly with leachate recirculation (Bigili et al., 2007; Manfredi and Christensen, 2009). This low emission potential depends on pH mainly but also by COD, especially Humic substances, because metals can be bonded to them. The ideal conditions for landfills metals extraction are the anaerobic methanogenic phase (because its low pH respect acid or aerobic reactions) with low recirculation of leachate (to not return the metals to landfill) (Qu et al., 2008). Heavy metals emissions in leachate are generally low, always under 1% for Cr, Cd, Hg and Pb (Manfredi and Christensen, 2009) and so their concentration in landfill leachate is not a major concern (Bigili et al., 2007).

2.4 Solids data elaboration

The analysis on solids are fundamental for the mass balance and for the evaluation of the extracted pollutants with biogas or leachate. The waste characterization in different phase of the experiment are reported in Table 2.2, the analyses are performed in triplicate.

Table 2.2: Phase 1-5, Solid Waste Analysis and Leaching test. The upper results refers to the sample tal-quale, in columns from left to right: Phase, date, L/S (l/Kg) ratio of water injection, Total Solids (%), Volatile Total Solids (%TS), Total Organic Carbon (%TS), Total Kjeldahl Nitrogen (%TS), Ammonia (%TS), Heavy metals Cadmium, Chrome, Copper, Iron, Manganese, Nickel, Lead, Zink (mg/KgTS). The lower part Refers to analysis on leaching test elute, in columns from left to right: Phase, date, L/S (l/Kg) ratio of water injection, pH, Total Organic Carbon (mgC/l), Chemical Oxygen Demand (mgO2/l), Biological Oxygen Demand (mgO2/l), Total Kjeldahl Nitrogen (mgN/l), Ammonia (mgN/l), Nitrates (mgN/l), Chlorine (mg/l), Sulphates (mg/l). In nov 2004 the sample is take from fresh waste under-sieve, it is not milled, 3 saple are made and the results are the average. In 2007 the sample are take from the three sampling pipes of the reactor, they are not milled, the analysis results are the average. In may 2013 the samples are take excavating the first 75 cm of reactor, the sample is milled 5 mm, the sample is unique. In sept 2013 five samples are taken from a manual drilling of the residual waste, the sample is milled 5 mm, the analytical result is the average.

Solid Waste sample	date	L/S ratio	TS (%)	TVS (%TS)	TOC (%TS)	TKN (%TS)	NH3 (%TS)	Cd (mg/KgTS)	Cr (mg/kgTS)	Cu (mg/KgTS)	Fe (mg/KgTS)	Mg (mg/KgTS	Ni (mg/KgTS)	Pb (mg/KgTS)	Zn (mg/KgTS
Start Phase 1	nov-04	0	44,5	48,5	31,1	1,50	0,27	1,0	11,3	52,0	3862,3	83,0	4,4	20,0	974,9
Start Phase 3	jun 07	0,331	47	28	20,1	1,03	0,12	1,8	30,0	2226,8	31053,7	275,7	276,6	61,5	2192,0
End Phase 3	jul 07	0,481	41,4	26,5	19	0,98	0,11	1,0	34,7	202,2	11290,8	244,1	23,9	235,0	595,1
Start Phase 5	may 13	0,511	86,1	40,1	46,6	1,33	0,10	1	71	277	8369	145	51	257	548
End Phase 5	sep 13	1,241	71,5	25,0	25,3	0,93	0,07	0,97	37,1	3117,0	13860,0	167,0	38,7	309,1	2038,0
Leaching test	date	L/S ratio	PH	TOC (mg/l)	COD (mg/l)	BOD5 (mg/l)	TKN (mg/l)	NH3 (mg/l)	NO3$^-$ (mg/l)	Cl$^-$ (mg/l)	SO4$^=$ (mg/l)		IR4 (mgO2/gTS)	IR7 (mgO2/gTS)	B21 (Nl/KgTS)
Start Phase 1	nov-04	0		570	1482	917	36	18,4					66,4	106,7	29,8
Start Phase 3	jun 07	0,331	8,1	83,6	191,7	10	<10	3,4	55,1				1,8	2,7	3,2
End Phase 3	jul 07	0,481	7,6	58,2	93,5	0	<10	1,5	428				0,7	1,3	2,7
Start Phase 5	may 13	0,511	7,71	46	220,5	0		5,6	103,5	160	303		1,67	2,23	
End Phase 5	sep 13	1,241	7,93	32	184,24	0		4,7	17,16	31	259		0,69	0,88	

At the end of the experiment, residual waste is sampled at various depths (0-25 cm, 25-45, 45-75, 75-95, 95-125) with a manual drill that allows to collect the sample according with the stratigraphy of reactor. No significant differences are measured in the solid analysed; the only difference noted is in leaching test where the upper samples are less murky and less coloured than deeper ones. This absence of differences is probably due to the characteristic of washing test that, recirculating often all leachate, homogenize the compound presence in all reactor. This is a proof of the effectiveness of recirculation capacity of redistribute nutrients inside the reactor.

In Table 2.2, the values of May 2013 are different form previous and following ones. They have a consistent increase: the reason can be the milling, the heterogeneity of waste and the collection of sample only in upper part. The great increase of TS and TVS at the start of Phase 5 is due to the evaporation of moisture inside the reactor and the absence of high infiltration of water to replace it. This increase cannot be seen in heavy metals concentration that does not have a visible decreasing behaviour. The November 2004 value of metals is much lower respect the following ones. For all these reason it is impossible to build a reliable mass balance of heavy metals in this work, having too low initial values and too variable intermediate ones.

All other indexes decrease rapidly in all phases, because the washing effect and the aerobic degradation, having only a small visible increase in May 2013, for the reasons explained before. Despite this, the bigger parts of mobile compounds have been washed away and the waste is considerable stable: all the emissions in leachate are low and the concentration in solids seems to be constant (excluding May 2013 values). Leaching test shows very low residual emission potential in the last two samples of 2013 and confirm the washing test efficiency. The only compound that has growth in concentration is the nitrate that comes from nitrification process. The stability is true even for biologically point of view because IR4 index, initially high (November 2013), falls down and become around 1mgO2/gTS since the start of third phase (Figure 2.6). The little step around 0.5 l/Kg of L/S is due to milling of solid sample, again. The IR7 reach 0.88 mgO2/gTS and, after the sixth days of respiration test, the oxygen consumption rate became very slow.

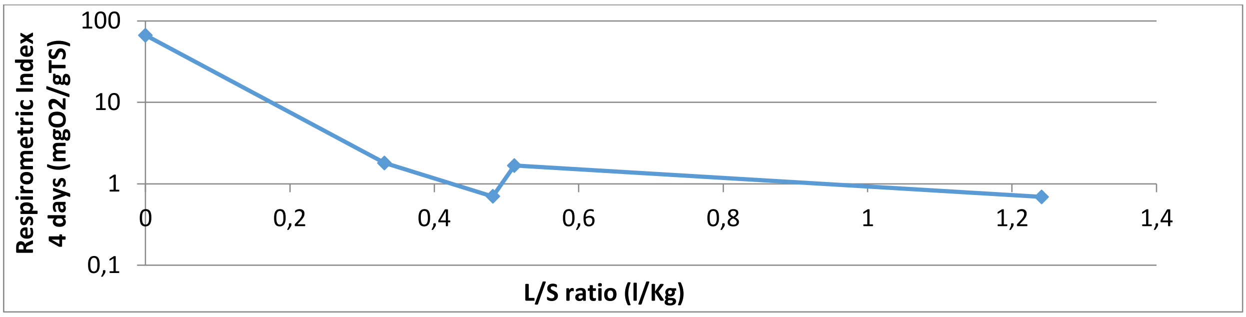

Figure 2.6: Phase 1-5, Solids analysis, Respirometric index IR4 (mgO2/gTS) versus L/S ratio (l/Kg). The vertical axe is logarithmic to better evidence the rapid decrease of organic compounds since the Second-Third phase.

3. FSQ Threshold Values Evaluation

Results of various laboratory columns and lysimeter tests compared to the present one are reported in Table 2.3. The test name L stands for lysimeter (more than 100 Kg of waste), the C stands for columnar test, the M for mathematical model and the La for real landfills. The data samples all refers to MSW landfills or simulations with a at least a sorting and a pre-treatment of waste.

Table 2.3: Comparative Tests Characteristics. From left to right: progressive number, author of test, Type, code-name assigned, aeration characteristics, water injection, initial mass of waste and Total solids. These characteristic are useful for build a L/S comparison for each test. The Code-name: L stands for Lysimeter (more than 100 Kg of waste), C stands for columnar test, M for mathematical model and La for real landfill data. Every one of this test is a Semi-aerobic test of MSW waste with a source sorting and a mechanical pre-treatment. (Cossu et al., 2003; Cossu and Rossetti, 2006; Manfredi and Christensen, 2009; Shimaoka et al., 2013; Raga and Cossu, 2013; Ritzkowski and Stegmann, 2013; Bigiliet al., 2007; Ritzkowski et al., 2006; Oygard et al., 2004).

N°	Author	Test Type	Test name	Aeration	Water (l/d)	Initial mass (kg)	TS (%)
1	Morello 2013	Lysimeter Morello	L1	High aeration	Various	750	45
2	Cossu et al., 2003	Column Aerobic	C1	100 Nl/h continuous	0,175	8,14	67
3	Cossu et al., 2003	Column Semi-aerobic	C2	50 Nl/h, 20 d/w	0,175	8,81	67
4	Cossu et al., 2003	Column PAF model	C3	50 Nl/h, 20 d/w	0,5	8,29	67
5	Cossu, Rossetti, 2003	Lysimeter Rossetti PAF	L2	High aeroation	Various	750	67
6	Manfredi, Cristensen, 2009	Model Semi-aerobic	M1	Semi-aerobic	Various	1000	100
7	Shimaoka et al., 2013	Lysimeter Jap1	L3	0,5-1 l/m	1,9	2551	58
8	Shimaoka et al., 2013	Lysimeter Jap2	L4	0,5-1 l/m	1,9	2551	58
9	Raga, Cossu 2013	Column Semi-aerobic C2	C4	2 Nl/h	Saturated	32,8	49,9
10	Raga, Cossu 2013	Column Semi-aerobic C3	C5	2 Nl/h	Saturated	32,1	43,7
11	Raga, Cossu 2013	Column Semi-aerobic C4	C6	2 Nl/h	Saturated	33,3	44,2
12	Raga, Cossu 2013	Column Semi-aerobic C6	C7	2 Nl/h	Saturated	31,2	39,8
13	Bilgili et al., 2007	Column Aerobic A1	C8	0,84 l/m/Kg waste	0,47	179	
14	Ritzkowski, Stegmann, 2013	Column Aerobic average 6	C9	0,4 m3/Mg TS d			
15	Ritzkowski et al., 2006	Column Aerobic Kuh 1-8	C10	0,2-0,6 l/KgTS d	0,07	39,64	100
16	Oygard et al., 2004	Landfill 1	La1		77260	190000000	
17	Oygard et al., 2004	Landfill 2	La2		309315	350000000	
18	Oygard et al., 2004	Landfill 3	La3		150685	98000000	
19	Oygard et al., 2004	Landfill 4	La4		529041	544000000	

Even if tests are similar each other, an elaboration of the information collected is necessary. The evaluation of L/S ratio will be useful for a standardization of the age of the waste, this is not true for the carbon mass balance that depends on aeration rate (Ritzkowski and Stegmann, 2013) but is a good tool for all the other pollutants that can be extract only by leaching. For all the compounds considered in the Table 2.4 below are reported the mass percentage extracted by leaching respect to initial concentration in solids and the final concentration in leachate when the test reach the stability. In the bottom part of the table is evaluated the range and the average values for each pollutant. Not considering some extreme values, the average is quite similar for all tests, so it is representative of the maximum extraction capacity of the pollutant.

Table 2.4: Results of test comparison. In the first column the test code-name, in the same order than in Table 2. In the second the L/S ratio, through which the test can be compared. In the following columns every pollutant has been consider (Carbon, Nitrogen, Chloride, Iron, other Heavy Metals) with its % of leachate emission after the indicate l/S, respect to the initial waste presence and with its final concentration in leachate. (Cossu et al., 2003; Cossu and Rossetti, 2006; Manfredi and Christensen, 2009; Shimaoka et al., 2013; Raga and Cossu, 2013; Ritzkowski and Stegmann, 2013; Bigiliet al., 2007; Ritzkowski et al., 2006; Oygard et al., 2004).

Test	L/S	TOC				Nitrogen			Chlorine		Iron		Cadmium		Chromo		Lead	
	(l/Kg)	% Leachate emission	Final TOC conc (mg/l)	Final COD conc (mg/l)	Final BOD5/COD	% Leachate emission	Final TKN conc (mg/l)	Final nitrates conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)
L1	1,24	8,94				16,28	5,04			486	0,29	0,288	2,76	0,01	1,73	0,01	0,66	0,03
C1	2,58	1,44	1000	3000	0,01	19,89	100											
C2	2,57	2,40	1000	1000	0,30	38,14	200											
C3	7,24	5,29	800	800	0,09	59,29	20											
L2	1,71			3000	0,01	20,53	100	200										
M1	1,49	3,35		400	0,10	13,79	400		55,10	980							0,74	
L3	0,78	0,69	250			15,89	100	100										
L4	0,78	0,36	200			16,51	50	50										
C4	0,69	0,44	427	316		11,32	25		60,61	1773								
C5	0,70	0,85	316	510		22,86	22		64,77	3546								
C6	0,68	1,26	477	6884		20,78	69		64,77	3439								
C7	0,72	0,96	310	470		15,73	18		63,28	2127								
C8	0,78										6,52	40	2,24	0,1000	0,04	0,100	0,02	0,010
C9		1,07																
C10	1,29	2,00	100					0,2										
La1	3,27										8,01	180	0,02	0,0002	0,82	0,045	0,00	0,003
La2	6,13										3,87	41	0,56	0,0004	1,04	0,026	0,01	0,004
La3	19,08										17,90	85	0,04	0,0001	0,61	0,007	0,01	0,002
La4	3,19										1,91	25	0,02	0,0002	0,82	0,024	0,01	0,006
		TOC				Nitrogen			Chlorine		Iron							
		% Leachate emission	Final TOC conc (mg/l)	Final COD conc (mg/l)	Final BOD5 conc (mg/l)	% Leachate emission	Final TKN conc (mg/l)	Final nitrates conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)
Average	3,05	2,23	488,00	1820,00	0,10	22,59	92,42	87,55	61,70	2058,50	6,42	61,88	0,94	0,02	0,84	0,04	0,21	0,01
Range max	19,08	8,94	1000,00	6884,00	0,30	59,29	400,00	200,00	64,77	3546,00	17,90	180,00	2,76	0,10	1,73	0,10	0,74	0,03
Range min	0,68	0,36	100,00	316,00	0,01	11,32	5,04	0,20	55,10	486,00	0,29	0,29	0,02	0,00	0,04	0,01	0,00	0,00

In Table 2.4, the main comparison index between tests is the L/S ratio that is always higher than 0,7 l/Kg and generally is no more than 3 l/kg. There is only an extreme value of 19 l/Kg of a real old landfill. All this L/S ratios are at stability of emissions, when the mass emission in leachate becomes constant, or very near to it.

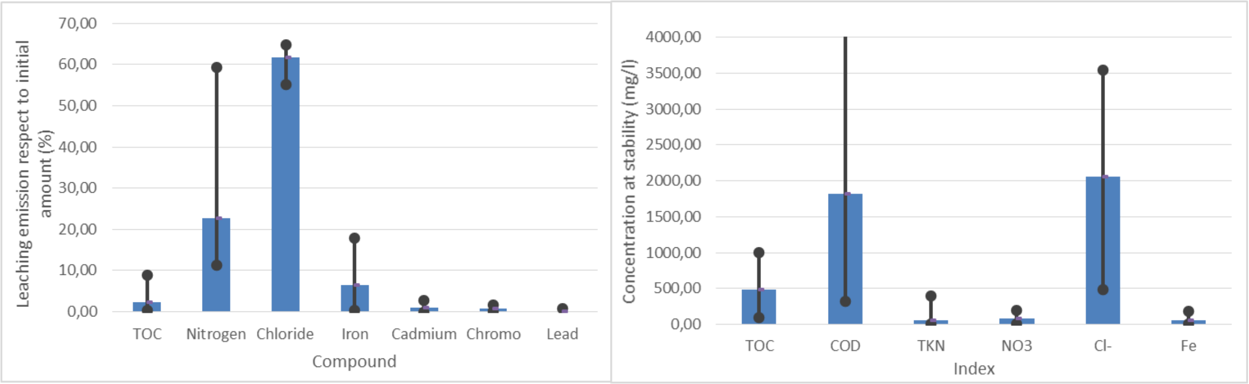

Figure 2.7: Total emission by leaching of each compound, evaluated through Table 4. Final concentration at stability of the FSQ indexes after reaching stability. The blue column represents the average value without extreme data. The black line is the range of variation of the statistical sample of tests. Generally parameters has not a high standard deviation respect the average value, except nitrogen emission and COD and chlorides final concentration that are very variable.

As is visible in Figure 2.7 and in Table 2.4, carbon emission percentage, respect the initial carbon concentration in solids, is around 2% and always under 5% except in the present test where the initial part is anaerobic and so emit more by leaching and increase this value. In presence of oxygen, the emission of carbon by leachate is low because the high power of aerobic degradation transforms the bigger part of organic carbon into CO2 that escapes in air (Ritzkowski and Stegmann, 2013). The final TOC concentration in leachate is low, around 500 mg/l, because the aerobic reaction can degrade more compounds than anaerobic one, and so only very slowly degradable compounds like fulvic and humic acids or lignine can resist very long in this environment. It is possible to extract maximum the 5% of initial carbon with a L/S ratio that reach 2-3 l/Kg and have a final concentration under 500 mg/l. Under full-scale conditions, a complete reduction of organic carbon would be unrealistic and not achievable in a reasonable time (Ritzkowsky and Stegmann 2013).

Nitrogen can be extracted by leaching in form of organic nitrogen, ammonia or nitrates if the oxygenation is sufficiently high. In case of anaerobic and anoxic zones, pure nitrogen can be produced: it escapes with gas in the atmosphere. Generally the percentage of extraction in leachate is between 10 and 30 % with a concentration of TKN that can reach quite low values (50 mg/l or less) if the nitrification is efficient. Nitrates are soluble and leachate away very fast.

Chlorine emissions are all around 60 % of initial quantity in solids, final concentration can remain still high (2000 mg/l) because the only way to extract this compound is leaching. It is not degraded or gassified. The range of data is strictly around the average to the estimation is good.

Iron is the only heavy metal that can be found in appreciable concentration in leachate (150 mg/l) and the total extracted percentage is around 7-8 %. All the others heavy metals can be found in low content, always very close to the discharge limit value, and their potential emission percentage is always under 1%. This means that heavy metals, in landfill conditions, stay in solid matter and their concentration in landfill leachate is not a major concern (Bigili et al., 2007). If initial content of metals and salts is higher than imposed limits, it is very difficult to decrease it only with dissolution, all others parameters can be flushed away increasing water input even in anaerobic phase (Valencia et al., 2008). For other metals the limits for leaching test are suggested, in the Italian Law the test is DM n5-2/98 allegato 3, Test di Cessione.

The FSQ threshold values purpose comes from these average observations of L/S, percentage leachate emission and concentration reachable in a reasonable time with a feasible water supply. In the Table 2.5 below the evaluate concentration for all indexes considered is reported (Cossu et al., 2007).

Table 2.5: Leacahte FSQ Table. In the columns from left to right: the FSQ index choose, the average L/S at which it is stable in considered test, the average % of emission in leachate respect to initial presence in solids, the final concentration in elacahte and the FSQ concentration purposed.

FSQ	Final L/S (l/Kg)	% Leacahte emission	Concentration (mg/l)	FSQ propose (mg/l)
TOC	1,73	2,23	488	500
COD	2,04		1820	1800
BOD5/COD	2,04		0,10	0,1
TKN	1,77	22,59	51	50
NO3-	1,14		88	90
Cl-	0,92	61,70	2059	2000
Iron	5,62	6,42	62	150
Cadmium	5,62	0,94	0,02	
Chromo	5,62	0,84	0,04	
Lead	5,03	0,21	0,01	

FSQ proposed for leachate: TOC 500 mg/l, COD 1800 mg/l, BOD5/COD 0,1, TKN 50 mg/l, NO3- 90 mg/l, Cl- 2000 mg/l, Fe 150 mg/l.

Concerning solids, their analysis is useful especially for verify the emission potential through a leaching test and for verify stability with biodegradability test. IR4 and B21 are parameters that can define the stabilization, reached by an aerated waste, in combination with results of elution test (Ritzkowski et al., 2006; Ritzkowsky and Stegmann 2013). If IR4 index is lower than 2,5 mgO2/gTS, the waste can be considered stable (Cossu et al., 2007; Ritzkowsky et al., 2006; Laner et al., 2012). This is a low value but the aerobic degradation of semi-aerobic landfills can guarantee even a lower result, the average of IR4 analysis of tests in Table 2.3 gives 1,62 mgO2/gTS after 2-3 l/Kg of L/S ratio. Concerning the leaching test, its results depend highly on the procedure, it can be useful for verify the extraction capacity of leachate. If the test (with an L/S of 10 l/Kg) gives results similar to the FSQ for leachate purposed, its emissions will be sufficiently low.

FSQ proposed for solids: IR4 1,5 mg/l, eventually leaching test with the same FSQ of leachate.

Regarding biogas, the only FSQ index proposed is a methane superficial emission test, to verify the possible presence of gas “hotspots” (Cossu et al., 2007; Ritzkowsky et al., 2007).

FSQ proposed for biogas: CH4 surface emission 0,0005 Nm3/m2*h

3.1 Comparison between FSQ Evaluated and Purposed by Other Authors

In Table 2.6 some indexes are listed, with proper values that can be useful as reference for FSQ proposal. The final storage quality parameters must be designed for indicate the total state of a landfill and the possibility to declare it closed. Obviously, every case has its peculiarities and so a site-specific analysis will always be provide (Cossu et al., 2007). An index must be introduced if can be significant for all landfills cases and its value must be balanced considering the environmental requirements (emission concentration values) and the technical achievability (Cossu et al., 2007).

Biogas emissions are difficult to measure. Generally, the anaerobic landfill's emissions are quite constant in quality and they decrease only in quantity. Semi-aerobic landfill, on the other hand, does not emit nothing more than carbon dioxide. This happens if the landfill is well aerated and the top cover guarantees the methanotrophic conditions for destroy occasional methane production.

Leachate emissions of carbon and nitrogen are dependent by L/S ratio but also they are very influenced by presence of oxygen and by the reaction kinetics. Leachate is not emitted directly in the environment because it is collected with pipes in the bottom of the landfill and treated off situ. The uncontrolled leakage is avoided with an impermeable bottom liner that guarantees both the containment of leachate and the natural attenuation of pollutants that will pass through that. Thanks to this, FSQ values for leachate emission can be higher than environmental threshold values (used to declare a site contaminated), because they will be attenuated before the real emission in environment (Cossu et al., 2007). In the following Table 2.6, the FSQ purposed in the present work and in other works are listed compared with some threshold values for discharging in environment, fixed by Italian legislation.

Table 2.6: Left: Comparison between leachate FSQ proposed by some Authors (Krumpelback, Knox, Stegmann, Cossu), the present FSQ proposal, the legislation values for discharging in environment, and the Italian CSC.

Suggested index	Unit	FSQ proposed					Present Italian legislation						
		Kruempelbeck (2000)	Knox at al. (2005)	Stegmann (2006)	Cossu (2007), Pivato (2004)	Semi-aerobic test (2013)	DM n5-2/98 allegato 3, Test di Cessione	Limiti allo scarico sul suolo, D.lgs.152/2006	Limiti allo scarico in acque superficiali, D.lgs.152/2006	Limiti allo scarico in fognatura, D.lgs.152/2006	CSC, tabella A, suolo siti residenziali, D.lgs.152/2006	CSC, tabella B, suolo siti industriali-commerciali, D.lgs.152/2006	CSC, acque sotterranee, D.lgs.152/2006
COD	mg/l	16 ; 70			200	1800	30	100	160	500			
COD surface specific	g/m2*y	3 ; 14		5 ; 20									
BOD_5	mg/l							20	40	250			
BOD_5/COD					0,01	0,10							
TOC	mg/l					500							
TKN	mgN/l					50		15					
$N\text{-}NH_4^+$	mgN/l	9 ; 20	10		300				15	30			
N-NH4+ surface specific	g/m2*y	1,8 ; 4		2,5 ; 10									
N-Nox	mgN/l					90	50		20	30			
SO4	mg/l						250		1000	1000			250
Cl-	mg/l					2000	200		1200	1200			
P tot	mgP/l							2	10	10			
Cd	mg/l						0,005		0,02	0,02	2	15	0,005
Cr	mg/l						0,05	1	2	4	2	15	0,005
Cu	mg/l						0,05	0,1	0,1	0,4	120	600	1
Fe	mg/l					150		2	2	4			0,2
Mg	mg/l							0,2	2	4			0,05
Ni	mg/l						0,01	0,2	2	4	120	500	0,2
Pb	mg/l						0,05	0,1	0,2	0,3	100	1000	0,1
Zi	mg/l						3	0,5	0,5	1	150	1500	3

The values purposed in this work are generally higher than values given by other researches or by law, because they are evaluated with a mathematical performance based on analysis. In any case, the order of magnitude is comparable. The law values refer to environmental concentration and the purposed FSQ refer to leachate concentration inside the landfill. Between the two values, there is the natural attenuation of a clay liner. Considering the natural attenuation of bottom liner, the law concentration will always be respected.

Residual waste FSQ are useful as control of biological stability in all landfill parts. IR4 is the main index of control for the waste stabilization (Ritzkowski et al., 2006) and the purposed value for a general landfill (2,5 mgO2/gTS) can be decreased for Semi-aerobic landfills to 1 mgO2/gTS. This test is made as last control for FSQ procedure; for this reason, the sampling must be appropriate to well characterize all the landfill.

4. Conclusions

In conclusion, the purposed FSQ threshold values for declare aftercare end of semi-aerobic landfills are the following, as listed in the Table 2.7.

Table 2.7: FSQ proposed for semi-aerobic landfills, basing on a performance approach on a sample of 20 landfilling tests.

FSQ	Unit	Threshold value
Biogas		
CH4 Superficial emission	Nm3/m2*h	0,0005
Leachate		
COD	mgO2/l	1800
BOD5/COD		0,10
TOC	mgC/l	500
TKN	mgN/l	50
N-NO3	mgN/l	90
CL-	mg/l	2000
Fe	mg/l	150
Solids		
IR4	mgO2/g TS	1,5

The statistical analysis can be more accurate by increasing the number of considered tests. However, the values are good, because all the analysed cases give similar results. Reaching 2 l/Kg of L/S ratio in a well aerated semi-aerobic landfill means, statistically, reaching the stability of emissions. Total extraction by leachate will reach 2-3% of carbon, 20-25% on nitrogen, 60-65% of chloride, 7-8 % of iron and 1-2% maximum of other heavy metals respect to initial amount in waste. The final average concentrations at stability are taken as FSQ values for leachate emissions: 1800 mgO2/l COD, 0,1 BOD5/COD ratio, 500 mgC/l TOC, 50 mgN/l TKN, 90 mgN/l N-NO3, 2000 mg/l Cl- and 150 mg/l Iron. Decreasing more these values requires high increases of L/S ratio. This will be useless because the stability is reached and the landfill is safe. These concentrations are threshold values for leachate that does not considers the natural attenuation of clayey bottom liners, before uncontrolled emission happens. The only parameter suggest for biogas is a methane superficial emission (0,0005 Nm3/m2*h) for ensure aeration of the landfill and the well-functioning of methanotrophic top cover. The solid samples must be analysed for IR4 (1,5 mgO2/g TS) as final control for the biological stability of waste and a leaching test can be eventually made with the same leachate parameters. Particular attention must be paid by using concentration values, which depend on dilution of the leachate and so on water input.

FSQ threshold values are strictly bonded to the kind of waste and landfill, but it can be made for all other possible cases in presence of a sufficient data for the statistical comparison. Different technologies require different indexes, different threshold values and a risk assessment must be made for the site specific refining. An interesting upload of the methodology could be widening the simulation outside the liner, in order to verify the migration of pollutants through the clay with a mathematical model.

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Part 3

Annexes

Annex 1: Leachate Analysis Results

Washing steps data

Table 3.1: Step 1. In first column the recirculation number (the first number stands for the step and the second for the number of previous recirculation of the same leachate. The start date is the day in which the water-leachate is input. The end date is the day in which the leachate exit monitoring is stop for another recirculation. Length is the length of single recirculation test. Days is the cumulate count of length. IN measures the liquid input in litres. OUT measures the total leachate exiting from the reactor in litres. ACC is the difference between IN and OUT and measures the water evaporated and/or trapped in interstitial pores. Sample is the date in which a leachate sample is take. The analysis made on the sample are pH, conductibility, Total Organic Carbon, Totoal Kjendahl Nitrogen, ammonia, nitrates, chlorines, sulphates, cadmium, chromo, copper, iron, manganese, nickel, lead and zinc.

Step	Start Date	End Date	Lenght (d)	Days (d)	IN (l)	OUT (l)	Acc (l)	Sample	PH	Cond	COD (mg/l)	TOC (mg/l)	TKN (mg/l)	NH3 (mg/l)	NO3 (mg/l)	Cl (mg/l)	SO4 (mg/l)	Cd (ug/l)	Cr (ug/l)	Cu (ug/l)	Fe (ug/l)	Mg (ug/l)	Ni (ug/l)	Pb (ug/l)	Zn (ug/l)
0.0	20-mag	22-mag	2	0	0	23	23	20-mag	8,01	8,05	515	121	11,2	2,8	414	1085	886	10	10	222	910	44,8	75,4	30	117
1.1	22-mag	27-mag	5	5	150	114,5	35,5																		
1.2	27-mag	29-mag	2	7	115	92	23	29 mah	7,75	17,97	811	302	10,1	10,1	1361	2287	1469	10	10	394	1638	40,2	106	30	510
1.3	29-mag	03-giu	5	12	91,5	83	8,5																		
1.4	03-giu	05-giu	2	14	83	73,5	9,5	05-giu	9,21	21,9	829	306		11,2	3381	2588	1554								
1.5	05-giu	07-giu	2	16	73	67	6																		
1.6	07-giu	12-giu	5	21	67	64	3	12-giu	8,28	21,8	893,4	305		5	1874	2588	1847								
1.7	12-giu	19-giu	7	28	63,5	58	5,5	19-giu	8,52	21,7	883,2	303		5	2275	2570	2011								
1.8	19-giu	25-giu	6	34	57	43	14	25-giu	7,3	22,5	1000	323	5,4	3,9	1976	2677	1772	10	10	368	288	386	110	30	980

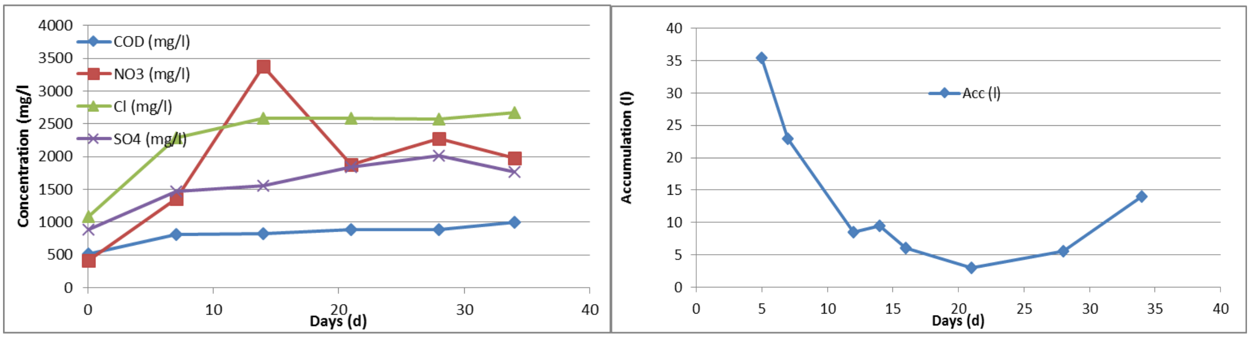


Figure 3.1: A: Leachate concentration in Step 1, plot on the time in days. B Accumulation (IN-OUT) of each recirculation, plot on time in days. The plot A is useful for control the stability of concentration values after some recirculation, the plot B is useful for control the progressive decrease of accumulated water. The Step 1 is use as pilot test so the days and recirculation required and more than following steps.

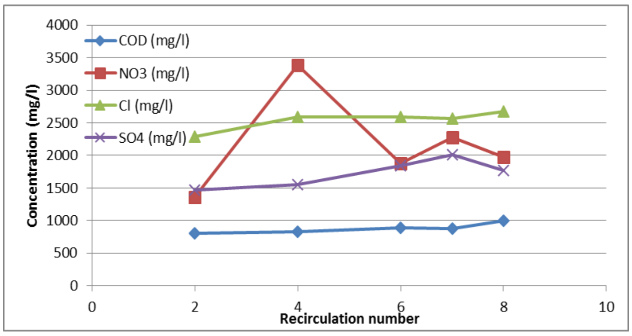


Figure 3.2: Leachate concentration in Step 1, plot on the recirculation progressive number. This plot is used for establish the number of recirculation need for reach the maximum extraction of pollutants with the same water.

Table 3.2: Step 2. Description equal to Table one.

Step	Start Date	End Date	Lenght (d)	Days (d)	IN (l)	OUT (l)	Acc (l)	Sample	PH	Cond	COD (mg/l)	TOC (mg/l)	TKN (mg/l)	NH3 (mg/l)	NO3 (mg/l)	Cl (mg/l)	SO4 (mg/l)	Cd (ug/l)	Cr (ug/l)	Cu (ug/l)	Fe (ug/l)	Mg (ug/l)	Ni (ug/l)	Pb (ug/l)	Zn (ug/l)
2.1	01-lug	02-lug	1	1	110	90	20																		
2.2	02-lug	03-lug	1	2	90	84	6	02-lug	8,11	12,8	593,1	208		3,9	1060	1294	1538								
2.3	03-lug	04-lug	1	3	84	81	3																		
2.4	04-lug	08-lug	4	7	81	81	0	04-lug	7,84	13,9	603,10	220	9,5	3,9	1155	1418	1703	10	10	294	258	224	84,8	30	784

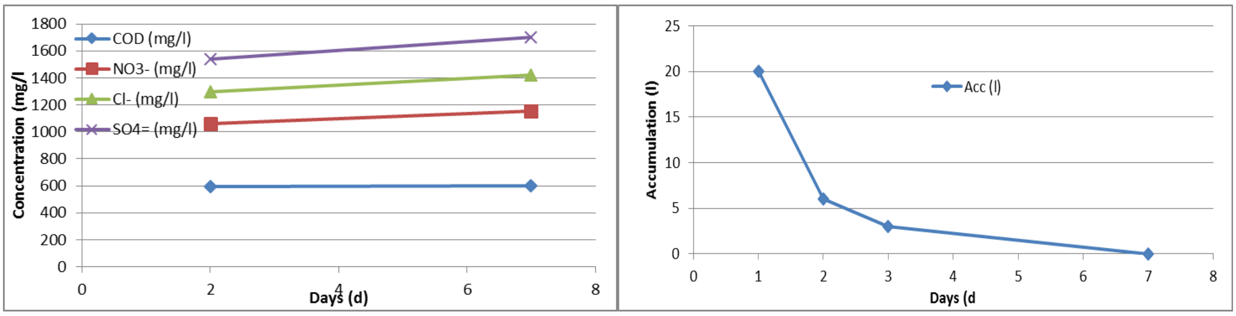


Figure 3.3: A: Leachate concentration in Step 2, plot on the time in days. B Accumulation (IN-OUT) of each recirculation, plot on time in days. The plot A is useful for control the stability of concentration values after some recirculation, the plot B is useful for control the progressive decrease of accumulated water.

Table 3.3: Step 3. Description equal to Table one.

Step	Start Date	End Date	Length (d)	Days (d)	IN (l)	OUT (l)	Acc (l)	Sample	PH	Cond	COD (mg/l)	TOC (mg/l)	TKN (mg/l)	NH3 (mg/l)	NO3 (mg/l)	Cl (mg/l)	SO4 (mg/l)	Cd (ug/l)	Cr (ug/l)	Cu (ug/l)	Fe (ug/l)	Mg (ug/l)	Ni (ug/l)	Pb (ug/l)	Zn (ug/l)
3.1	08-lug	10-lug	2	2	90	79	11																		
3.2	10-lug	11-lug	1	3	79	73	6	10-lug	8,01	10	538,3	188		2,8	725	975	1196								
3.3	11-lug	15-lug	4	7	73	75	-2																		
3.4	15-lug	16-lug	1	8	75	66	9	15-lug	8,08	11,37	559,70	202	2,8	2,9	933	1117	1587	10	10	300	246	139	79,8	30	588

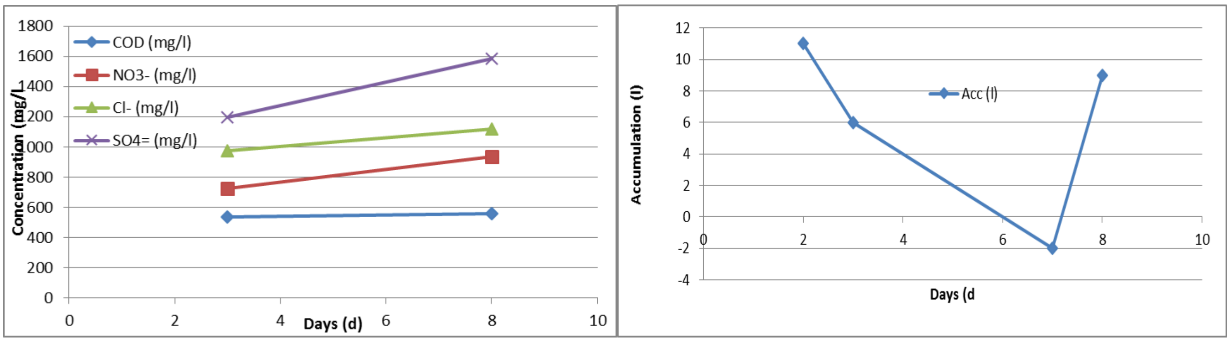


Figure 3.4: A: Leachate concentration in Step 3, plot on the time in days. B Accumulation (IN-OUT) of each recirculation, plot on time in days. The plot A is useful for control the stability of concentration values after some recirculation, the plot B is useful for control the progressive decrease of accumulated water.

Table 3.4: Step 4. Description equal to Table one.

Step	Start Date	End Date	Length (d)	Days (d)	IN (l)	OUT (l)	Acc (l)	Sample	PH	Cond	COD (mg/l)	TOC (mg/l)	TKN (mg/l)	NH3 (mg/l)	NO3 (mg/l)	Cl (mg/l)	SO4 (mg/l)	Cd (ug/l)	Cr (ug/l)	Cu (ug/l)	Fe (ug/l)	Mg (ug/l)	Ni (ug/l)	Pb (ug/l)	Zn (ug/l)
4.1	16-lug	17-lug	1	1	100	96	4																		
4.2	17-lug	18-lug	1	2	96	93	3	17-lug	8,27	7,61	423,5	155		2,8	518	709	1069								
4.3	18-lug	19-lug	1	3	93	92	1																		
4.4	19-lug	22-lug	3	6	92	94	-2	18-lug	8,28	8,46	477,10	164	2,8	2,8	658	798	1119	10	10	306	514	106	80	30	546

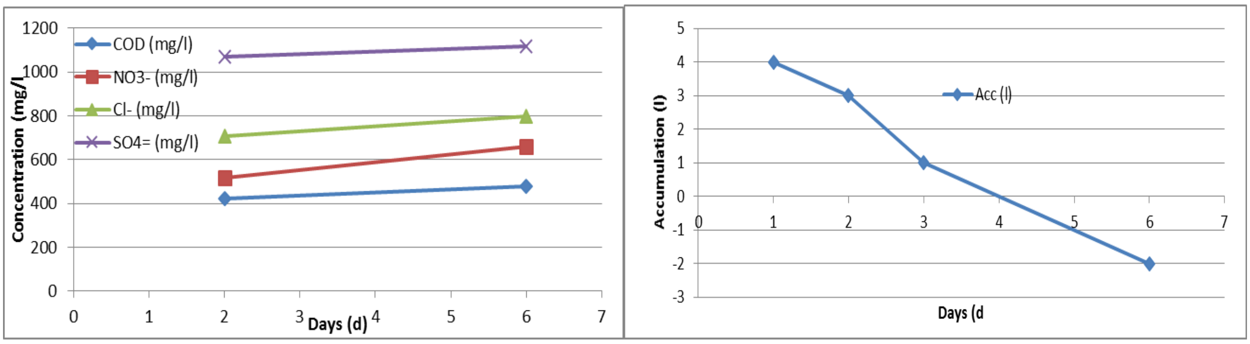


Figure 3.5: A: Leachate concentration in Step 4, plot on the time in days. B Accumulation (IN-OUT) of each recirculation, plot on time in days. The plot A is useful for control the stability of concentration values after some recirculation, the plot B is useful for control the progressive decrease of accumulated water.

Table 3.5: Step 5. Description equal to Table one.

Step	Start Date	End Date	Lenght (d)	Days (d)	IN (l)	OUT (l)	Acc (l)	Sample	PH	Cond	COD (mg/l)	TOC (mg/l)	TKN (mg/l)	NH3 (mg/l)	NO3 (mg/l)	Cl (mg/l)	SO4 (mg/l)	Cd (ug/l)	Cr (ug/l)	Cu (ug/l)	Fe (ug/l)	Mg (ug/l)	Ni (ug/l)	Pb (ug/l)	Zn (ug/l)
5.1	22-lug	23-lug	1	1	90	83	7																		
5.2	23-lug	24-lug	1	2	83	79	4	23-lug	8,18	5,78	391	138		2,8	397	514	928								
5.3	24-lug	25-lug	1	3	79	76	3																		
5.4	25-lug	29-lug	4	7	76	78	-2	25-lug	8,2	6,58	444	154	2,8	2,8	484	585	1107	10	10	324	302	64,4	90,8	30	610

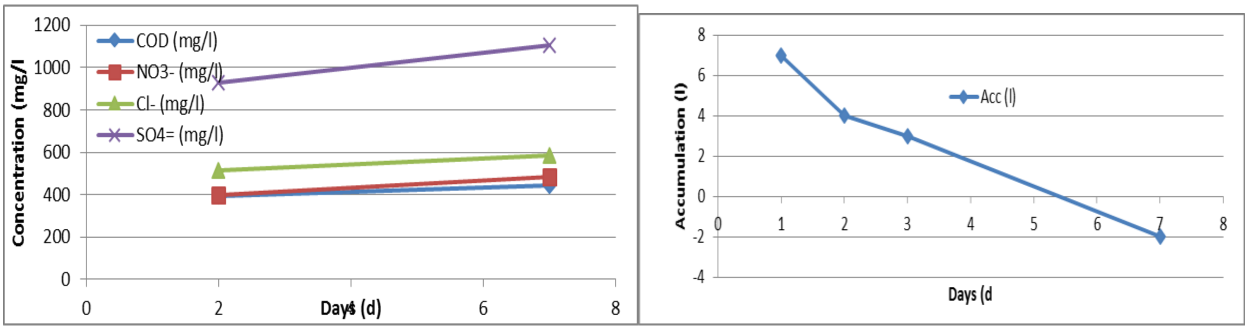


Figure 3.6: A: Leachate concentration in Step 5, plot on the time in days. B Accumulation (IN-OUT) of each recirculation, plot on time in days. The plot A is useful for control the stability of concentration values after some recirculation, the plot B is useful for control the progressive decrease of accumulated water.

Table 3.6: Step 6. Description equal to Table one.

Step	Start Date	End Date	Lenght (d)	Days (d)	IN (l)	OUT (l)	Acc (l)	Sample	PH	Cond	COD (mg/l)	TOC (mg/l)	TKN (mg/l)	NH3 (mg/l)	NO3 (mg/l)	Cl (mg/l)	SO4 (mg/l)	Cd (ug/l)	Cr (ug/l)	Cu (ug/l)	Fe (ug/l)	Mg (ug/l)	Ni (ug/l)	Pb (ug/l)	Zn (ug/l)
6.0	29-lug	30-lug	1	1	90	83	7																		
6.1	30-lug	31-lug	1	2	83	81	2	30-lug	8,17	4,65	407	146		2,8	643	372	845								
6.2	31-lug	01-ago	1	3	81	77	4																		
6.3	01-ago	05-ago	4	7	77	78	-1	01-ago	8,13	5,28	438	154	2,8	2,8	687	425	983	10	10	352	354	49,2	92,4	30	580

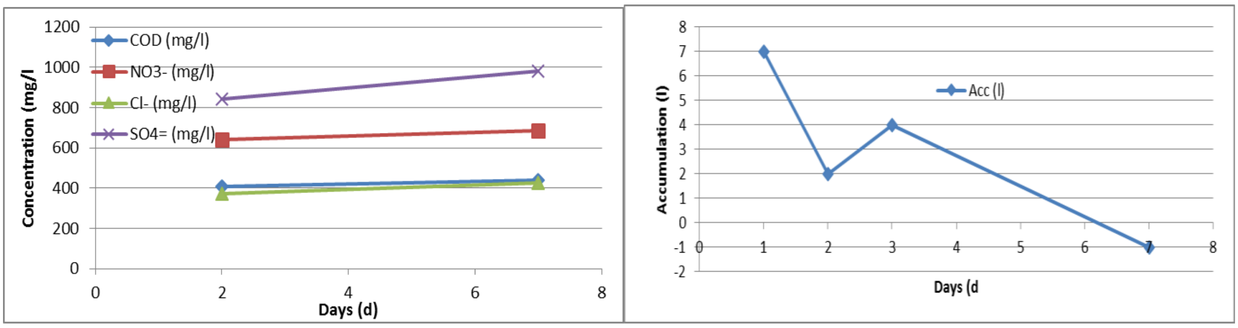


Figure 3.7: A: Leachate concentration in Step 6, plot on the time in days. B Accumulation (IN-OUT) of each recirculation, plot on time in days. The plot A is useful for control the stability of concentration values after some recirculation, the plot B is useful for control the progressive decrease of accumulated water.

Table 3.7: Step 7. Description equal to Table one.

Step	Start Date	End Date	Lenght (d)	Days (d)	IN (l)	OUT (l)	Acc (l)	Sample	PH	Cond	COD (mg/l)	TOC (mg/l)	TKN (mg/l)	NH3 (mg/l)	NO3 (mg/l)	Cl (mg/l)	SO4 (mg/l)	Cd (ug/l)	Cr (ug/l)	Cu (ug/l)	Fe (ug/l)	Mg (ug/l)	Ni (ug/l)	Pb (ug/l)	Zn (ug/l)
7.0	05-ago	06-ago	1	1	120	107	13																		
7.1	06-ago	07-ago	1	2	107	104	3	06-ago	8,3	3,76	417	143		2,8	486	266	528								
7.2	07-ago	08-ago	1	3	104	101	3																		
7.3	08-ago	09-ago	1	4	101	97	4	08-ago	8,12	4,41	460	154	7,28	2,8	568	355	663	10	10	396	496	46	99,6	30	636

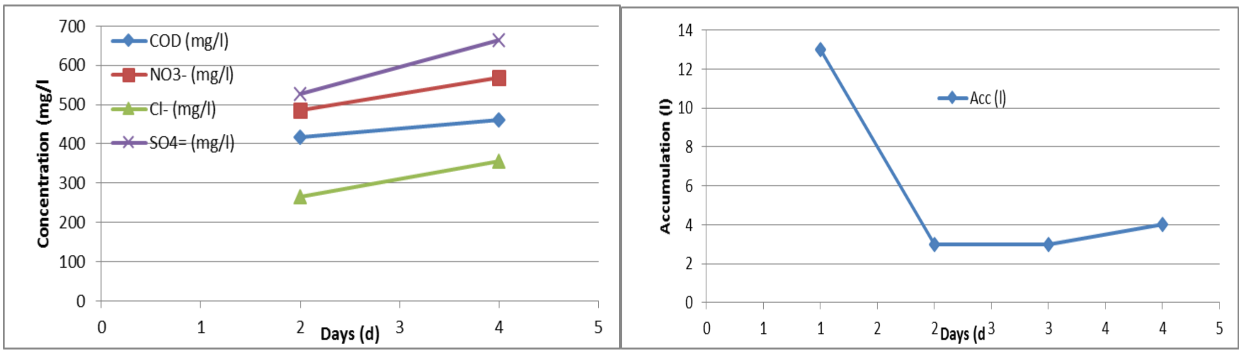


Figure 3.8: A: Leachate concentration in Step 7, plot on the time in days. B Accumulation (IN-OUT) of each recirculation, plot on time in days. The plot A is useful for control the stability of concentration values after some recirculation, the plot B is useful for control the progressive decrease of accumulated water.

Table 3.8: Step 8. Description equal to Table one.

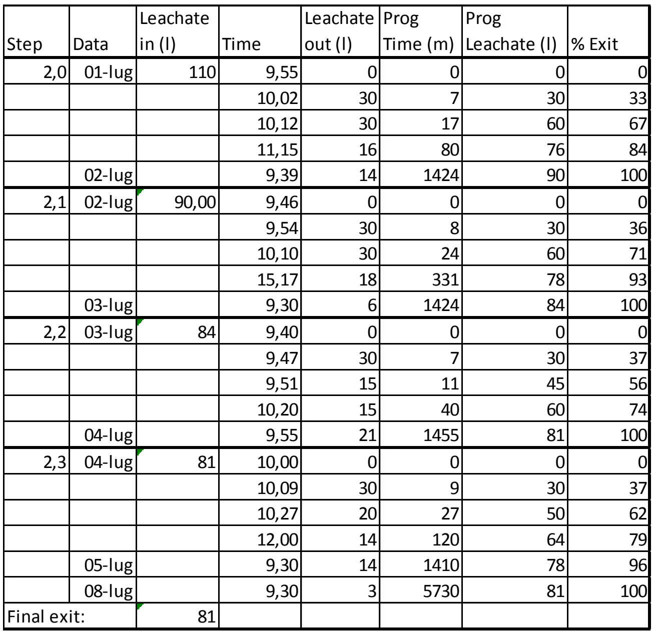
Step	Start Date	End Date	Lenght (d)	Days (d)	IN (l)	OUT (l)	Acc (l)	Sample	PH	Cond	COD (mg/l)	TOC (mg/l)	TKN (mg/l)	NH3 (mg/l)	NO3 (mg/l)	Cl (mg/l)	SO4 (mg/l)	Cd (ug/l)	Cr (ug/l)	Cu (ug/l)	Fe (ug/l)	Mg (ug/l)	Ni (ug/l)	Pb (ug/l)	Zn (ug/l)
8.1	09-ago	26-ago	17	17	0	10	-10	26-ago	9,66	5,31	475	175	5,04	2,8	353	486	854	10	10	344	288	10	90,1	30	134

Hydraulic data of reactor

Table 3.9: Hydraulic balance Step 1. Leachate exit from the reactor, hydraulic data. For each step and for each recirculation in first column, are collect information regarding the exit velocity of the liquid. In columns, two and four are the date and the hour of the rilevation. In third column is the water initial input or the leachate recirculate, which is always equal to the leachate extract from the passage before. In column five the exiting liquid amount in litres. Than the progressive time in minutes since the injection until the end of recirculation. In column seven is the cumulate leachate exiting every recirculation. In the last column the percentage of leachate exit respect to the total output of each recirculation (Prog leachate/leachate total exit *100).

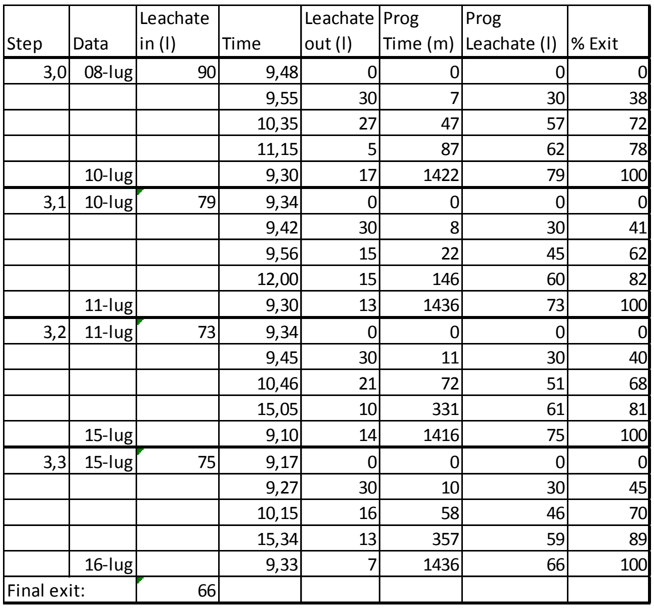
Step	Data	Leachate in (l)	Time	Leachate out (l)	Prog Time (m)	Prog Leachate (l)	% Exit
1,1	22-mag	150	10,15	0	0	0	0
			10,27	30	12	30	26
			10,35	25	20	55	48
			10,47	30	32	85	74
			12,00	25	105	110	96
	23-mag		9,30	3	1395	113	98
	27-mag		9,30	2	7155	115	100
1,2	27-mag	115	9,42	0	0	0	0
			10,04	30	22	30	33
			10,15	30	33	60	65
			11,25	21	83	81	88
			13,00	4	118	85	92
	29-mag		9,45	7	2803	92	100
1,3	29-mag	92	9,55	0	0	0	0
			10,14	30	19	30	36
			10,37	30	42	60	72
			12,55	10	108	70	84
			17,30	5	413	75	90
	30-mag		9,30	4	1373	79	95
	03-giu		10,05	4	3028	83	100
1,4	03-giu	83	10,14	0	0	0	0
			10,35	30	21	30	41
			11,45	30	91	60	82
	04-giu		9,25	11,5	1391	72	97
	05-giu		15,25	2	3191	74	100
1,5	05-giu	73,5	15,30	0	0	0	0
			15,44	30	14	30	45
			17,15	25	105	55	82
	06-giu		10,30	10	1200	65	97
	07-giu		9,20	2	2630	67	100
1,6	07-giu	67	9,30	0	0	0	0
			9,35	10	5	10	16
			9,36	10	6	20	31
			9,38	10	8	30	47
			9,53	10	23	40	63
			11,20	10	110	50	78
			13,50	5	260	55	86
	10-giu		9,10	9	4360	64	100
	12-giu		9,40	0	7270	64	100
1,7	12-giu	64	9,45	0	0	0	0
			10,32	15	57	15	26
			10,44	10	69	25	43
			11,25	10	110	35	60
			15,32	10	288	45	78
			19,00	4	510	49	84
	17-giu		9,30	9	7260	58	100
	19-giu		9,30	0	8700	58	100
1,8	19-giu	58	9,40	0	0	0	0
			10,02	24	22	24	56
			11,38	8	118	32	74
			17,50	6,5	470	39	90
	20-giu		10,20	3,5	1480	42	98
	24-giu		12,30	1	7300	43	100
Final exit:		43					

Table 3.10: Hydraulic balance Step 2. Leachate exit from the reactor, hydraulic data. Description equal to Table nine.



Step	Data	Leachate in (l)	Time	Leachate out (l)	Prog Time (m)	Prog Leachate (l)	% Exit
2,0	01-lug	110	9,55	0	0	0	0
			10,02	30	7	30	33
			10,12	30	17	60	67
			11,15	16	80	76	84
	02-lug		9,39	14	1424	90	100
2,1	02-lug	90,00	9,46	0	0	0	0
			9,54	30	8	30	36
			10,10	30	24	60	71
			15,17	18	331	78	93
	03-lug		9,30	6	1424	84	100
2,2	03-lug	84	9,40	0	0	0	0
			9,47	30	7	30	37
			9,51	15	11	45	56
			10,20	15	40	60	74
	04-lug		9,55	21	1455	81	100
2,3	04-lug	81	10,00	0	0	0	0
			10,09	30	9	30	37
			10,27	20	27	50	62
			12,00	14	120	64	79
	05-lug		9,30	14	1410	78	96
	08-lug		9,30	3	5730	81	100
Final exit:		81					

Table 3.11: Hydraulic balance Step 3. Leachate exit from the reactor, hydraulic data. Description equal to Table nine.



Step	Data	Leachate in (l)	Time	Leachate out (l)	Prog Time (m)	Prog Leachate (l)	% Exit
3,0	08-lug	90	9,48	0	0	0	0
			9,55	30	7	30	38
			10,35	27	47	57	72
			11,15	5	87	62	78
	10-lug		9,30	17	1422	79	100
3,1	10-lug	79	9,34	0	0	0	0
			9,42	30	8	30	41
			9,56	15	22	45	62
			12,00	15	146	60	82
	11-lug		9,30	13	1436	73	100
3,2	11-lug	73	9,34	0	0	0	0
			9,45	30	11	30	40
			10,46	21	72	51	68
			15,05	10	331	61	81
	15-lug		9,10	14	1416	75	100
3,3	15-lug	75	9,17	0	0	0	0
			9,27	30	10	30	45
			10,15	16	58	46	70
			15,34	13	357	59	89
	16-lug		9,33	7	1436	66	100
Final exit:		66					

Table 3.12: Hydraulic balance Step 4. Leachate exit from the reactor, hydraulic data. Description equal to Table nine.

Step	Data	Leachate in (l)	Time	Leachate out (l)	Prog Time (m)	Prog Leachate (l)	% Exit
4,0	16-lug	100,00	9,50	0	0	0	0
			9,58	30	8	30	31
			10,06	30	16	60	63
			10,40	15	50	75	78
			13,00	10	190	85	89
	17-lug		9,38	11	1428	96	100
4,1	17-lug	96	9,46	0	0	0	0
			9,52	30	8	30	32
			10,02	30	18	60	65
			17,00	28	436	88	95
	18-lug		9,58	5	1454	93	100
4,2	18-lug	93	10,01	0	0	0	0
			10,08	30	7	30	33
			10,29	30	28	60	65
			13,00	21	179	81	88
	19-lug		9,20	11	1399	92	100
4,3	19-lug	92	9,26	0	0	0	0
			9,34	30	8	30	32
			9,50	30	24	60	64
			12,30	17	184	77	82
			15,30	5	364	82	87
	22-lug		9,35	12	5769	94	100
Final exit:		94					

Table 3.13: Hydraulic balance Step 5. Leachate exit from the reactor, hydraulic data. Description equal to Table nine.

Step	Data	Leachate in (l)	Time	Leachate out (l)	Prog Time (m)	Prog Leachate (l)	% Exit
5,0	22-lug	90	9,50	0	0	0	0
			9,59	30	9	30	36
			10,35	30	45	60	72
			15,40	15	230	75	90
	23-lug		9,40	8	1430	83	100
5,1	23-lug	83	9,47	0	0	0	0
			9,55	30	8	30	38
			11,00	30	73	60	76
	24-lug		9,25	19	1418	79	100
5,2	24-lug	79	9,27	0	0	0	0
			9,35	30	8	30	39
			11,00	30	33	60	79
	25-lug		10,00	16	1413	76	100
5,3	25-lug	76	10,02	0	0	0	0
			10,11	30	9	30	38
			12,25	30	143	60	77
	26-lug		9,25	14	1497	74	95
	29-lug		10,59	4	5851	78	100
Final exit:		78					

Table 3.14: Hydraulic balance Step 6. Leachate exit from the reactor, hydraulic data. Description equal to Table nine.

Step	Data	Leachate in (l)	Time	Leachate out (l)	Prog Time (m)	Prog Leachate (l)	% Exit
6,0	29-lug	90	11,35	0	0	0	0
			11,45	30	10	30	36
			12,00	25	25	55	66
			13,00	12	85	67	81
	30-lug		14,00	16	1585	83	100
6,1	30-lug	83	14,05	0	0	0	0
			14,12	30	7	30	37
			17,00	30	175	60	74
	31-lug		12,50	21	1365	81	100
6,2	31-lug	81	12,53	0	0	0	0
			13,01	30	8	30	39
			14,10	30	77	60	78
	01-ago		9,40	17	1247	77	100
6,3	01-ago	77	9,44	0	0	0	0
			9,50	30	6	30	38
			11,36	30	112	60	77
	02-ago		9,45	15	1441	75	96
	05-ago		9,20	3	5736	78	100
Final exit:		78					

Table 3.15: Hydraulic balance Step 7. Leachate exit from the reactor, hydraulic data. Description equal to Table nine.

Step	Data	Leachate in (l)	Time	Leachate out (l)	Prog Time (m)	Prog Leachate (l)	% Exit
7,0	05-ago	120	9,42	0	0	0	0
			9,49	30	7	30	28
			9,52	30	10	60	56
			10,00	15	18	75	70
			14,00	23	258	98	92
	06-ago		9,25	9	1423	107	100
7,1	06-ago	107	9,40	0	0	0	0
			9,48	30	8	30	29
			9,51	25	11	55	53
			9,56	10	16	65	63
			10,00	5	20	70	67
			14,00	25	160	95	91
	07-ago		9,50	9	1430	104	100
7,2	07-ago	104	10,00	0	0	0	0
			10,09	30	9	30	30
			10,15	30	15	60	59
			10,50	15	50	75	74
			12,30	13	150	88	87
	08-ago		9,25	13	1405	101	100
7,3	08-ago	101	9,30	0	0	0	0
			9,40	30	10	30	31
			9,44	20	14	50	52
			9,50	15	20	65	67
			16,00	25	390	90	93
	09-ago		9,00	7	1410	97	100
Final exit:		97					

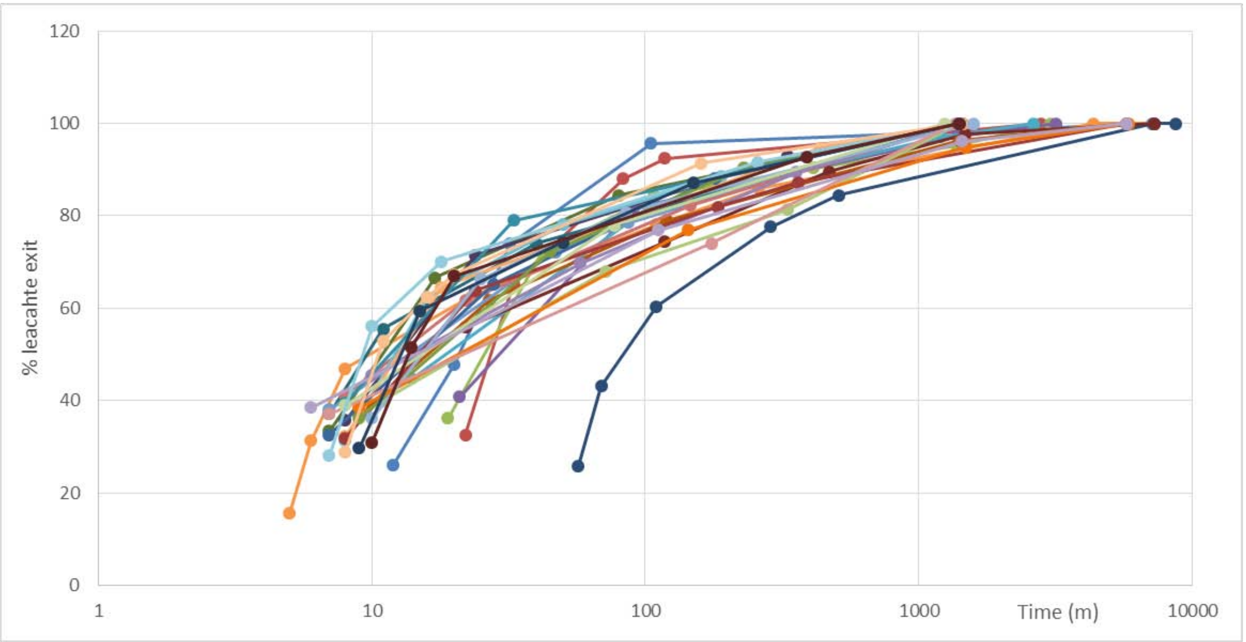


Figure 3.9: Leachate exit in time from the lysimeter. In horizontal axe the time in minutes since the beginning of each recirculation (logarithmic scale). In vertical axe the percentage of leachate exit (in corresponding time) respect to the total exit of each recirculation. This plot is useful for setting of test (Pilot test) because is quite visible that 70-80% of leachate emission Is in the first 2 hours since the injecting and after one day (1440 minutes) the emission is nearly 100%.

Leachate emission data of Phase 5

Table 3.16: Leachate emissions in the Phase 5. In these four tables are reported the concentrations in final exit of each step (1 – 8), the emission in mass of pollutant for kilo of waste, the total emission of each step and the cumulate emission per kilo of waste from the beginning of test to the end. Leachate stands for exiting liquid for each step, L/S is the liquid-solid ratio (l/Kg) than there is the concentration or the mass of all compounds considered: pH, conductibility, Total Organic Carbon, Totoal Kjendahl Nitrogen, ammonia, nitrates, chlorines, sulphates, cadmium, chromo, copper, iron, manganese, nickel, lead and zinc.

Emissions Concentration in Leachate

step	Leachate (l)	L/S (l/kg)	PH	Conducibility	COD (mg/l)	TOC (mg/l)	TKN (mg/l)	NH3 (mg/l)	NO3 (mg/l)	Cl (mg/l)	SO4 (mg/l)	Cd (ug/l)	Cr (ug/l)	Cu (ug/l)	Fe (ug/l)	Mg (ug/l)	Ni (ug/l)	Pb (ug/l)	Zn (ug/l)
1	43	0,057	7,30	22,5	1000	323	5,4	3,9	1976	2677	1772	10	10	368	288	386	110	30	980
2	81	0,108	7,84	13,9	603,1	220	9,5	3,9	1155	1418	1703	10	10	294	258	224	84,8	30	784
3	66	0,088	8,08	11,37	559,7	202	2,8	2,9	933	1117	1587	10	10	300	246	139	79,8	30	588
4	94	0,125	8,28	8,46	477,1	164	2,8	2,8	658	798	1119	10	10	306	514	106	80	30	546
5	78	0,104	8,20	6,58	444	154	2,8	2,8	484	585	1107	10	10	324	302	64	91	30	610
6	78	0,104	8,13	5,28	438	154	2,8	2,8	687	425	983	10	10	352	354	49	92	30	580
7	97	0,129	8,12	4,41	460	154	7,3	2,8	568	355	663	10	10	396	496	46	100	30	636
8	10	0,013	9,66	5,31	475	175	5,0	2,8	353	486	854	10	10	344	288	10	90,1	30	134

Emissions in Leachate per kilogram

step	Leachate (l)	L/S (l/kg)	PH	Conducibility	COD (mg/kg)	TOC (mg/kg)	TKN (mg/kg)	NH3 (mg/kg)	NO3 (mg/kg)	Cl (mg/kg)	SO4 (mg/kg)	Cd (ug)	Cr (ug)	Cu (ug)	Fe (ug)	Mg (ug)	Ni (ug)	Pb (ug)	Zn (ug)
1	43	0,057	7,30	22,5	57,33	18,52	0,31	0,22	113,29	153,48	101,59	0,57	0,57	21,10	16,51	22,13	6,31	1,72	56,19
2	81	0,108	7,84	13,9	65,13	23,76	1,03	0,42	124,74	153,14	183,92	1,08	1,08	31,75	27,86	24,19	9,16	3,24	84,67
3	66	0,088	8,08	11,37	49,25	17,78	0,25	0,26	82,10	98,30	139,66	0,88	0,88	26,40	21,65	12,23	7,02	2,64	51,74
4	94	0,125	8,28	8,46	59,80	20,55	0,35	0,35	82,47	100,02	140,25	1,25	1,25	38,35	64,42	13,29	10,03	3,76	68,43
5	78	0,104	8,2	6,58	46,18	16,02	0,29	0,29	50,34	60,84	115,13	1,04	1,04	33,70	31,41	6,70	9,44	3,12	63,44
6	78	0,104	8,13	5,28	45,55	16,02	0,29	0,29	71,45	44,20	102,23	1,04	1,04	36,61	36,82	5,12	9,61	3,12	60,32
7	97	0,129	8,12	4,41	59,49	19,92	0,94	0,36	73,46	45,91	85,75	1,29	1,29	51,22	64,15	5,95	12,88	3,88	82,26
8	10	0,013	9,66	5,31	6,33	2,33	0,07	0,04	4,71	6,48	11,39	0,13	0,13	4,59	3,84	0,13	1,20	0,40	1,79

Emission Total per step

step	Leachate (l)	L/S (l/kg)	PH	Conducibility	COD (mg)	TOC (mg)	TKN (mg)	NH3 (mg)	NO3 (mg)	Cl (mg)	SO4 (mg)	Cd (ug)	Cr (ug)	Cu (ug)	Fe (ug)	Mg (ug)	Ni (ug)	Pb (ug)	Zn (ug)
1	43	0,057	7,30	22,5	43000	13889	232,2	167,7	84968	115111	76196	430	430	15824	12384	16598	4730	1290	42140
2	81	0,108	7,84	13,9	48851	17820	769,5	315,9	93555	114858	137943	810	810	23814	20898	18144	6869	2430	63504
3	66	0,088	8,08	11,37	36940	13332	185	191	61578	73722	104742	660	660	19800	16236	9174	5267	1980	38808
4	94	0,125	8,28	8,46	44847	15416	263	263	61852	75012	105186	940	940	28764	48316	9964	7520	2820	51324
5	78	0,104	8,2	6,58	34632	12012	218	218	37752	45630	86346	780	780	25272	23556	5023	7082	2340	47580
6	78	0,104	8,13	5,28	34164	12012	218	218	53586	33150	76674	780	780	27456	27612	3838	7207	2340	45240
7	97	0,129	8,12	4,41	44620	14938	706	272	55096	34435	64311	970	970	38412	48112	4462	9661	2910	61692
8	10	0,013	9,66	5,31	4750	1750	50	28	3530	4860	8540	100	100	3440	2880	100	901	300	1340

Cumulate Emissions per kilogram

step	Leachate (l)	L/S (l/kg)	PH	Conducibility	COD (mg/kg)	TOC (mg/kg)	TKN (mg/kg)	NH3 (mg/kg)	NO3 (mg/kg)	Cl (mg/kg)	SO4 (mg/kg)	Cd (ug)	Cr (ug)	Cu (ug)	Fe (ug)	Mg (ug)	Ni (ug)	Pb (ug)	Zn (ug)
1	43	0,057	7,30	22,5	57,33	18,52	0,31	0,22	113,29	153,48	101,59	0,57	0,57	21,10	16,51	22,13	6,31	1,72	56,19
2	124	0,165	7,84	13,9	122,47	42,28	1,34	0,64	238,03	306,63	285,52	1,65	1,65	52,85	44,38	46,32	15,47	4,96	140,86
3	190	0,253	8,08	11,37	171,72	60,05	1,58	0,90	320,13	404,92	425,17	2,53	2,53	79,25	66,02	58,55	22,49	7,60	192,60
4	94	0,379	8,28	8,46	231,52	80,61	1,93	1,25	402,60	504,94	565,42	3,79	3,79	117,60	130,45	71,84	32,51	11,36	261,03
5	78	0,483	8,2	6,58	277,69	96,63	2,22	1,54	452,94	565,78	680,55	4,83	4,83	151,30	161,85	78,54	41,96	14,48	324,47
6	78	0,587	8,13	5,28	323,25	112,64	2,52	1,83	524,39	609,98	782,78	5,87	5,87	187,91	198,67	83,65	51,57	17,60	384,79
7	97	0,716	8,12	4,41	382,74	132,56	3,46	2,20	597,85	655,89	868,53	7,16	7,16	239,12	262,82	89,60	64,45	21,48	467,05
8	10	0,729	9,66	5,31	389,07	134,89	3,52	2,23	602,56	662,37	879,92	7,29	7,29	243,71	266,66	89,74	65,65	21,88	468,84

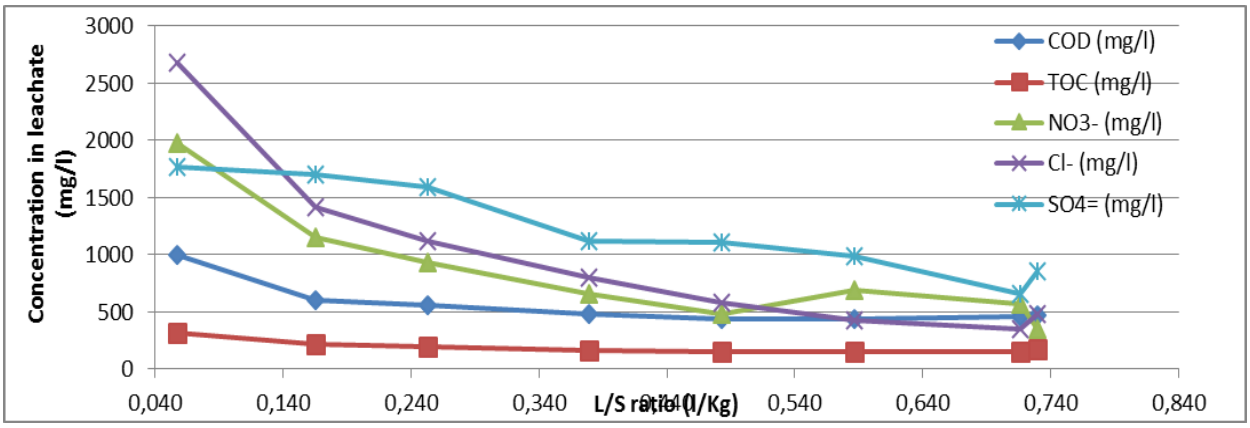


Figure 3.10: Concentration (mg/l) of main compounds in leachate extracted during phase 5 respect liquid/solid ratio (l/Kg).

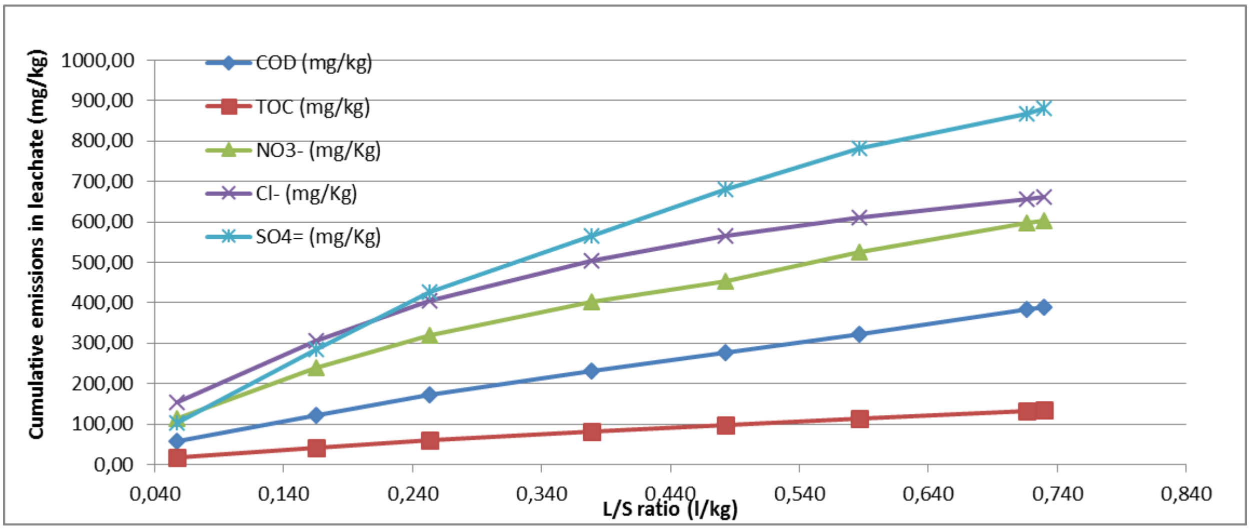


Figure 3.11: Cumulative mass extracted (mg/Kg) of main compounds with leachate during phase 5 respect liquid/solid ratio (l/Kg).

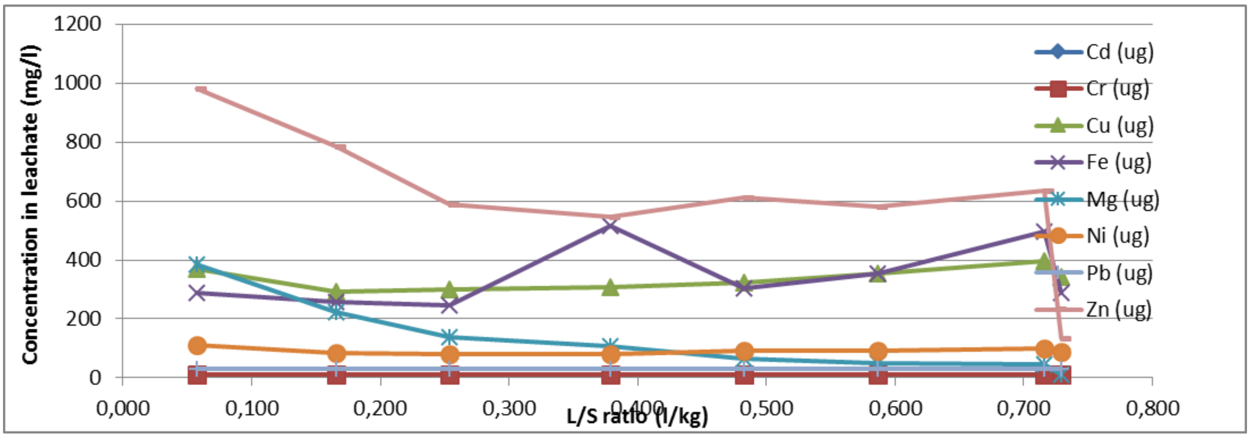


Figure 3.12: Concentration (mg/l) of heavy metals in leachate extracted during phase 5 respect liquid/solid ratio (l/Kg).

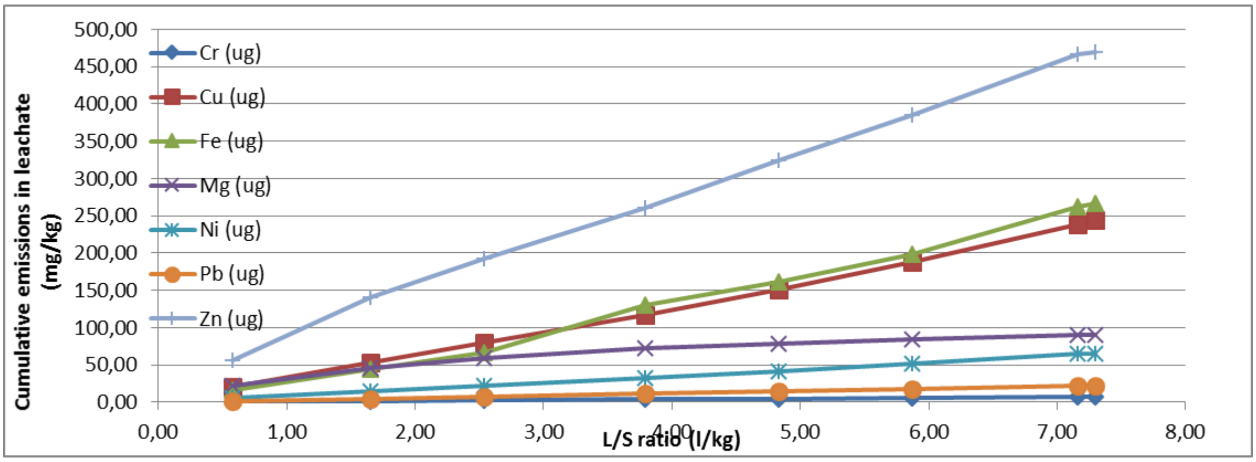


Figure 3.13: Cumulative mass extracted (mg/Kg) of heavy metals with leachate during phase 5 respect liquid/solid ratio (l/Kg).

Leachate emission data of all Phases

Table 3.17: Leachate emissions in the all Phases. The first phase starts in November 2004 and end in May 2005, the third phase starts in June 2007 and ends in July 2007, the fifth phase starts in May 2013 and ends in September 2013, the second anf fourth phases has no data collection. Days are the time skip between two analysis and Tot days are the complex length of analysis since the beginning of first phase. The Water balance is construct with the water ratio (Qi l/w), the water circulate in the time skip (Qe) and the liquid solid ratio (L/S). The other columns are concentration of compounds analysed: pH, conductibility, Total Organic Carbon, Totoal Kjendahl Nitrogen, ammonia, nitrates, chlorines, sulphates, cadmium, chromo, copper, iron, manganese, nickel, lead and zinc. The red values are not present so it was necessary to evaluate them for build a general mass balance and evaluate the cumulate emission.

Date	Days (d)	Tot days (d)	QI (l/w)	Qe (l)	L/S ratio (l/kg)	PH	Cond	BOD5 (mg/l)	COD (mg/l)	TOC (mg/l)	TKN (mg/l)	NH3 (mg/l)	NO3 (mg/l)	Cl (mg/l)	SO4 (mg/l)	Cd (mg/l)	Cr (mg/l)	Cu (mg/l)	Fe (mg/l)	Mg (mg/l)	Ni (mg/l)	Pb (mg/l)	Zn (mg/l)
23/11/2004	13	13	10	19	0,025	6,84		2400,00	3000,00	1400,00	427,00	576,00	1,52	1099,00	1133,00	0,01	0,42	0,24	20,20	1,34	0,69	0,01	2,32
30/11/2004	7	20	10	10	0,038	6,66		2920,00	3946,00	4197,00	588,00	495,00	1,17	2297,00	1171,00	0,01	0,40	0,27	19,55	1,30	0,69	0,02	2,27
07/12/2004	7	27	10	10	0,051	6,77		3440,00	9800,00	6994,00	1064,00	612,00	2,70	3495,00	403,00	0,01	0,39	0,30	18,90	1,25	0,69	0,02	2,22
16/12/2004	9	36	10	13	0,069	6,51		3960,00	23000,00	9791,00	1491,00	1152,00	6,60	4693,00	3299,00	0,01	0,37	0,32	18,25	1,21	0,70	0,03	2,17
21/12/2004	5	41	10	7	0,078	6,52		4480,00	32762,00	15612,00	1491,00	1152,00	6,30	5891,00	3434,00	0,01	0,35	0,35	17,60	1,17	0,70	0,03	2,12
28/12/2004	7	48	10	10	0,091	6,58		5000,00	33344,00	15744,00	1463,00	1170,00	6,15	7091,00	3445,00	0,01	0,34	0,38	16,95	1,13	0,70	0,04	2,07
04/01/2005	7	55	10	10	0,105	6,53		4820,00	31070,00	10055,00	1456,00	1269,00	7,30	6949,00	3500,00	0,01	0,32	0,41	16,29	1,08	0,70	0,04	2,02
11/01/2005	7	62	10	10	0,118	6,49		4640,00	32315,00	11643,00	1372,00	1233,00	8,75	6807,00	3635,00	0,01	0,30	0,44	15,64	1,04	0,70	0,05	1,97
18/01/2005	7	69	10	10	0,131	6,35		4460,00	29703,00	14950,00	1155,00	1134,00	8,00	6665,00	4000,00	0,01	0,28	0,46	14,99	1,00	0,71	0,05	1,92
25/01/2005	7	76	10	10	0,145	6,93		4280,00	30385,00	12701,00	1295,00	1161,00	7,10	6523,00	4509,00	0,01	0,27	0,49	14,34	0,95	0,71	0,06	1,87
01/02/2005	7	83	10	10	0,158	6,85		4100,00	27560,00	9129,00	1344,00	1071,00	5,00	6381,00	4300,00	0,01	0,25	0,52	13,69	0,91	0,71	0,06	1,82
08/02/2005	7	90	10	10	0,171	6,62		3920,00	37811,00	9791,00	1400,00	1107,00	4,02	6239,00	3906,00	0,01	0,23	0,55	13,04	0,87	0,71	0,07	1,77
15/02/2005	7	97	10	10	0,185	6,50		3740,00	30364,00	9526,00	1372,00	1215,00	4,50	6097,00	3700,00	0,01	0,22	0,58	12,39	0,82	0,71	0,07	1,72
22/02/2005	7	104	10	10	0,198	6,42		3560,00	30521,00	11643,00	1232,00	1116,00	4,84	5955,00	3545,00	0,01	0,20	0,60	11,74	0,78	0,72	0,08	1,67
01/03/2005	7	111	10	10	0,211	6,46		3380,00	28235,00	14553,00	1274,00	1152,00	5,50	5813,00	3200,00	0,01	0,18	0,63	11,09	0,74	0,72	0,08	1,62
08/03/2005	7	118	10	10	0,225	6,38		3200,00	32727,00	13098,00	1288,00	1080,00	6,83	5673,00	3081,00	0,01	0,17	0,66	10,44	0,70	0,72	0,09	1,57
16/03/2005	8	126	10	11	0,240	6,32		2675,00	29406,00	13892,00	1260,00	1152,00	6,20	5425,00	2750,00	0,01	0,15	0,69	9,78	0,65	0,72	0,09	1,52
23/03/2005	7	133	10	10	0,253	6,26		2150,00	30000,00	14818,00	1232,00	1134,00	5,71	5177,00	2507,00	0,01	0,13	0,72	9,13	0,61	0,72	0,10	1,47
29/03/2005	6	139	10	9	0,265	6,19		1625,00	31795,00	16141,00	1204,00	1062,00	5,67	4929,00	2100,00	0,01	0,11	0,74	8,48	0,57	0,73	0,10	1,42
05/04/2005	7	146	10	10	0,278	6,20		1100,00	32500,00	19316,00	1050,00	1098,00	5,65	4680,00	1762,00	0,01	0,10	0,77	7,83	0,52	0,73	0,11	1,37
13/04/2005	8	154	10	11	0,293	6,14		2075,00	33010,00	21566,00	980,00	1170,00	5,00	4272,00	1300,00	0,01	0,08	0,80	7,18	0,48	0,73	0,11	1,32
19/04/2005	6	160	10	9	0,305	6,15		3050,00	34000,00	16935,00	868,00	1152,00	4,65	3864,00	937,00	0,01	0,06	0,83	6,53	0,44	0,73	0,12	1,27
26/04/2005	7	167	10	10	0,318	6,15		4025,00	34470,00	15612,00	826,00	1170,00	4,00	3456,00	450,00	0,01	0,05	0,86	5,88	0,39	0,73	0,12	1,22
03/05/2005	7	174	10	10	0,331	6,15		5000,00	17244,00	6880,00	850,00	900,00	3,03	3049,00	20,00	0,01	0,03	0,88	5,23	0,35	0,74	0,13	1,17
29/06/2007	787	961	0	0	0,331	7,00		0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
06/07/2007	7	968	28	28	0,369	7,97		30,00	3316,00	933,00	54,88	25,20	870,00	4928,50	1071,00	0,01	0,04	0,92	4,58	0,32	0,74	0,14	1,11
13/07/2007	7	975	28	28	0,406	8,32		35,00	3014,00	675,00	54,32	16,10	638,00	5602,20	1803,00	0,01	0,03	0,84	3,58	0,25	0,54	0,11	0,99
20/07/2007	7	982	28	28	0,443	8,11		30,00	2412,00	465,00	49,28	16,24	553,00	4290,30	1911,00	0,01	0,02	0,76	2,58	0,18	0,34	0,08	0,87
27/07/2007	7	989	28	28	0,481	8,15		14,00	1421,00	415,00	53,20	17,36	473,00	4220,00	1785,00	0,01	0,01	0,68	1,59	0,12	0,14	0,06	0,75
22/05/2013	2126	3115		23	0,511	8,01	8,05	0,00	515,00	121,00	11,20	2,80	414,00	1085,00	886,00	0,01	0,01	0,222	0,91	0,044	0,075	0,03	0,117
25/06/2013	34	3149		43	0,569	7,3	22,5	0,00	1000,00	323,00	5,40	3,90	1976,00	2677,00	1772,00	0,01	0,01	0,37	0,29	0,39	0,11	0,03	0,98
08/07/2013	13	3162		81	0,677	7,84	13,9	0,00	603,10	220,00	9,50	3,90	1155,00	1418,00	1703,00	0,01	0,01	0,29	0,26	0,22	0,08	0,03	0,78
16/07/2013	8	3170		66	0,765	8,08	11,37	0,00	559,7	202	2,8	2,9	933	1117	1587	0,01	0,01	0,30	0,246	0,139	0,08	0,03	0,588
22/07/2013	6	3176		94	0,890	8,28	8,46	0,00	477,1	164	2,8	2,8	658	798	1119	0,01	0,01	0,306	0,514	0,106	0,08	0,03	0,546
29/07/2013	7	3183		78	0,994	8,20	6,58	0,00	444	154	3	2,8	484	585	1107	0,01	0,01	0,324	0,302	0,064	0,091	0,03	0,61
05/08/2013	7	3190		78	1,098	8,13	5,28	0,00	438	154	3	3	687	425	983	0,01	0,01	0,352	0,354	0,049	0,092	0,03	0,58
09/08/2013	4	3194		97	1,227	8,12	4,41	0,00	460	154	7	3	568	355	663	0,01	0,01	0,396	0,496	0,046	0,1	0,03	0,636
26/08/2013	17	3211		10	1,241	9,66	5,31		475	175	5,04	2,8	353	486	854	0,01	0,01	0,344	0,288	0,01	0,09	0,03	0,134

Table 3.18: Leachate emissions in the all Phases. This table is the following part respect the table 17. For every compound considered is evaluate the progressive total emission in mg/Kg of waste.

Date	L/S ratio (l/kg)	BOD5 (mg/kg)	COD (mg/kg)	TOC (mg/kg)	TKN (mg/kg)	NH3 (mg/kg)	NO3 (mg/kg)	Total N (mg/Kg)	Cl (mg/kg)	SO4 (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
23/11/2004	0,025	132	165	77	23	32	0	24	60	62	0,00	0,02	0,01	1,11	0,07	0,04	0,00	0,13
30/11/2004	0,038	219	282	201	41	46	0	41	129	97	0,00	0,04	0,02	1,69	0,11	0,06	0,00	0,19
07/12/2004	0,051	321	572	409	72	64	0	73	232	109	0,00	0,05	0,03	2,25	0,15	0,08	0,00	0,26
16/12/2004	0,069	471	1449	782	129	108	0	130	411	235	0,00	0,06	0,04	2,95	0,20	0,11	0,00	0,34
21/12/2004	0,078	566	2142	1112	161	133	1	161	536	307	0,00	0,07	0,05	3,32	0,22	0,12	0,00	0,39
28/12/2004	0,091	714	3130	1579	204	167	1	205	746	409	0,00	0,08	0,06	3,82	0,25	0,14	0,00	0,45
04/01/2005	0,105	857	4050	1876	247	205	1	248	952	513	0,00	0,09	0,07	4,30	0,29	0,16	0,01	0,51
11/01/2005	0,118	995	5008	2221	288	242	1	289	1153	621	0,00	0,10	0,09	4,77	0,32	0,18	0,01	0,57
18/01/2005	0,131	1127	5888	2664	322	275	1	324	1351	739	0,00	0,10	0,10	5,21	0,35	0,20	0,01	0,62
25/01/2005	0,145	1254	6788	3041	361	310	2	362	1544	873	0,00	0,11	0,11	5,64	0,37	0,22	0,01	0,68
01/02/2005	0,158	1375	7605	3311	400	341	2	402	1733	1000	0,00	0,12	0,13	6,04	0,40	0,25	0,01	0,73
08/02/2005	0,171	1491	8725	3601	442	374	2	444	1918	1116	0,00	0,13	0,15	6,43	0,43	0,27	0,01	0,79
15/02/2005	0,185	1602	9625	3884	482	410	2	485	2099	1226	0,00	0,13	0,16	6,79	0,45	0,29	0,02	0,84
22/02/2005	0,198	1708	10529	4229	519	443	2	521	2275	1331	0,00	0,14	0,18	7,14	0,47	0,31	0,02	0,89
01/03/2005	0,211	1808	11366	4660	557	477	2	559	2447	1426	0,00	0,14	0,20	7,47	0,50	0,33	0,02	0,93
08/03/2005	0,225	1902	12336	5048	595	509	3	598	2615	1517	0,00	0,15	0,22	7,78	0,52	0,35	0,02	0,98
16/03/2005	0,240	1993	13331	5518	638	548	3	640	2799	1610	0,01	0,15	0,24	8,11	0,54	0,38	0,03	1,03
23/03/2005	0,253	2057	14220	5957	674	582	3	677	2952	1684	0,01	0,16	0,26	8,38	0,56	0,40	0,03	1,08
29/03/2005	0,265	2098	15028	6367	705	609	3	708	3078	1738	0,01	0,16	0,28	8,60	0,57	0,42	0,03	1,11
05/04/2005	0,278	2131	15991	6940	736	641	3	739	3216	1790	0,01	0,16	0,31	8,83	0,59	0,44	0,03	1,15
13/04/2005	0,293	2201	17108	7670	769	681	3	772	3361	1834	0,01	0,17	0,33	9,07	0,60	0,46	0,04	1,20
19/04/2005	0,305	2278	17972	8100	791	710	4	795	3459	1858	0,01	0,17	0,35	9,24	0,61	0,48	0,04	1,23
26/04/2005	0,318	2398	18993	8562	815	745	4	819	3561	1871	0,01	0,17	0,38	9,41	0,63	0,50	0,04	1,27
03/05/2005	0,331	2546	19504	8766	841	772	4	844	3652	1872	0,01	0,17	0,41	9,57	0,64	0,52	0,05	1,30
29/06/2007	0,331	2546	19504	8766	841	772	4	844	3652	1872	0,01	0,17	0,41	9,57	0,64	0,52	0,05	1,30
06/07/2007	0,369	2548	19779	8844	845	774	76	921	4061	1960	0,01	0,17	0,48	9,95	0,66	0,59	0,06	1,39
13/07/2007	0,406	2551	20029	8900	850	775	129	979	4525	2110	0,01	0,18	0,55	10,24	0,68	0,63	0,07	1,48
20/07/2007	0,443	2554	20229	8938	854	776	175	1029	4881	2269	0,01	0,18	0,61	10,46	0,70	0,66	0,08	1,55
27/07/2007	0,481	2555	20347	8973	858	778	214	1072	5232	2417	0,01	0,18	0,67	10,59	0,71	0,67	0,08	1,61
22/05/2013	0,511	2555	20382	8981	859	778	242	1101	5305	2477	0,01	0,18	0,69	10,65	0,71	0,68	0,08	1,62
25/06/2013	0,569	2555	20510	9022	860	779	494	1354	5647	2703	0,01	0,18	0,73	10,69	0,76	0,69	0,09	1,74
08/07/2013	0,677	2555	20655	9075	862	779	771	1633	5987	3111	0,02	0,18	0,80	10,75	0,81	0,71	0,09	1,93
16/07/2013	0,765	2555	20764	9114	862	780	954	1816	6205	3422	0,02	0,19	0,86	10,80	0,84	0,73	0,10	2,05
22/07/2013	0,890	2555	20897	9160	863	781	1137	2000	6428	3733	0,02	0,19	0,95	10,94	0,87	0,75	0,11	2,20
29/07/2013	0,994	2555	21000	9196	864	781	1249	2113	6563	3989	0,02	0,19	1,02	11,01	0,89	0,77	0,11	2,34
05/08/2013	1,098	2555	21101	9231	865	782	1408	2272	6661	4216	0,02	0,19	1,10	11,09	0,90	0,79	0,12	2,47
09/08/2013	1,227	2555	21233	9276	867	783	1571	2437	6763	4407	0,03	0,20	1,22	11,24	0,91	0,82	0,13	2,66
26/08/2013	1,241	2555	21247	9281	867	783	1581	2448	6777	4432	0,03	0,20	1,23	11,25	0,91	0,82	0,13	2,66

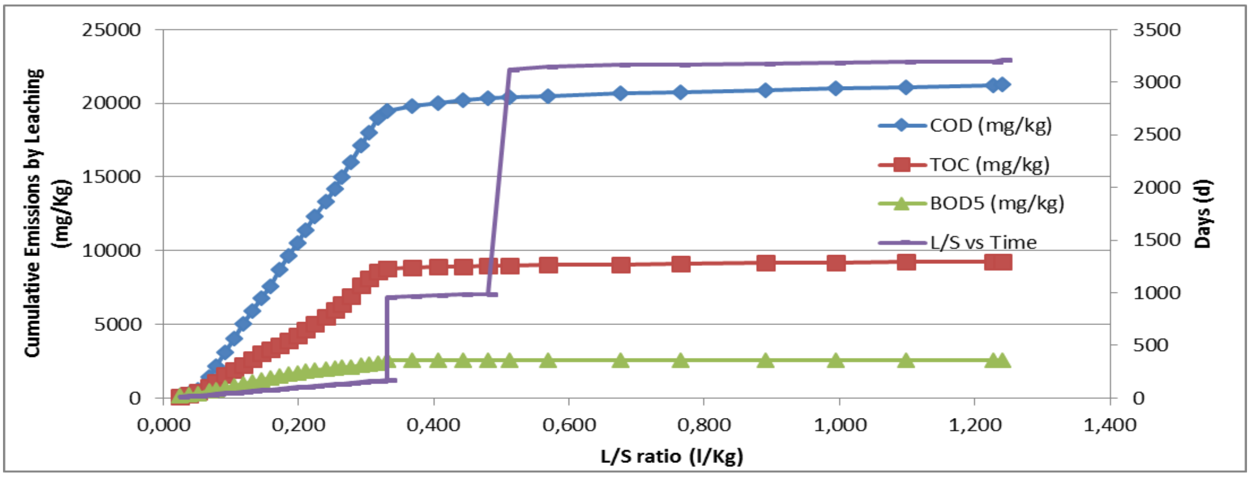


Figure 3.14: Cumulative emissions of TOC, COD, BOD5 (mg/Kg) respect liquid-solid ratio (l/Kg) for the whole phases. The purple line is L/S vs time used for plot the time (in vertical right axe) respect to the water balance. The two stairs at 0,3 and 0,5 l/Kg corresponds to the long phases 2 and 4 where water is not extract or inject in reactor.

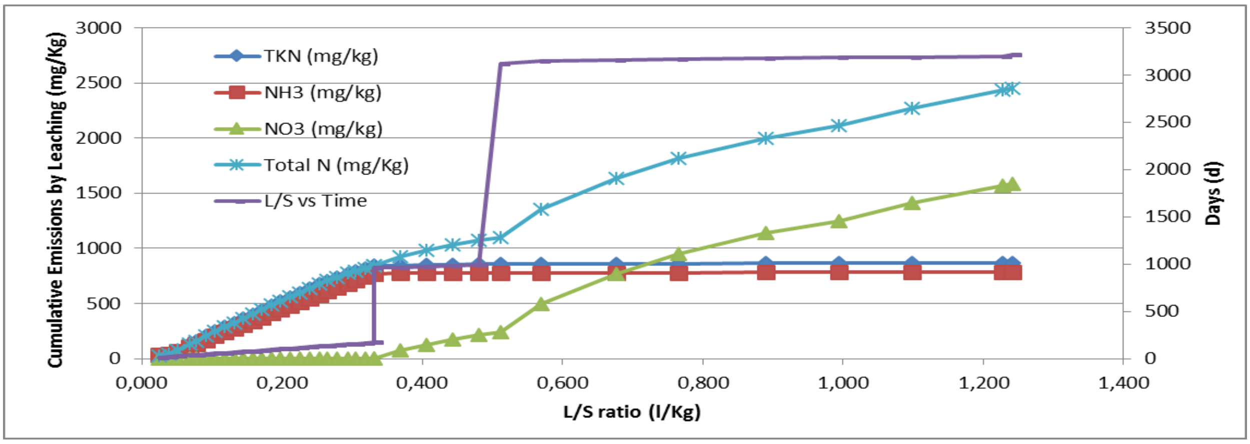


Figure 3.15: Cumulative emissions of TKN, NH3, NO3 and total nitrogen emission (mg/Kg) respect liquid-solid ratio (l/Kg) for the whole phases. The purple line is L/S vs time used for plot the time (in vertical right axe) respect to the water balance. The two stairs at 0,3 and 0,5 l/Kg corresponds to the long phases 2 and 4 where water is not extract or inject in reactor.

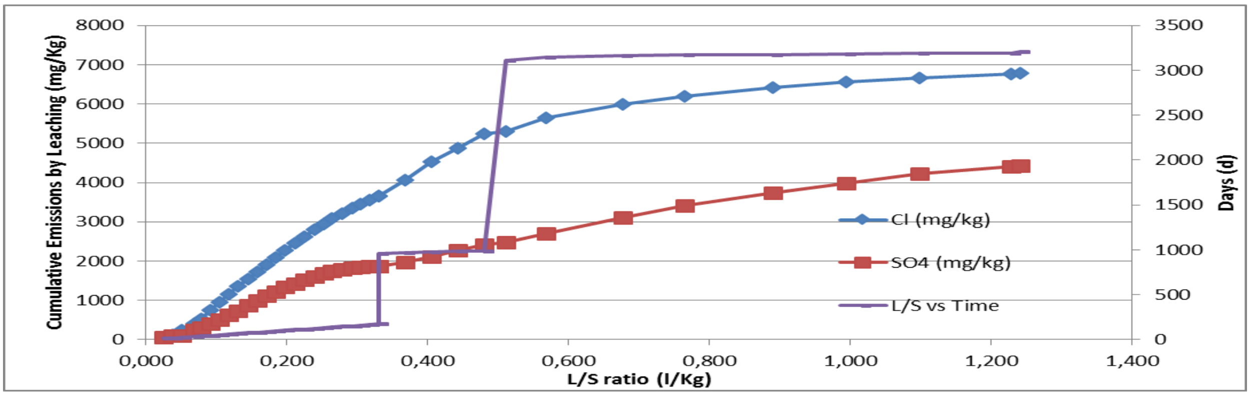


Figure 3.16: Cumulative emissions of chlorine and sulphates (mg/Kg) respect liquid-solid ratio (l/Kg) for the whole phases. The purple line is L/S vs time used for plot the time (in vertical right axe) respect to the water balance. The two stairs at 0,3 and 0,5 l/Kg corresponds to the long phases 2 and 4 where water is not extract or inject in reactor.

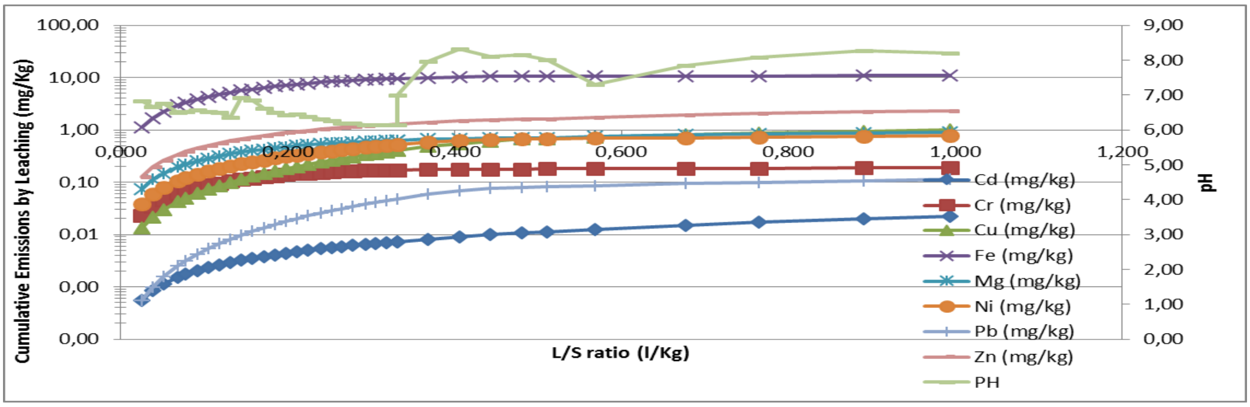


Figure 3.17: Cumulative emissions of heavy metals (logarithmic mg/Kg) respect liquid-solid ratio (l/Kg) for the whole phases. In right vertical axe is the pH, plot in green in the graph. It is useful for relate the solubilisation of the metals with the pH value.

Annex 2: Solid Analysis results

Residual waste test

Table 3.19: Residual waste analysis and leaching test at the beginning of Phase 5 (Sample S0, May 2013) and at the end of phase 5 (Samples S1, S2, S3, S4, S5 and average, September 2013). The sample S0 is taken only in the upper part of the reactor, between 0 and 75 cm. The sampling activity of July 2013 considers all the height of the lysimeter and the samples are different according to the deepness of the drilling. S1 is the sample of the upper part and is collected in the first 25 cm removing the waste material. The other samples are collected drilling the residual waste as described in annex 6. Analysis on the sample are made on Total Solids (%), Total Volatile Solids (%TS), Total Organic Carbon (%TS), Total Kjenahl Nitrogen (mgN/KgTS) and Ammonia (mgN/KgTS). Leaching test analysis are pH, Chemical Oxygen Demand (mgo2/l), ammonia (mgN/l), nitrates (mgN/l), Chlorine (mg/l), Sulphates (mg/l) and Total Organic Carbon (mgC/l). Heavy metals analysed are cadmium, chromo, cupper, iron, nickel, lead, Zinc (mg/KgTS).

On the sample

date	Sample	Deep (cm)	L/S ratio	TS (%)	TVS (%TS)	TOC (%TS)	TKN (mgN/kgTS)	NH3 (mgN/kgTS)
May 2013	S0	0 - 75	0,511	86,11	40,1	46,6	13332	999
Sep 2013	S1	0 - 25	1,241	73,47	28,29	22,54	10480	803
Sep 2013	S2	25 - 45	1,241	69,9	28,93	32,12	8412	562
Sep 2013	S3	45 - 75	1,241	71,15	22,72	33,03	10035	815
Sep 2013	S4	75 - 95	1,241	73,16	21,3	20,1	8229	727
Sep 2013	S5	95 - 125	1,241	69,81	23,63	18,52	9225	678
Sep 2013	Average			71,50	24,97	25,26	9276	717

Leaching test

date	Sample	S (g TS)	L (ml)	L/S test	PH	COD (mg/l)	NH3 (mg/l)	NO3 (mg/l)	Cl (mg/l)	SO4 (mg/l)	TOC (mg/l)
May 2013	S0	105	885	10,0	7,71	220,5	5,6	103,5	160	303	46
Sep 2013	S1	123	868	10,0	8,16	186,2	6,7	17,8	35	185	41
Sep 2013	S2	129	861	10,0	7,83	132,3	4,5	18,5	28	244	29
Sep 2013	S3	127	864	10,0	7,94	176,4	3,9	14,9	28	258	31
Sep 2013	S4	123	867	10,0	7,90	284,2	4,5	15,3	28	303	32
Sep 2013	S5	129	861	10,0	7,84	142,1	3,9	19,3	35	306	27
Sep 2013	Average	126	864	10,0	7,93	184,2	4,7	17,2	31	259	32

Metals

date	Sample	Cd (mg/KgTS)	Cr (mg/kgTS)	Cu (mg/KgTS)	Fe (mg/KgTS)	Mg (mg/KgTS)	Ni (mg/KgTS)	Pb (mg/KgTS)	Zn (mg/KgTS)
May 2013	S0A	0,58	29	288	8291	145	30	240	109
May 2013	S0B	0,58	114	266	8447	145	71	274	987
May 2013	Average	0,58	71	277	8369	145	51	257	548
Sep 2013	Average	0,97	37	3117	13860	167	39	309	2038

Table 3.20: Respirometric index IR4 and IR7 (mgO2/gTS) with SAPROMAT equipment. This table is the output of SAPROMAT equipment that measures the oxygen consumption through the oxygen production of a hydrolysis pile. Every oxygen production is of the same quantity and generates a click in a counter. Click results are cumulatively report every six hours, first column. For the sample of 22 may (S0) are made three parallel tests, for the sample if 29 July are made another three parallel tests of an average mix of the five samples (S1, S2, S3, S4, S5). The possible differences due to deepness are not considered. In last two lines are evaluate the IR4 and IR7 data that are the IR values of the fourth day and seventh day.

	S0a (mgO2/gTS)	S0b (mgO2/gTS)	S0c (mgO2/gTS)	Ava (mgO2/gTS)	Avb (mgO2/gTS)	Avc (mgO2/gTS)
	Sapromat 1 cell 1:	Sapromat 1 cell 2:	Sapromat 1 cell 3:	Sapromat 1 cell 4:	Sapromat 1 cell 5:	Sapromat 1 cell 6:
	O2 - Factor: 1	O2 - Factor: 1	O2 - Factor: 1	O2 - Factor: 1	O2 - Factor: 1	O2 - Factor: 1
	Reduction: 1:0	Reduction: 1:0	Reduction: 1:0	Reduction: 1:0	Reduction: 1:0	Reduction: 1:0
	Sample quantity: Ground	Sample quantity: Ground	Sample quantity: Ground	Sample quantity: Ground	Sample quantity: Ground	Sample quantity: Ground
	Measurements: 16834	Measurements: 16834	Measurements: 16833	Measurements: 16833	Measurements: 16833	Measurements: 16833
	Values:	Values:	Values:	Values:	Values:	Values:
0 06:00:00	8	24	17	6	18	20
0 12:00:00	18	45	30	6	25	28
0 18:00:00	32	63	44	6	29	30
1 00:00:00	42	77	54	8	33	32
1 06:00:00	50	89	63	8	33	32
1 12:00:00	62	105	75	12	36	36
1 18:00:00	72	116	85	16	41	40
2 00:00:00	88	136	102	27	52	52
2 06:00:00	88	140	104	27	52	52
2 12:00:00	98	153	114	27	54	54
2 18:00:00	106	161	122	30	57	56
3 00:00:00	116	173	130	34	63	62
3 06:00:00	120	177	136	36	65	64
3 12:00:00	126	186	142	39	66	66
3 18:00:00	130	190	148	41	68	66
4 00:00:00	146	208	164	53	82	80
4 06:00:00	150	212	168	55	84	83
4 12:00:00	154	216	172	55	84	83
4 18:00:00	156	218	176	55	84	83
5 00:00:00	166	228	186	61	90	87
5 06:00:00	170	232	190	63	92	91
5 12:00:00	172	235	194	63	92	91
5 18:00:00	174	235	196	63	92	91
6 00:00:00	182	243	204	65	94	91
6 06:00:00	184	245	206	65	94	91
6 12:00:00	190	253	214	68	98	95
6 18:00:00	196	259	220	70	98	95
7 00:00:00	201	265	226	73	102	99
7 06:00:00	203	267	226	73	102	99
IR4	1,41	2,01	1,59	0,51	0,79	0,77
IR7	1,95	2,56	2,19	0,71	0,99	0,96

Table 3.21: Progressive oxygen consumption during SAPROMAT test. The cumulative oxygen consumption is evaluate every six hours for the average values of May 2013 sample and September 2013 sample. Test totally lasts 174 hours that is more than seven days.

	May 2013	Sep 2013
Time (h)	mgO2/gTS	mgO2/gTS
6	0,16	0,14
12	0,30	0,19
18	0,45	0,21
24	0,56	0,24
30	0,65	0,24
36	0,78	0,27
42	0,88	0,31
48	1,05	0,42
54	1,07	0,42
60	1,18	0,44
66	1,25	0,46
72	1,35	0,51
78	1,40	0,53
84	1,46	0,55
90	1,51	0,56
96	1,67	0,69
102	1,71	0,72
108	1,75	0,72
114	1,77	0,72
120	1,87	0,77
126	1,91	0,79
132	1,94	0,79
138	1,95	0,79
144	2,03	0,81
150	2,05	0,81
156	2,12	0,84
162	2,18	0,85
168	2,23	0,88
174	2,25	0,88

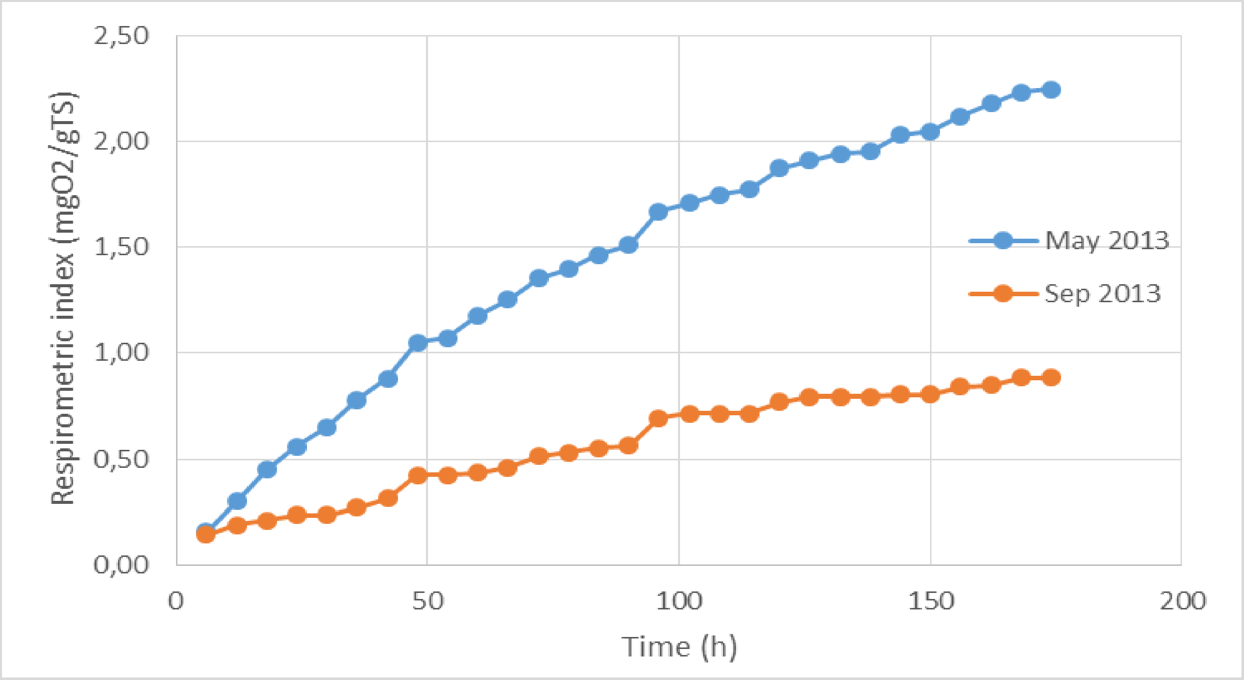


Figure 3.18: Cumulative respirometric index in May 2013 (before washing test) and in September 2013 (after washing test). IR4 corresponds to 96 hours value and IR7 to 168 value. In all test cells the September values are half than the May one. In any case the index is very low.

Residual waste analysis of all Phases

Table 3.22: Residual waste analysis during all the 5 phases of the lysimeter history. The analysis are performed for Total Solids (%), Total Volatile Solids (%TS), Total Organic Carbon (%TS), Total Kjenahl Nitrogen (%TS), Ammonia (%TS), Heavy metals (cadmium, chromo, cupper, iron, nickel, lead, Zinc) in (mg/KgTS). Leaching test analysis are pH, Total Organic Carbon (mgC/l), Chemical Oxygen Demand (mgo2/l), Biological Oxygen Demand (mgO2/l), Total Kjenahl Nitrogen (mgN/l), ammonia (mgN/l), nitrates (mgN/l), Chlorine (mg/l), Sulphates (mg/l). Stability analysis are Respirometric Index IR4 and IR7 (mgO2/gTS) and B21 anaerobic digestion index (Nl/KgTS). A lack of data regards the first phases of the test for chlorine and sulphates, B21 index is not considered in 2013.

Solid Waste sample	date	L/S ratio	TS (%)	TVS (%TS)	TOC (%TS)	TKN (%TS)	NH3 (%TS)	Cd (mg/KgTS)	Cr (mg/kgTS)	Cu (mg/KgTS)	Fe (mg/KgTS)	Mg (mg/KgTS	Ni (mg/KgTS)	Pb (mg/KgTS)	Zn (mg/KgTS
Start Phase 1	nov-04	0	44,5	48,5	31,1	1,50	0,27	1,0	11,3	52,0	3862,3	83,0	4,4	20,0	974,9
Start Phase 3	jun 07	0,331	47	28	20,1	1,03	0,12	1,8	30,0	2226,8	31053,7	275,7	276,6	61,5	2192,0
End Phase 3	jul 07	0,481	41,4	26,5	19	0,98	0,11	1,0	34,7	202,2	11290,8	244,1	23,9	235,0	595,1
Start Phase 5	may 13	0,511	86,1	40,1	46,6	1,33	0,10	1	71	277	8369	145	51	257	548
End Phase 5	sep 13	1,241	71,5	25,0	25,3	0,93	0,07	0,97	37,1	3117,0	13860,0	167,0	38,7	309,1	2038,0
Leaching test	date	L/S ratio	PH	TOC (mg/l)	COD (mg/l)	BOD5 (mg/l)	TKN (mg/l)	NH3 (mg/l)	NO3 (mg/l)	Cl (mg/l)	SO4 (mg/l)		IR4 (mgO2/gTS)	IR7 (mgO2/gTS)	B21 (Nl/KgTS)
Start Phase 1	nov-04	0		570	1482	917	36	18,4					66,4	106,7	29,8
Start Phase 3	jun 07	0,331	8,1	83,6	191,7	10	<10	3,4	55,1				1,8	2,7	3,2
End Phase 3	jul 07	0,481	7,6	58,2	93,5	0	<10	1,5	428				0,7	1,3	2,7
Start Phase 5	may 13	0,511	7,71	46	220,5	0		5,6	103,5	160	303		1,67	2,23	
End Phase 5	sep 13	1,241	7,93	32	184,24	0		4,7	17,16	31	259		0,69	0,88	

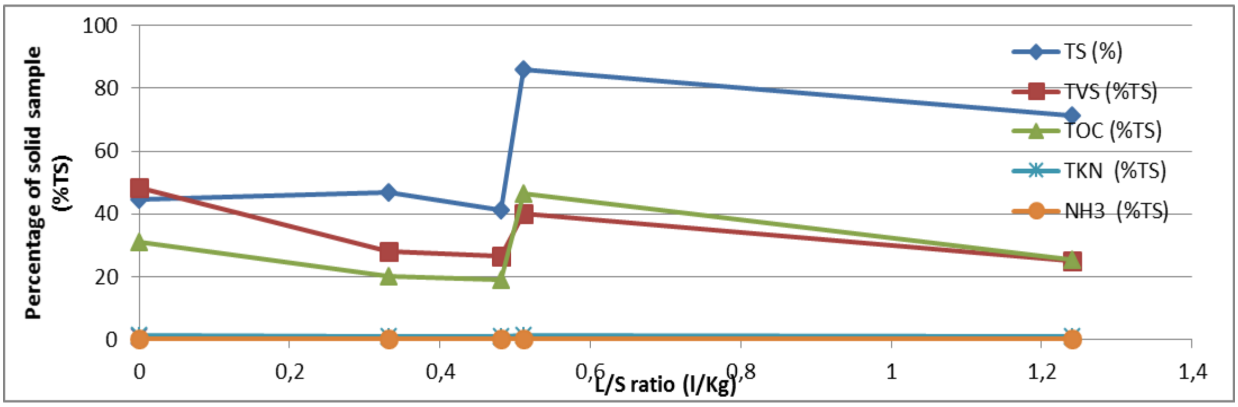


Figure 3.19: Residual waste analysis in all phases, carbon and nitrogen indexes print respect the liquid-solid ratio. The behaviour is constantly decreasing due to the washing and the degradation of compounds, except for the last two values that are milled and so gives higher results. TS depends on the moisture content that is very low after years of solar explosion without water injection. Nitrogen values remains always very low in percentage on total residual waste.

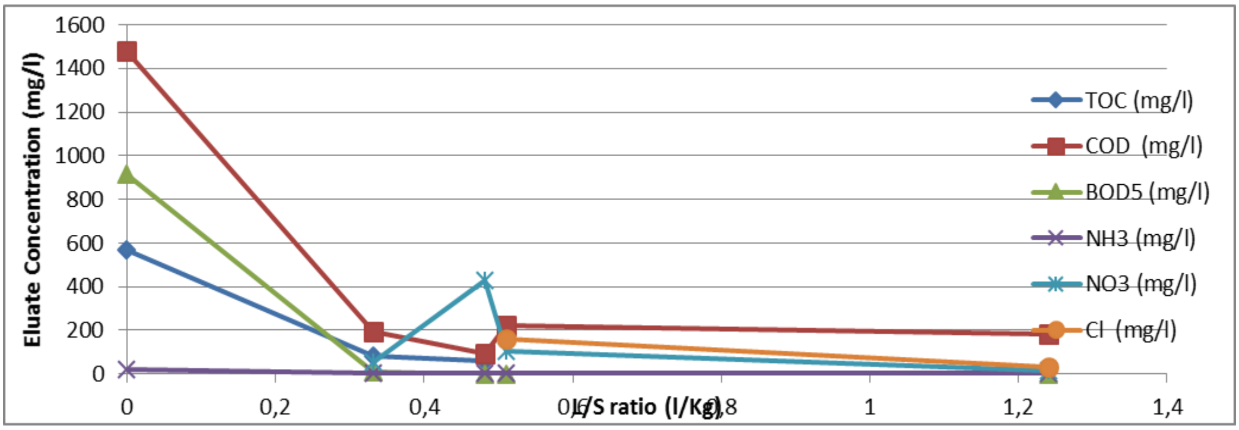


Figure 3.20: Residual waste analysis in all phases, leaching test analysis print respect the liquid-solid ratio. All index are constantly decreasing, especially in the first analysis, than the behaviour became virtually stable. The little increase of all compounds at 0.5 L/S ratio depends on the milling of the sample. Nitrates increases at 0,3 because aerobic conditions start, from 0,5 L/S they decrease constantly due to heavy washing.

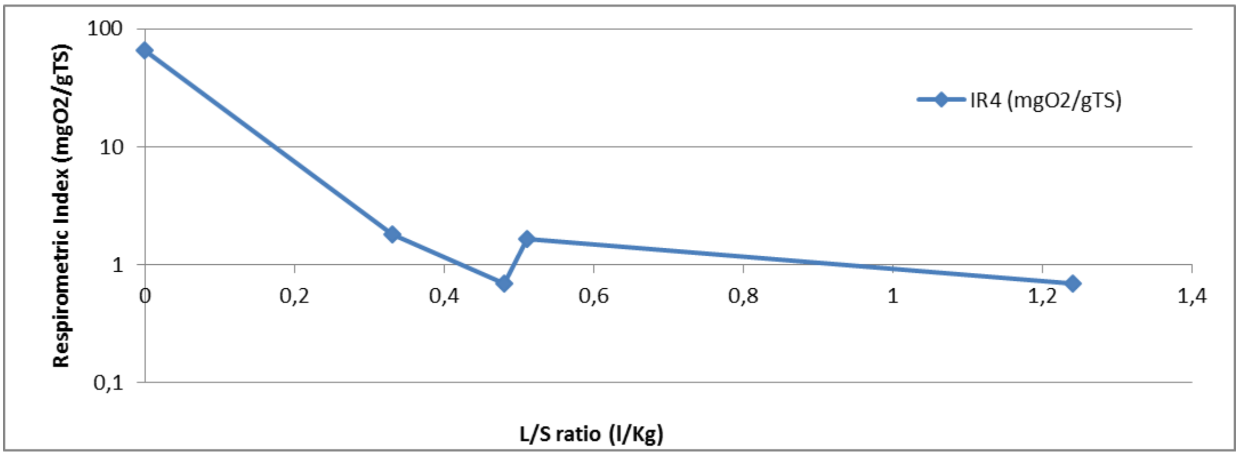


Figure 3.21: Residual waste analysis in all phases, Respirometric Index (four days) analysis print respect the liquid-solid ratio. The biological stability index falls down very rapidly since the first phases and after the end of second semi-aerobic aftercare phase has values near one, that means waste biological stability. Even in this test is visible the effect of milling the last two samples, little increase of 0,5 l/S value.

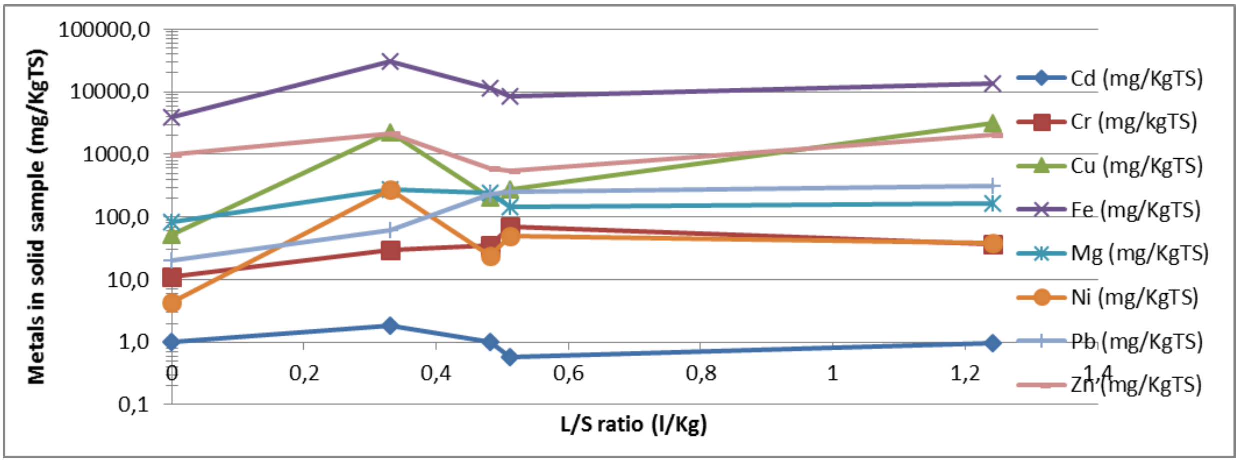


Figure 3.22: Residual waste analysis in all phases, Heavy metals analysis print respect the liquid-solid ratio. The biological stability index falls down very rapidly since the first phases and after the end of second semi-aerobic aftercare phase has values near one, that means waste biological stability. Even in this test is visible the effect of milling the last two samples, little increase of 0,5 l/S value. The values are quite variable because metals analysis on residual waste are very sensible to its heterogeneity. Moreover no significant behaviours can be seen, this verify the low emission potential of metals in general.

Annex 3: FSQ evaluation

Comparative Tests characterization table

Table 3.24: Comparative Tests characterization table. In this table are listed all tests considered for comparison with the lysimeter one and for the evaluation of FSQ threshold values. From left to right: progressive number, author of test, Type, code-name assigned, aeration characteristics, water injection, initial mass of waste and Total solids. These characteristic are useful for build a L/S comparison for each test. The Code-name: L stands for Lysimeter (more than 100 Kg of waste), C stands for columnar test, M for mathematical model and La for real landfill data. Every one of this test is a Semi-aerobic test of MSW waste with a source sorting and a mechanical pre-treatment.

N°	Author	Test Type	Test name	Aeration	Water (l/d)	Initial mass (kg)	TS (%)
1	Lysimeter test 2013	Lysimeter Morello	L1	High aeration	Various	750	45
2	Cossu et al., 2003	Column Aerobic	C1	100 Nl/h continuous	0,175	8,14	67
3	Cossu et al., 2003	Column Semi-aerobic	C2	50 Nl/h, 20 d/w	0,175	8,81	67
4	Cossu et al., 2003	Column PAF model	C3	50 Nl/h, 20 d/w	0,5	8,29	67
5	Cossu, Rossetti, 2003	Lysimeter Rossetti PAF	L2	High aeroation	Various	750	67
6	Manfredi, Cristensen, 2009	Model Semi-aerobic	M1	Semi-aerobic	Various	1000	100
7	Shimaoka et al., 2013	Lysimeter Jap1	L3	0,5-1 l/m	1,9	2551	58
8	Shimaoka et al., 2013	Lysimeter Jap2	L4	0,5-1 l/m	1,9	2551	58
9	Raga, Cossu 2013	Column Semi-aerobic C2	C4	2 Nl/h	Saturated	32,8	49,9
10	Raga, Cossu 2013	Column Semi-aerobic C3	C5	2 Nl/h	Saturated	32,1	43,7
11	Raga, Cossu 2013	Column Semi-aerobic C4	C6	2 Nl/h	Saturated	33,3	44,2
12	Raga, Cossu 2013	Column Semi-aerobic C6	C7	2 Nl/h	Saturated	31,2	39,8
13	Bilgili et al., 2007	Column Aerobic A1	C8	0,84 l/m/Kg waste	0,47	179	
14	Ritzkowski, Stegmann, 2013	Column Aerobic average 6	C9	0,4 m3/Mg TS d			
15	Ritzkowski et al., 2006	Column Aerobic Kuh 1-8	C10	0,2-0,6 l/KgTS d	0,07	39,64	100
16	Oygard et al., 2004	Landfill 1	La1		77260	190000000	
17	Oygard et al., 2004	Landfill 2	La2		309315	350000000	
18	Oygard et al., 2004	Landfill 3	La3		150685	98000000	
19	Oygard et al., 2004	Landfill 4	La4		529041	544000000	

Comparative table for each polluter

Table 3.25: TOC comparative table. For each test (first column), some useful information are reported, especially L/S ratio, residual waste analysis, leachate end gas emissions and final concentration in leachate. For the emissions, the percentage of compound emitted since the test begin is evaluated. In the last column, the percentage of compound still present in waste is reported. Often these values are given arbitrarily so are impossible to be verify. In other cases, the data must be evaluate from concentrations and test characteristics. TOC data are abundant because carbon mass balance is one of the most studied.

TOC									
		Solids (g/KgTS)		Leachate Emissions (g/KgTS)		Gasseous Emissions (g/kgTS)		Final Conc in Leachate	Storage initial-final
Test name	L/S ratio (l/Kg)	TOCi	TOCf	TOCl	% of TOCi	TOCg	% of TOCi	C (mg/l)	(%)
L1	1,24	104		9,3	8,9				
C1	2,58	208		3,0	1,4			1000	
C2	2,57	208		5	2,4			1000	
C3	7,24	208		11	5,3			800	
L2	1,71	208							
M1	1,49	194	111,7	6,5	3,3	75,9	39,1		57,5
L3	0,78	111		0,77	0,7			250	
L4	0,78	111		0,40	0,4			200	
C4	0,69	151	141,33	0,66	0,4	10,96	7,2	427	93,4
C5	0,70	141	97,43	1,20	0,8	9,47	6,7	316	68,9
C6	0,68	110	99,87	1,38	1,3	11,09	10,1	477	91,0
C7	0,72	107	93,65	1,02	1,0	12,73	11,9	310	87,7
C8	0,78								
C9		76,6	57,5	0,82	1,1	18,60	24,3		75,1
C10	1,29	220	151	4,39	2,0	48,30	22,0	100	69,0
La1	3,27								
La2	6,13								
La3	19,08								
La4	3,19								

Table 3.26: TKN comparative table. For each test (first column), some useful information are reported, especially L/S ratio, residual waste analysis, leachate end gas emissions and final concentration in leachate. For the emissions, the percentage of compound emitted since the test begin is evaluated. In the last column, the percentage of compound still present in waste is reported. Often these values are given arbitrarily so are impossible to be verify. In other cases, the data must be evaluate from concentrations and test characteristics. The nitrates are not always considered in this tests. The data quantity is abundant because the nitrogen balance is fundamental for the biological activity and because ammonia is on of the most frequent pollutants of a landfill.

N									
		Solids (g/KgTS)		Leachate Emissions (g/KgTS)		Gasseous Emissions (g/kgTS)		Final Conc in Leachate	Storage initial-final
Test name	L/S ratio (l/Kg)	Ni	Nf	Nl	% of Ni	Ng	% of Ni	C (mg/l)	(%)
L1	1,24	15,04		2,45	16,3			5,04	
C1	2,58	4,53	3,92	0,90	19,9			100	86,6
C2	2,57	4,98	3,78	1,90	38,1			200	75,8
C3	7,24	4,89	3,72	2,90	59,3			20	76,1
L2	1,71	5,27	4,38	1,08	20,5			100	83,0
M1	1,49	5,80	5,00	0,8	13,8			400	86,2
L3	0,78	7,00		1,11	15,9			100	
L4	0,78	7,00		1,16	16,5			50	
C4	0,69	4,53	3,61	0,51	11,3	0,01	0,2	25	79,7
C5	0,70	4,89	3,51	1,12	22,9	0,02	0,4	22	71,8
C6	0,68	4,89	3,55	1,02	20,8	0,02	0,4	69	72,6
C7	0,72	5,27	4,13	0,83	15,7	0,02	0,3	18	78,4
C8	0,78								
C9									
C10	1,29								
La1	3,27								
La2	6,13								
La3	19,08								
La4	3,19								

Table 3.27: Chlorine comparative table. For each test (first column), some useful information are reported, especially L/S ratio, residual waste analysis, leachate end gas emissions and final concentration in leachate. For the emissions, the percentage of compound emitted since the test begin is evaluated. In the last column, the percentage of compound still present in waste is reported. Often these values are given arbitrarily so are impossible to be verify. In other cases, the data must be evaluate from concentrations and test characteristics. Only small quantity of data are available because is a secondary polluter and because is difficult to measure in solid samples.

Cl-									
		Solids (g/KgTS)		Leachate Emissions (g/KgTS)		Gasseous Emissions (g/kgTS)		Final Conc in Leachate	Storage initial-final
Test name	L/S ratio (l/Kg)	Cli	Clf	Cll	% of Cli	Clg	% of Cli	C (mg/l)	(%)
L1	1,24			6,8				486	
C1	2,58								
C2	2,57								
C3	7,24								
L2	1,71								
M1	1,49	4,90	2,2	2,7	55,1			980	44,9
L3	0,78								
L4	0,78								
C4	0,69	2,64	1,25	1,60	60,6			1773	47,3
C5	0,70	2,98	1,39	1,93	64,8			3546	46,6
C6	0,68	2,98	1,66	1,93	64,8			3439	55,7
C7	0,72	3,05	1,42	1,93	63,3			2127	46,6
C8	0,78								
C9									
C10	1,29								
La1	3,27								
La2	6,13								
La3	19,08								
La4	3,19								

Table 3.28: Iron comparative table. For each test (first column), some useful information are reported, especially L/S ratio, residual waste analysis, leachate end gas emissions and final concentration in leachate. For the emissions, the percentage of compound emitted since the test begin is evaluated. In the last column, the percentage of compound still present in waste is reported. Often these values are given arbitrarily so are impossible to be verify. In other cases, the data must be evaluate from concentrations and test characteristics. Only small quantity of data are available because is a secondary polluter that generally does not cause problems in such low quantities.

Fe									
		Solids (mg/KgTS)		Leachate Emissions (g/KgTS)		Gasseous Emissions (g/kgTS)		Final Conc in Leachate	Storage initial-final
Test name	L/S ratio (l/Kg)	Fei	Fef	Fel	% of Fei	Feg	% of Fei	C (mg/l)	(%)
L1	1,24	3862		11,2	0,3			0,288	
C1	2,58								
C2	2,57								
C3	7,24								
L2	1,71								
M1	1,49								
L3	0,78								
L4	0,78								
C4	0,69								
C5	0,70								
C6	0,68								
C7	0,72								
C8	0,78	480	560	31,31	6,5			40	116,7
C9									
C10	1,29								
La1	3,27	0,58		0,05	8,01			180	
La2	6,13	0,59		0,02	3,87			41	
La3	19,08	0,46		0,08	17,90			85	
La4	3,19	0,80		0,02	1,91			25	

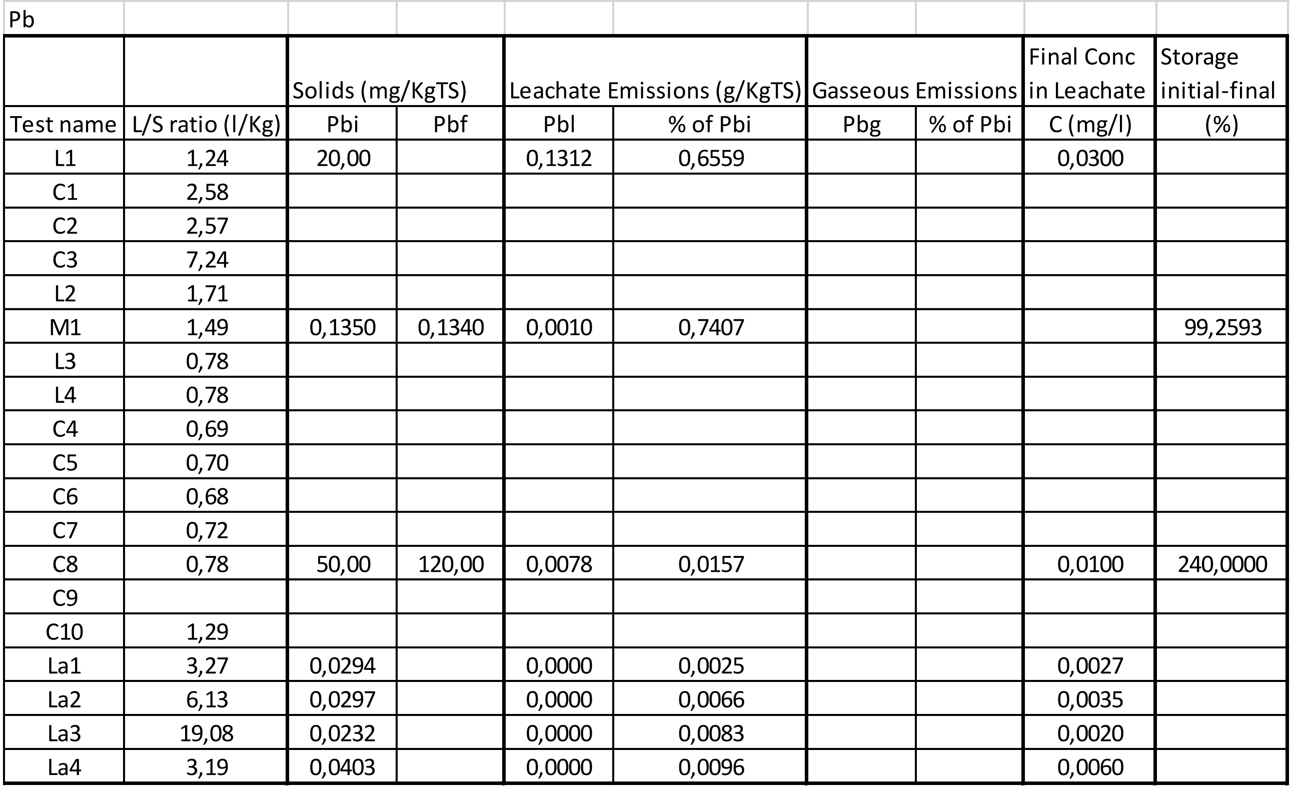
Table 3.29: Cadmium comparative table. For each test (first column), some useful information are reported, especially L/S ratio, residual waste analysis, leachate end gas emissions and final concentration in leachate. For the emissions, the percentage of compound emitted since the test begin is evaluated. In the last column, the percentage of compound still present in waste is reported. Often these values are given arbitrarily so are impossible to be verify. In other cases, the data must be evaluate from concentrations and test characteristics. Only small quantity of data are available because is a secondary polluter that generally does not cause problems in such low quantities.

Cd									
		Solids (mg/KgTS)		Leachate Emissions (g/KgTS)		Gasseous Emissions (g/kgTS)		Final Conc in Leachate	Storage initial-final
Test name	L/S ratio (l/Kg)	Cdi	Cdf	Cdl	% of Cdi	Cdg	% of Cdi	C (mg/l)	(%)
L1	1,24	1,0000		0,0276	2,7572			0,0100	
C1	2,58								
C2	2,57								
C3	7,24								
L2	1,71								
M1	1,49	0,0070	0,0069	0,0002					97,8571
L3	0,78								
L4	0,78								
C4	0,69								
C5	0,70								
C6	0,68								
C7	0,72								
C8	0,78	0,0035	0,0045	0,0001	2,2366			0,1000	128,5714
C9									
C10	1,29								
La1	3,27	0,0004		0,0000	0,0153			0,0002	
La2	6,13	0,0004		0,0000	0,5616			0,0004	
La3	19,08	0,0003		0,0000	0,0438			0,0001	
La4	3,19	0,0005		0,0000	0,0209			0,0002	

Table 3.30: Chromo comparative table. For each test (first column), some useful information are reported, especially L/S ratio, residual waste analysis, leachate end gas emissions and final concentration in leachate. For the emissions, the percentage of compound emitted since the test begin is evaluated. In the last column, the percentage of compound still present in waste is reported. Often these values are given arbitrarily so are impossible to be verify. In other cases, the data must be evaluate from concentrations and test characteristics. Only small quantity of data are available because is a secondary polluter that generally does not cause problems in such low quantities.

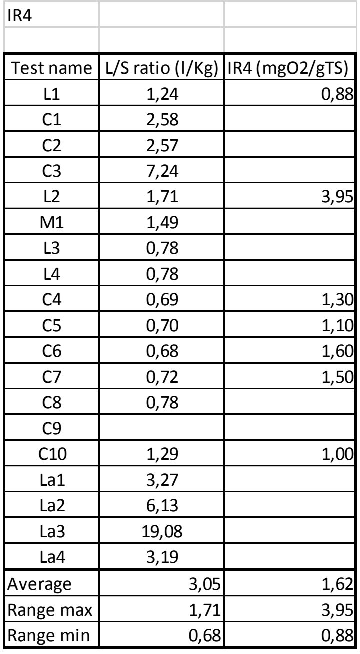
Cr									
		Solids (mg/KgTS)		Leachate Emissions (g/KgTS)		Gasseous Emissions		Final Conc in Leachate	Storage initial-final
Test name	L/S ratio (l/Kg)	Cri	Crf	Crl	% of Cri	Crg	% of Cri	C (mg/l)	(%)
L1	1,24	11,30		0,1959	1,7332			0,0100	
C1	2,58								
C2	2,57								
C3	7,24								
L2	1,71								
M1	1,49	0,0072	0,0062	0,0002					86,2500
L3	0,78								
L4	0,78								
C4	0,69								
C5	0,70								
C6	0,68								
C7	0,72								
C8	0,78	200,00	300,00	0,0783	0,0391			0,1000	150,0000
C9									
C10	1,29								
La1	3,27	0,0014		0,0000	0,8182			0,0450	
La2	6,13	0,0014		0,0000	1,0420			0,0260	
La3	19,08	0,0011		0,0000	0,6051			0,0067	
La4	3,19	0,0019		0,0000	0,8236			0,0240	

Table 3.31: Lead comparative table. For each test (first column), some useful information are reported, especially L/S ratio, residual waste analysis, leachate end gas emissions and final concentration in leachate. For the emissions, the percentage of compound emitted since the test begin is evaluated. In the last column, the percentage of compound still present in waste is reported. Often these values are given arbitrarily so are impossible to be verify. In other cases, the data must be evaluate from concentrations and test characteristics. Only small quantity of data are available because is a secondary polluter that generally does not cause problems in such low quantities.



Pb									
		Solids (mg/KgTS)		Leachate Emissions (g/KgTS)		Gasseous Emissions		Final Conc in Leachate	Storage initial-final
Test name	L/S ratio (l/Kg)	Pbi	Pbf	Pbl	% of Pbi	Pbg	% of Pbi	C (mg/l)	(%)
L1	1,24	20,00		0,1312	0,6559			0,0300	
C1	2,58								
C2	2,57								
C3	7,24								
L2	1,71								
M1	1,49	0,1350	0,1340	0,0010	0,7407				99,2593
L3	0,78								
L4	0,78								
C4	0,69								
C5	0,70								
C6	0,68								
C7	0,72								
C8	0,78	50,00	120,00	0,0078	0,0157			0,0100	240,0000
C9									
C10	1,29								
La1	3,27	0,0294		0,0000	0,0025			0,0027	
La2	6,13	0,0297		0,0000	0,0066			0,0035	
La3	19,08	0,0232		0,0000	0,0083			0,0020	
La4	3,19	0,0403		0,0000	0,0096			0,0060	

Table 3.32: Respirometric index four days comparative table. For each test (first column), some useful information are reported, especially L/S ratio, and final value.



IR4		
Test name	L/S ratio (l/Kg)	IR4 (mgO2/gTS)
L1	1,24	0,88
C1	2,58	
C2	2,57	
C3	7,24	
L2	1,71	3,95
M1	1,49	
L3	0,78	
L4	0,78	
C4	0,69	1,30
C5	0,70	1,10
C6	0,68	1,60
C7	0,72	1,50
C8	0,78	
C9		
C10	1,29	1,00
La1	3,27	
La2	6,13	
La3	19,08	
La4	3,19	
Average	3,05	1,62
Range max	1,71	3,95
Range min	0,68	0,88

General comparative table

Table 3.33: Results of test comparison. In the first column the test code-name, in the same order than in Table 23. In the second the L/S ratio, through which the test can be compared. In the following columns every pollutant has been consider (Carbon, Nitrogen, Chloride, Iron, other Heavy Metals) with its percentages of leachate emission after the indicate l/S, respect to the initial waste presence and with its final concentration in leachate. This table is useful for a common trend finding and for common values estimation.

Test	L/S	TOC				Nitrogen			Chlorine		Iron		Cadmium		Chromo		Lead	
	(l/Kg)	% Leachate emission	Final TOC conc (mg/l)	Final COD conc (mg/l)	Final BOD5/COD	% Leachate emission	Final TKN conc (mg/l)	Final nitrates conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)
L1	1,24	8,94				16,28	5,04			486	0,29	0,288	2,76	0,01	1,73	0,01	0,66	0,03
C1	2,58	1,44	1000	3000	0,01	19,89	100											
C2	2,57	2,40	1000	1000	0,30	38,14	200											
C3	7,24	5,29	800	800	0,09	59,29	20											
L2	1,71			3000	0,01	20,53	100	200										
M1	1,49	3,35		400	0,10	13,79	400		55,10	980							0,74	
L3	0,78	0,69	250			15,89	100	100										
L4	0,78	0,36	200			16,51	50	50										
C4	0,69	0,44	427	316		11,32	25		60,61	1773								
C5	0,70	0,85	316	510		22,86	22		64,77	3546								
C6	0,68	1,26	477	6884		20,78	69		64,77	3439								
C7	0,72	0,96	310	470		15,73	18		63,28	2127								
C8	0,78										6,52	40	2,24	0,1000	0,04	0,100	0,02	0,010
C9		1,07																
C10	1,29	2,00	100					0,2										
La1	3,27										8,01	180	0,02	0,0002	0,82	0,045	0,00	0,003
La2	6,13										3,87	41	0,56	0,0004	1,04	0,026	0,01	0,004
La3	19,08										17,90	85	0,04	0,0001	0,61	0,007	0,01	0,002
La4	3,19										1,91	25	0,02	0,0002	0,82	0,024	0,01	0,006
		TOC				Nitrogen			Chlorine		Iron							
		% Leachate emission	Final TOC conc (mg/l)	Final COD conc (mg/l)	Final BOD5 conc (mg/l)	% Leachate emission	Final TKN conc (mg/l)	Final nitrates conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)	% Leachate emission	Final conc (mg/l)
Average	3,05	2,23	488,00	1820,00	0,10	22,59	92,42	87,55	61,70	2058,50	6,42	61,88	0,94	0,02	0,84	0,04	0,21	0,01
Range max	19,08	8,94	1000,00	6884,00	0,30	59,29	400,00	200,00	64,77	3546,00	17,90	180,00	2,76	0,10	1,73	0,10	0,74	0,03
Range min	0,68	0,36	100,00	316,00	0,01	11,32	5,04	0,20	55,10	486,00	0,29	0,29	0,02	0,00	0,04	0,01	0,00	0,00

FSQ tables

Table 3.34: Leacahte FSQ Table. In the columns from left to right: the FSQ index choose, the average L/S at which it is stable in considered test, the average % of emission in leachate respect to initial presence in solids, the final concentration in leachate and the FSQ concentration purposed. The estimation is made using the average of the values of the emissions of the tests considered.

FSQ	Final L/S (l/Kg)	% Leacahte emission	Concentration (mg/l)	FSQ propose (mg/l)
TOC	1,73	2,23	488	500
COD	2,04		1820	1800
BOD5/COD	2,04		0,10	0,1
TKN	1,77	22,59	51	50
NO3-	1,14		88	90
Cl-	0,92	61,70	2059	2000
Iron	5,62	6,42	62	150
Cadmium	5,62	0,94	0,02	
Chromo	5,62	0,84	0,04	
Lead	5,03	0,21	0,01	

Table 3.35: Comparison between leachate FSQ proposed by some Authors (Krumpelback, Knox, Stegmann, Cossu), the present FSQ proposal, the legislation values for discharging in environment, and the Italian CSC. The evaluated FSQ are higher of the emission limits but the values are without considering the natural attenuation of the clay liner.

Suggested index	Unit	FSQ proposed					Present Italian legislation						
		Kruempelbeck (2000)	Knox at al. (2005)	Stegmann (2006)	Cossu (2007), Pivato (2004)	Semi-aerobic test (2013)	DM n5-2/98 allegato 3, Test di Cessione	Limiti allo scarico sul suolo, D.lgs.152/2006	Limiti allo scarico in acque superficiali, D.lgs.152/2006	Limiti allo scarico in fognatura, D.lgs.152/2006	CSC, tabella A, suolo siti residenziali, D.lgs.152/2006	CSC, tabella B, suolo siti industriali-commerciali, D.lgs.152/2006	CSC, acque sotterranee, D.lgs.152/2006
COD	mg/l	16 ; 70			200	1800	30	100	160	500			
COD surface specific	g/m2*y	3 ; 14		5 ; 20									
BOD_5	mg/l							20	40	250			
BOD_5/COD					0,01	0,10							
TOC	mg/l					500							
TKN	mgN/l					50		15					
$N\text{-}NH_4^+$	mgN/l	9 ; 20	10		300				15	30			
N-NH4+ surface specific	g/m2*y	1,8 ; 4		2,5 ; 10									
N-Nox	mgN/l					90	50		20	30			
SO4	mg/l						250		1000	1000			250
Cl-	mg/l					2000	200		1200	1200			
P tot	mgP/l							2	10	10			
Cd	mg/l						0,005		0,02	0,02	2	15	0,005
Cr	mg/l						0,05	1	2	4	2	15	0,005
Cu	mg/l						0,05	0,1	0,1	0,4	120	600	1
Fe	mg/l					150		2	2	4			0,2
Mg	mg/l							0,2	2	4			0,05
Ni	mg/l						0,01	0,2	2	4	120	500	0,2
Pb	mg/l						0,05	0,1	0,2	0,3	100	1000	0,1
Zi	mg/l						3	0,5	0,5	1	150	1500	3

Annex 4: Analytical Methodology

Analysis on Liquids

For all the leachate analysis are necessary 500 ml of liquid, 250 (more or less) for analytical tests and 250 as stock; the samples are stored in fridge for all time. The bottle is made of plastic and it has the same capacity of the liquid taken, to avoid air presence in headspace. Italian and European law certifies all the analytical procedures used.

pH: IRSA-CNR 29/2003, Vol1, n.2060. The test is carried on immediately after the sampling because requires environment temperature to be precise and because can be performed very fast. It consist in a probe input that gives immediately the pH measure.

Conducibility: IRSA-CNR 29/2003, Vol1, n.2030. Conducibility measurement is very similar to pH one and generally it is made in the same time. The analysis are made with a probe.

Total Organic Carbon (TOC): IRSA-CNR 29/2003, Vol2, n.5040. TOC is measured with the "TOC-V CSN" analytical equipment that gives directly the concentration value.

Ammonia (NH3, titration): IRSA-CNR 29/2003, Vol2, n.4030 C. Ammonia concentration is evaluated distilling a note volume of sample with NaOH addition. The condensation liquid is collected with boric acid and titrate with sulphuric acid. The concentration can be evaluate with a stoichiometric formula, starting from the sulphuric acid consumption.

Total Kjeldahl Nitrogen (TKN): IRSA-CNR 29/2003, Vol2, n.5030. The procedure is the same as for ammonia except that, before distillation, a digestion in acid environment is necessary, with the addition on kjeldahl tabs.

Nitrates (NO3-) IRSA-CNR 29/2003, Vol2, n.4040 A1. The procedure starts with the addition of Na salicylate to the sample and with the drying in stove of the sample. After that, the sample is recover with acid, a base solution is added and the nitrates value is read on a spectrophotometer.

Biological Oxygen Demand (BOD5): IRSA-CNR 29/2003, Vol2, n.5120 B2. The test is a batch reactor test long for five days after which the oxygen consumption is read.

Chemical Oxygen Demand (COD): IRSA-CNR 29/2003, Vol2, n.5130. COD test consist in an acid digestion (150°C for 120 minutes) with great quantities of sulphuric acid and potassium dichromate. After that the solution is titrate with Mohr salt that gives the chemical consumption of oxygen.

Sulphates (SO4--): IRSA-CNR 29/2003, Vol2, n.4140 B. The test is made with a turbidity reading of spectrophotometer. The problem of the procedure can be the sample turbidity before reagents addition that can false the results.

Chlorine (Cl-): IRSA-CNR 29/2003, Vol2, n.4090 A1. Test is a titration with argent nitrate 0,1 molar.

Metals: IRSA-CNR 29/2003, Vol1, n.3010 mod.+3020.

Analysis on Solids

Solids samples are stored in fringe, in large glass containers, before the milling procedure. After that they are transfer in smaller plastic bottles to avoid air in headspace. The quantity sampled is one kilo more or less, with a volume of 2 liters.

Total Solids (TS) IRSA-CNR Q. 64/84, Vol2, n.2. A fix quantity of milled sample is weighted and dried in hoven for 12 hours. This procedure avoids the presence of water and allows the evaluation of the Total Solids in percentage respect to initial mass.

Total Volatile Solids (TVS) IRSA-CNR Q. 64/84, Vol2, n.2. The same sample coming out form TS analysis can be used. The procedure requires the burning in Moffola at the temperature of 550 °C for 3 hours. The effect is the consumption of everything organic is present in the sample. The residues are weighted and the TVS are the difference between initial TS and final inorganic residues remaining after the Moffola treatment.

Total Organic Carbon (TOC): UNI-EN 13137. The test is carried on with the same equipment of liquid TOC analysis: “TOC-V CSN”.

Ammonia (NH3): IRSA-CNR Q. 64/86, Vol3, n.7 mod. The procedure is the same of the liquid sample, only is necessary weight a certain quantity of sample.

Total Kjeldahl Nitrogen (TKN): IRSA-CNR Q. 64/85, Vol3, n.6 mod. The procedure is the same of the liquid sample, only is necessary weight a certain quantity of sample and be more careful about the digestion.

Respirometric Index ANPA 3/2001 n.12.1.2.3. Is made with the “SAPROMAT” equipment that is a semi-dynamic test of oxygen consumption under controlled conditions. The test is perform in 4 days and in 7 days, the oxygen consumption can be visualize even continuously.

Annex 5: Leaching test

The leaching test is a tool for analyse how much compounds are extractable from a solid sample, increasing the L/S ratio with a controlled washing of a small quantity of waste. The method must be a standard certified for ensure the comparability of the results with other ones. The standard choose is the UNI EN12457-2.

In a 2 litres bottle, solid sample and distilled water for reach L/S of 10 l/Kg are injected, considering the moisture content too. The bottles are fix to a agitating machine (Figure 3.23) that turns for 20 rounds per minute for 24 hours in a room at stable temperature around 20°C. After the washing time the sample is heavily filter to obtain 500 ml of elute for each solid sample (Figure 3.24). The analysis on this liquid are pH, COD, ammonia, nitrates, chloride and sulphates with the standards of leachate samples.

Figure 3.23: Agitating machine. The equipment has 6 place, three visible and three in the opposite side, at which bottles are attached. In bottles the water and the sample are continuously turned by the machine to extract all possible compounds. The turning rate is 20 rounds per minute, for 24 hours.

Figure 3.24: Leaching test result. A: final eluate extract by leaching test, more or less 500 ml per sample. B: Filtering process with filter paper, the process requires a lot of time because the high turbidity of the samples.

Annex 6: Sampling methodology

Leachate Samples

Leachate exits form the bottom part of the reactor and is collect in tanks with through plastic and/or rubber pipes (Figure 3.25). A system of valves allows the flux interruption for accumulate leachate inside reactor or for change the filled tanks. The leachate exit is generally between 70-120 liters that is more than one tank (canisters are 30-25 liters capacity). Leachate is homogeneous so take samples characteristic for all emitted leachate is not a problem in columnar tests. In Lysimeter case, liquid exiting is too much for one single canister, moreover the leachate that comes out immediately after recirculation can be very different form the ones collected the following days. For this reason, is necessary find a sampling procedure for leachate collected in different canisters without analyze many different samples. During the first pilot washing step this problem is engage, considering that the leachate cannot stay too much in the open air tank to not loose ammonia. Injection procedure, on the top of reactor, requires only 10-15 minutes to be make, leachate start exiting from the bottom after 5-10 minutes maximum, when the injecting procedure was still happening. 50-60 % of leachate recirculated (or fresh water for a new step) exits in the first thirty minutes, 90% exits in the first day (Figure 3.9). The sampling procedure is studied during the first analysis: a sample for each one of the 4 tanks of leachate is take and analyze for chloride (that is the most easy and fast analytical test; chloride does not be influenced by temperature or air presence). The results reveals that the differences between canisters are negligible, because recirculation mixes all compounds and biodegradable compounds and ammonia are almost zero. For this reason, during the following steps, the sampling of leachate is made from the middle exiting leachate (only for ensure to avoid the first exit, that is not well mixed, and the last exit, that stays open air for days). Each sample is take in a proper plastic bottle (500 ml), the pH is immediately measured and the leachate is preserved always in fridge.

Figure 3.25: Lysiemter leachate collection system. The structure on left is the lysimeter. The rubber pipes on the left comes from the bottom of reactor, and reach the plastic pipe in the centre of the figure. From the plastic pipe, another rubber tube reach the canister on the right. The flux can be manage with the blue valve. The system is always in pressure because the low space for tanks under the reactor.

Soil Samples

Soil samples are taken in various ways during the test. The first sample (November 2004) is hand take form the fresh waste before inserting it in reactor and so comes from a cake sampling and a characterization analysis. The second (June 2007) and the third sample (July 2007) comes from the three sampling pipes on the right side of reactor, analyze separately and the final result is the average of the three values. This procedure is made for decrease the uncertainty due to heterogeneity. The fourth sample (May 2013) is collected digging the waste until a deepness of 75 cm (on the total 125 cm) so is representative of only the upper part of waste, the side sampling pipes are clogged so cannot be used. The fifth sample (September 2013) wants to characterize all waste and to investigate eventual differences due to deepness. The samples collected with a plastic manual drill of 5 cm of diameter, are five: each one form a different deepness,. Because the presence of big chunk in upper part of the reactor, the first 25 cm are excavated completely. From this 60-70 kg of waste is handily take the first sample. For the others eight vertical drills are made and the extracted material is divided by deepness in four samples (25-45, 45-75, 75-95, 95-125), only three drills reach the bottom of reactor because presence of some chunks in the bottom part of reactor too.

An important difference between the last two samples of 2013 and the other ones is the sampling of all solids (without sorting) and the milling to 1 cm of all sample. Before 2013 this procedure is not made so the data is less reliable and the leaching test concentrations seems increase suddenly. In truth, the better performance of the sample acquisition and preparation allows to have more precise data.

Annex 7: Static Chamber Test

Static Chamber Protocol for Biogas Monitoring

The Static Chamber is a procedure on field for the evaluation of superficial biogas flow and composition. The procedure is the one suggested by Cossu: it consist in measuring the difference of concentration in a well known volume over time and evaluate the gas flux with this variation data (Cossu et al., 1997).

The Apparatus is show in Figure 3.26, composed by the chamber, the LFG20 (gas concentration measurement), the pressure monitoring probe and the iron stick for drive the chamber into soil. The pressure monitoring is not necessary because inner pressure will not change from atmospheric one. The Chamber diameter is 50 cm and the evaluated height over soil after planting is 50 cm too. According to this, the total volume is 0,39 m^3 and the planted surface is 0,76 m^2. The volume can change if the chamber is drilled more inside the soil.

Figure 3.26 Static chamber equipment planted in soil, connected with the LFG20 (red instrument) for the concentration of oxygen, carbon dioxide and methane and with the pressure probe (orange instrument) for the pressure monitoring.

The chamber must be planted in a possible “hotspot”: this site can be found visually in an area with yellow or absent grass. The ideal soil for the test has to be fine grained, possibly moist but not completely wet. The drilling of the chamber must be done until a deepness of 10 cm minimum and the bottom insulation must be guarantee compacting the soil around chamber. If it’s insufficient, some compacted moist clay can be putted on the borders. All holes in the apparatus must be close. Before the LFG20 set up, a calibration with fresh air or with balloons at note concentrations is necessary. After that, the instrument is fix to the chamber and the tube between them is equipped with a gate valve to close the passage when sampling is not active.

The monitored parameter will be oxygen, carbon dioxide and methane, their concentration must be take every ten-twenty minutes, not less. The monitoring must go on until the concentration becomes stable: in a “hotspot” the concentration of oxygen will fall down.

Data collected are reported in volumetric percentage (x1, x2, .., xn), with the corresponding time (t1, t2, …, tn) The volumetric change of concentration in time (dx/dt) is evaluate with Formula 1.

$$\frac{dx}{dt} = \frac{(x2 - x1)}{(t2 - t1)} \qquad 1$$

The volumetric gas production is evaluate with the Formula 2, where V is the Volume and S the soil bottom surface of the chamber.

$$E = \frac{\frac{dx}{dt} * V}{S} \qquad 2$$

The last passage (Formula 3) is the normalization of the volume: the pressure does not change from atmospheric one but the temperature is generally different from zero. Pm is the pressure observed, Pa is the atmospheric pressure, Ta is the absolute temperature (273 °K) and Tm is the measured temperature.

$$Normal\ E = \frac{Pm}{Pa} * \frac{Ta}{To} * E \qquad 3$$

The biogas quantity is the sum of the quantities of methane and carbon dioxide components. With this system, the oxygen consumption is due to oxidation of methane in the top cover of landfill and to the inhalation of the instruments (for the same reason the carbon dioxide will increase). No correction to this situation are required because the purpose of the test is measuring what can escape superficially from landfill, considering top cover effect too. The barometric pressure will affect significantly the biogas superficial flux. For have more correct data, the test can be repeated in the same place, in different days with a different climate (Cossu et al., 1997).

Static Chamber Test in Ciliverghe landfill: monitoring the biogas superficial production.

Some static chamber tests were performed during the Cilivierghe landfill survey (Brescia in March and April 2013) for the measurement of the biogas superficial production and quality. This landfill is an old anaerobic type, sutured of water and with a clayey top cover. The tests aims to verify the apparatus of the static chamber and to characterize the superficial biogas emission of the landfill.

The chamber is planted in some possible “hot spots” found visually in an area with yellow or absent grass and its insulation is guaranteed by the clayey soil compressed on the borders. Before the instruments set up, they are calibrated with fresh air. The measures of pressure are taken continuously, the measures of concentration are read every 10-20 minutes. The LFG20 instrument inhale air from the chamber and this can affect the data if turned on too frequently. The hotspots location is visible in Figure 3.27. B0, B1 and B2 are “hot-spots” found visually and shows an abundant emission of methane and carbon dioxide, especially with low barometric pressures. B3-B7 are casual points on top cover. Data collected are in Table 3.36.

Table 3.36: Biogas Emissions Summary. The test location in the first column, the data in second one, in other columns there are the emissions of CO2 and CH4, the O2 consumption (Nm3/m2 min).

Point	Data	CO2 (Nm3/m2 min)	CH4 (Nm3/m2 min)	O2 (Nm3/m2 min)
0	27/03/2013	0,00134	0,00106	0,00081
1	29/04/2013	0,00001	0,00001	0,00004
1	29-30/04/2013	0,00002	0,00005	0,00002
1	30/04/2013	0,00018	0,00098	0,00016
2	30/04/2013	0,00024	0,00027	0,00022
2	02/05/2013	0,00011	0,00014	0,00010
2	02-03/05/2013	0,00006	0,00020	0,00005
2	03/05/2013	0,00003	0,00024	0,00003
3	02/05/2013	0,00002	0,00000	0,00002
4	03/05/2013	0,00007	0,00002	0,00008
5	07/05/2013	0,00010	0,00016	0,00013
6	08/05/2013	0,00000	0,00000	0,00000
7	08/05/2013	0,00001	0,00000	0,00000

Results shows that the biogas emission is very low, always under 0,1 Nl/m2 min and often undetectable, in the normal top cover. On the contrary, the emissions of biogas can be quite high in “hot-spots” that are points where the top cover is badly made or where chimney effect takes place. The biogas production is proportional to an oxygen depletion due to metanotrophic conditions. This process consumes oxygen and methane producing carbon dioxide and is visible especially in point zero.

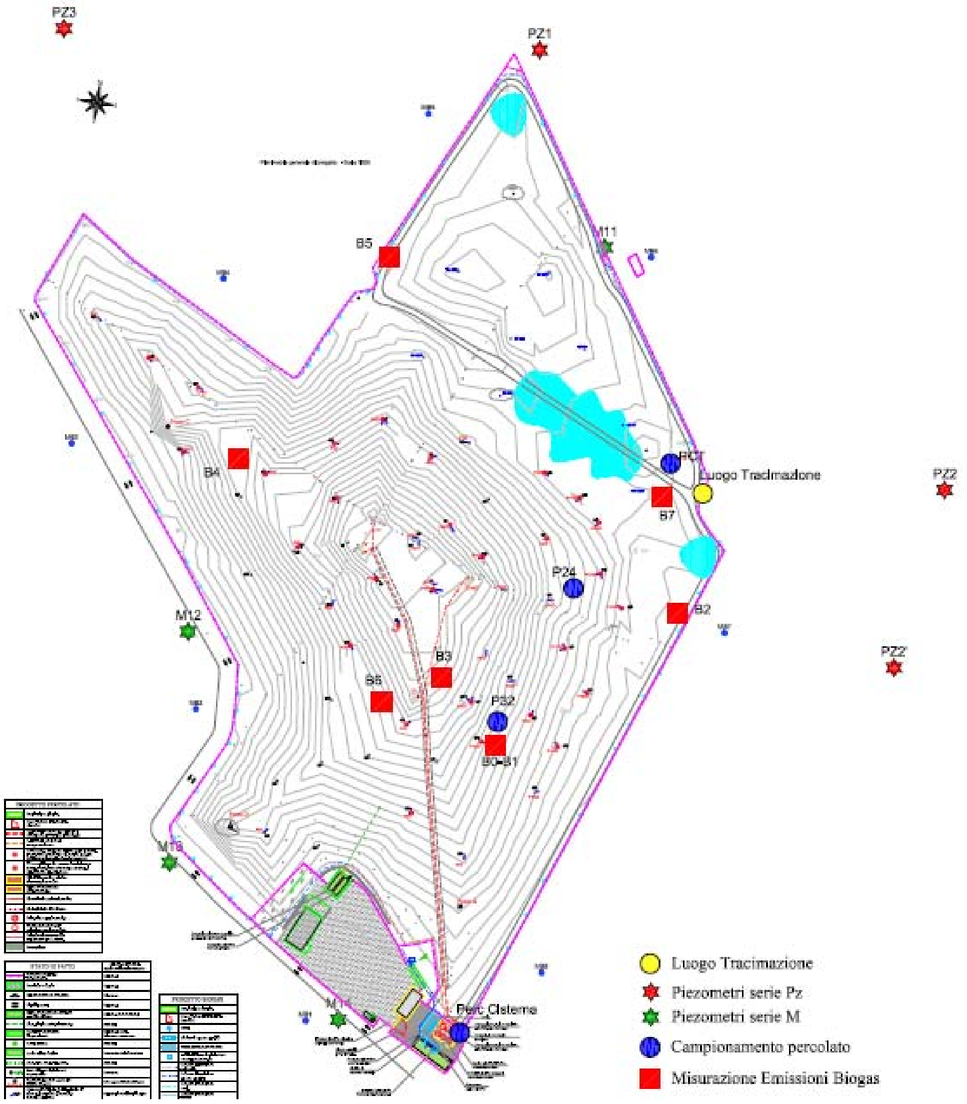


Figure 3.27: Location of the Biogas Measurement points, red squares.

In conclusion, the static chamber system is a valuable method for the estimation of the superficial emissions of a landfill, considering the methanotrophic effect too. The equipment is cheap and easy to be build, the time required is only some hours per point. In any case, apply this method has some problems. First, the location of the test must be choose with experience, not all “hotspots” are visible. Second, the gas emissions depends very much on the atmospheric conditions. Third the measurement are not effective if the soil is too wet or too dry.

References

Cossu R., Muntoni A., Chiarantini L., Massacci G., Serra P., Scolletta a., Sterzi G., 1997, Biogass emission measurement using static and dynamic flux chambers and infrared method, Sixth International Sardinia Symposium journal, Cagliari, Italy.

Meaurement data:

Table 3.37: Biogas emission monitoring, P0, P1, P2, Hotspots. Every table is specific for a single test. In the upper part, the test characteristics are present. In the middle part, LFG20 measurements and progressive time are present. In the lower part, the emissions are evaluated in Nm3/m2 min.

Point	Data	Starting time	Weather	T (°C)	P (mb)
P0	27/03/2013	14.30	nuvolo	10	

Hot-spot

Time	O2	dO2/dt	CO2	dCO2/dt	CH4	dCH4/dt
minutes	% vol	m3O2/m3 min	% vol	m3CO2/m3 min	%vol	m3CH4/m3 min
0	20,600	0,00000	0,000	0,00000	0,000	0,00000
10	20,400	-0,00020	0,000	0,00000	22,160	0,02216
20	17,800	-0,00260	0,000	0,00000	19,700	-0,00246
30	14,400	-0,00340	9,330	0,00933	12,160	-0,00754
44	13,000	-0,00100	11,900	0,00184	12,160	0,00000
53	10,000	-0,00333	17,500	0,00622	13,530	0,00152
Average		-0,00211		0,00348		0,00274

Carbon Dioxide Produc	(Nm3/m2 min)	0,00134
Methane Production	(Nm3/m2 min)	0,00106
Biogas Production	(Nm3/m2 min)	0,00240
Oxygen Consumption	(Nm3/m2 min)	0,00081

Point	Data	Starting time	Weather	T (°C)	P (mb)
P1	29/04/2013	16.25	nuvolo	19	1019,98

Hot-spot

Time	O2	dO2/dt	CO2	dCO2/dt	CH4	dCH4/dt
minutes	% vol	m3O2/m3 min	% vol	m3CO2/m3 min	%vol	m3CH4/m3 min
0	20,500	0,00000	0,000	0,00000	0,000	0,00000
15	20,300	-0,00013	0,000	0,00000	0,220	0,00015
30	20,300	0,00000	0,240	0,00016	0,380	0,00011
45	20,200	-0,00007	0,280	0,00003	0,340	-0,00003
60	20,100	-0,00007	0,320	0,00003	0,300	-0,00003
75	20,000	-0,00007	0,400	0,00005	0,300	0,00000
90	20,000	0,00000	0,440	0,00003	0,260	-0,00003
105	19,800	-0,00013	0,720	0,00019	0,580	0,00021
120	19,700	-0,00007	0,760	0,00003	0,660	0,00005
135	19,000	-0,00047	0,560	-0,00013	0,420	-0,00016
Average		-0,00010		0,00004		0,00003

Carbon Dioxide Produc	(Nm3/m2 min)	0,00001
Methane Production	(Nm3/m2 min)	0,00001
Biogas Production	(Nm3/m2 min)	0,00003
Oxygen Consumption	(Nm3/m2 min)	0,00004

Night emissions	Carbon Dioxide Producti	(Nm3/m2 min)	0,00002
Stimabili	Methane Production	(Nm3/m2 min)	0,00005
Punto P1	Biogas Production	(Nm3/m2 min)	0,00007
	Oxygen Consumption	(Nm3/m2 min)	0,00002

Point	Data	Starting time	Weather	T (°C)	P (mb)
P1	30/04/2013	10.55	pioggia	14	1017,95

Hot-spot Collegato da giorno prima

Time	O2	dO2/dt	CO2	dCO2/dt	CH4	dCH4/dt
minutes	% vol	m3O2/m3 min	% vol	m3CO2/m3 min	%vol	m3CH4/m3 min
0	14,800	0,00000	4,630	0,00000	12,500	0,00000
15	12,200	-0,00173	7,480	0,00190	26,300	0,00920
30	11,000	-0,00080	8,820	0,00089	20,300	-0,00400
45	10,300	-0,00047	9,600	0,00052	33,000	0,00847
60	9,800	-0,00033	10,000	0,00027	34,600	0,00107
75	9,200	-0,00040	10,800	0,00053	36,600	0,00133
90	8,800	-0,00027	11,200	0,00027	39,800	0,00213
105	8,400	-0,00027	11,600	0,00027	44,500	0,00313
120	8,200	-0,00013	11,900	0,00020	45,700	0,00080
200	7,000	-0,00015	13,100	0,00015	65,800	0,00251
215	7,000	0,00000	13,500	0,00027	71,300	0,00367
Average		-0,00041		0,00048		0,00257

Carbon Dioxide Produc	(Nm3/m2 min)	0,00018
Methane Production	(Nm3/m2 min)	0,00098
Biogas Production	(Nm3/m2 min)	0,00116
Oxygen Consumption	(Nm3/m2 min)	0,00016

Point	Data	Starting time	Weather	T (°C)	P (mb)
P2	30/04/2013	14.45	sole	18	1018,96

Hot-spot

Time	O2	dO2/dt	CO2	dCO2/dt	CH4	dCH4/dt
minutes	% vol	m3O2/m3 min	% vol	m3CO2/m3 min	%vol	m3CH4/m3 min
0	20,600	0,00000	0,000	0,00000	0,000	0,00000
5	18,700	-0,00380	0,720	0,00144	1,680	0,00336
10	19,700	0,00200	0,990	0,00054	4,080	0,00480
15	19,400	-0,00060	1,390	0,00080	4,170	0,00018
20	19,200	-0,00040	1,700	0,00062	3,300	-0,00174
25	18,800	-0,00080	2,060	0,00072	2,860	-0,00088
30	18,500	-0,00060	2,450	0,00078	2,750	-0,00022
45	17,600	-0,00060	3,400	0,00063	2,200	-0,00037
60	16,400	-0,00080	4,310	0,00061	3,800	0,00107
75	15,800	-0,00040	5,180	0,00058	4,840	0,00069
90	14,800	-0,00067	6,010	0,00055	6,300	0,00097
105	14,200	-0,00040	6,500	0,00033	7,330	0,00069
Average		-0,00059		0,00063		0,00071

Carbon Dioxide Produ	(Nm3/m2 min)	0,00024
Methane Production	(Nm3/m2 min)	0,00027
Biogas Production	(Nm3/m2 min)	0,00051
Oxygen Consumption	(Nm3/m2 min)	0,00022

Point	Data	Starting time	Weather	T (°C)	P (mb)
P2	02/05/2013	15.30	nuvolo	21	1014,9

Hot-spot

Time	O2	dO2/dt	CO2	dCO2/dt	CH4	dCH4/dt
minutes	% vol	m3O2/m3 min	% vol	m3CO2/m3 min	%vol	m3CH4/m3 min
0	20,600	0,00000	0,000	0,00000	0,000	0,00000
15	20,500	-0,00007	0,320	0,00021	1,400	0,00093
30	19,700	-0,00053	1,150	0,00055	3,570	0,00145
45	19,300	-0,00027	1,540	0,00026	4,830	0,00084
60	18,700	-0,00040	2,140	0,00040	4,440	-0,00026
75	18,100	-0,00040	2,810	0,00045	4,180	-0,00017
90	18,200	0,00007	3,240	0,00029	6,410	0,00149
105	17,600	-0,00040	3,640	0,00027	6,690	0,00019
120	16,900	-0,00047	4,150	0,00034	5,620	-0,00071
135	16,500	-0,00027	4,500	0,00023	5,550	-0,00005
150	16,100	-0,00027	4,940	0,00029	6,290	0,00049
Average		-0,00027		0,00030		0,00038

Carbon Dioxide Produ	(Nm3/m2 min)	0,00011
Methane Production	(Nm3/m2 min)	0,00014
Biogas Production	(Nm3/m2 min)	0,00025
Oxygen Consumption	(Nm3/m2 min)	0,00010

Night emissions	Carbon Dioxide Producti	(Nm3/m2 min)	0,00006
Stimabili	Methane Production	(Nm3/m2 min)	0,00020
Punto P2	Biogas Production	(Nm3/m2 min)	0,00026
	Oxygen Consumption	(Nm3/m2 min)	0,00005

Point	Data	Starting time	Weather	T (°C)	P (mb)
P2	03/05/2013	08.30	sole	14	1011,45

Hot-spot Collegato da giorno prima

Time	O2	dO2/dt	CO2	dCO2/dt	CH4	dCH4/dt
minutes	% vol	m3O2/m3 min	% vol	m3CO2/m3 min	%vol	m3CH4/m3 min
0	4,000	0,00000	19,000	0,00000	55,200	0,00000
15	3,800	-0,00013	19,000	0,00000	56,300	0,00073
30	3,600	-0,00013	19,000	0,00000	58,700	0,00160
45	3,500	-0,00007	19,400	0,00027	59,500	0,00053
75	3,100	-0,00013	19,800	0,00013	60,300	0,00027
90	3,000	-0,00007	19,800	0,00000	61,400	0,00073
105	2,900	-0,00007	20,200	0,00027	61,600	0,00013
120	2,800	-0,00007	20,200	0,00000	62,200	0,00040
135	2,700	-0,00007	20,200	0,00000	64,100	0,00127
Average		-0,00008		0,00007		0,00063

Carbon Dioxide Produ	(Nm3/m2 min)	0,00003
Methane Production	(Nm3/m2 min)	0,00024
Biogas Production	(Nm3/m2 min)	0,00027
Oxygen Consumption	(Nm3/m2 min)	0,00003

Table 3.38: Biogas emission monitoring, P3, P4, P5, P6, P7, Normal top cover. Every table is specific for a single test. In the upper part, the test characteristics are present. In the middle part, LFG20 measurements and progressive time are present. In the lower part, the emissions are evaluated in Nm3/m2 min.

Point	Data	Starting time	Weather	T (°C)	P (mb)
P3	02/05/2013	12.45	sole	20	1015,92

Normal cover

Time	O2	dO2/dt	CO2	dCO2/dt	CH4	dCH4/dt
minutes	% vol	m3O2/m3 min	% vol	m3CO2/m3 min	%vol	m3CH4/m3 min
0	20,500	0,00000	0,000	0,00000	0,000	0,00000
15	20,000	-0,00033	0,440	0,00029	0,000	0,00000
30	19,900	-0,00007	0,480	0,00003	0,020	0,00001
45	19,800	-0,00007	0,600	0,00008	1,000	0,00065
60	19,800	0,00000	0,640	0,00003	0,060	-0,00063
75	19,900	0,00007	0,680	0,00003	0,020	-0,00003
90	19,700	-0,00013	0,640	-0,00003	0,020	0,00000
105	19,700	0,00000	0,640	0,00000	-0,040	-0,00004
Average		-0,00007		0,00005		0,00000

Carbon Dioxide Produc	(Nm3/m2 min)	0,00002
Methane Production	(Nm3/m2 min)	0,00000
Biogas Production	(Nm3/m2 min)	0,00002
Oxygen Consumption	(Nm3/m2 min)	0,00002

Point	Data	Starting time	Weather	T (°C)	P (mb)
P4	03/05/2013	11.00	sole	19	1012,87

Normal cove

Time	O2	dO2/dt	CO2	dCO2/dt	CH4	dCH4/dt
minutes	% vol	m3O2/m3 min	% vol	m3CO2/m3 min	%vol	m3CH4/m3 min
0	20,600	0,00000	0,000	0,00000	0,000	0,00000
15	20,200	-0,00027	0,480	0,00032	0,220	0,00015
30	19,600	-0,00040	0,840	0,00024	1,920	0,00113
45	19,400	-0,00013	1,190	0,00023	0,420	-0,00100
60	19,200	-0,00013	1,470	0,00019	0,620	0,00013
75	18,700	-0,00033	1,780	0,00021	0,560	-0,00004
90	18,400	-0,00020	2,100	0,00021	0,460	-0,00007
105	18,000	-0,00027	2,420	0,00021	0,380	-0,00005
120	17,700	-0,00020	2,680	0,00017	0,660	0,00019
135	17,300	-0,00027	2,960	0,00019	1,320	0,00044
150	16,900	-0,00027	3,240	0,00019	0,820	-0,00033
Average		-0,00022		0,00020		0,00005

Carbon Dioxide Produc	(Nm3/m2 min)	0,00007
Methane Production	(Nm3/m2 min)	0,00002
Biogas Production	(Nm3/m2 min)	0,00009
Oxygen Consumption	(Nm3/m2 min)	0,00008

Point	Data	Starting time	Weather	T (°C)	P (mb)
P7	08/05/2013	14.15	sole	21	1014,94

Normal cove

Time	O2	dO2/dt	CO2	dCO2/dt	CH4	dCH4/dt
minutes	% vol	m3O2/m3 min	% vol	m3CO2/m3 min	%vol	m3CH4/m3 min
0	20,600	0,00000	0,000	0,00000	0,000	0,00000
15	20,600	0,00000	0,000	0,00000	0,000	0,00000
30	20,600	0,00000	0,040	0,00003	0,000	0,00000
45	20,600	0,00000	0,080	0,00003	0,000	0,00000
60	20,600	0,00000	0,120	0,00003	0,000	0,00000
75	20,600	0,00000	0,160	0,00003	0,000	0,00000
90	20,500	-0,00007	0,200	0,00003	0,000	0,00000
105	20,500	0,00000	0,260	0,00004	0,000	0,00000
120	20,400	-0,00007	0,280	0,00001	0,000	0,00000
135	20,400	0,00000	0,320	0,00003	0,000	0,00000
Average		-0,00001	4,270	0,00002		0,00000

Carbon Dioxide Produc	(Nm3/m2 min)	0,00001
Methane Production	(Nm3/m2 min)	0,00000
Biogas Production	(Nm3/m2 min)	0,00001
Oxygen Consumption	(Nm3/m2 min)	0,00000

Point	Data	Starting time	Weather	T (°C)	P (mb)
P5	07/05/2013	09.30	sole	20	1013,89

Normal cove

Time	O2	dO2/dt	CO2	dCO2/dt	CH4	dCH4/dt
minutes	% vol	m3O2/m3 min	% vol	m3CO2/m3 min	%vol	m3CH4/m3 min
0	20,800	0,00000	0,000	0,00000	0,000	0,00000
15	20,700	-0,00007	0,240	0,00016	1,620	0,00108
30	19,900	-0,00053	0,760	0,00035	3,850	0,00149
45	19,200	-0,00047	1,310	0,00037	5,110	0,00084
60	18,700	-0,00033	1,780	0,00031	5,750	0,00043
75	18,300	-0,00027	2,180	0,00027	5,510	-0,00016
90	17,500	-0,00053	2,690	0,00034	7,250	0,00116
105	16,700	-0,00053	3,280	0,00039	7,450	0,00013
120	16,200	-0,00033	3,680	0,00027	7,550	0,00007
135	15,500	-0,00047	4,270	0,00039	8,450	0,00060
150	15,000	-0,00033	4,620	0,00023	7,400	-0,00070
165	14,500	-0,00033	5,020	0,00027	7,710	0,00021
180	13,900	-0,00040	5,490	0,00031	9,700	0,00133
195	13,400	-0,00033	5,920	0,00029	9,250	-0,00030
210	12,800	-0,00040	6,390	0,00031	10,100	0,00057
225	12,400	-0,00027	6,750	0,00024	10,500	0,00027
Average		-0,00035		0,00028		0,00044

Carbon Dioxide Produ	(Nm3/m2 min)	0,00010
Methane Production	(Nm3/m2 min)	0,00016
Biogas Production	(Nm3/m2 min)	0,00027
Oxygen Consumption	(Nm3/m2 min)	0,00013

Point	Data	Starting time	Weather	T (°C)	P (mb)
P6	08/05/2013	12.30	sole	20	1014,9

Normal cove

Time	O2	dO2/dt	CO2	dCO2/dt	CH4	dCH4/dt
minutes	% vol	m3O2/m3 min	% vol	m3CO2/m3 min	%vol	m3CH4/m3 min
0	20,600	0,00000	0,000	0,00000	0,000	0,00000
15	20,500	-0,00007	0,040	0,00003	0,000	0,00000
30	20,500	0,00000	0,060	0,00001	0,000	0,00000
45	20,500	0,00000	0,080	0,00001	0,000	0,00000
60	20,600	0,00007	0,080	0,00000	0,000	0,00000
75	20,600	0,00000	0,080	0,00000	0,000	0,00000
90	20,500	-0,00007	0,080	0,00000	0,000	0,00000
Average		-0,00001		0,00001		0,00000

Carbon Dioxide Produ	(Nm3/m2 min)	0,00000
Methane Production	(Nm3/m2 min)	0,00000
Biogas Production	(Nm3/m2 min)	0,00000
Oxygen Consumption	(Nm3/m2 min)	0,00000