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SIMPLE-TECH SOLUTIONS FOR SUSTAINABLE WASTE MANAGEMENT

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"And you, who have found such an invention,
return to learn from nature [...]."

"E tu, che tale invenzione trovasti,
rito[r]na a imparare naturale [...]."

Leonardo Da Vinci (1452-1519)

PREFACE

I was born and raised in Lessinia, a small mountain area North of Verona, secluded among the Lessini mountains. San Francesco, my home village, has a total population of approx. 2.000 individuals, if we include cows. No more than 150 souls, if we exclude that cows have a soul.

Life in Lessinia is not always easy when compared to the comfortable life of the city, but, up there, the spring fills your lungs with green, the summer inebriates you with the sweet smell of hay, autumn delights your eyes with the warm colours of the woods and the winter ….. well, winter is freezing! But … in winter the stars are so beautiful!

Life in Lessinia is not always easy, when compared to the comfortable life of the city, but, up there, the relationships between people are open and sincere.

At high school I studied to be an accountant but soon realized that I wasn't prepared to devote my life to that. I had dreamed of doing something to make people happy, and this is not what you usually ask of your accountant. What should I do? The answer arrived from "Yahoo Answers". I abandoned any kind of perspective in the financial and commercial studies to join Environmental Engineering: from economic balance to environmental mass balance! Several people found this choice rather strange and unusual, but I have never regretted it!

After spending five years completing the first and second cycle degrees (Bachelor and Master), I graduated from the University of Padova with Prof. Raffaello Cossu and Prof. Maria Cristina Lavagnolo, both of whom were responsible for arousing my interest in two specific fields: solid waste management and developing countries. These two passions are at the basis of my doctoral work, condensed in this thesis.

PREFAZIONE

Sono nata e cresciuta in Lessinia, una piccola zona di montagna a nord di Verona, isolata tra i monti Lessini. San Francesco è il mio paese di origine. La popolazione totale è di circa 2.000 individui, se includiamo le mucche. Non più di 150 anime, se escludiamo che le mucche hanno un anima.

La vita in Lessinia non è sempre facile se confrontata con la vita agiata di città, ma lassù la primavera riempie di verde i polmoni, l'estate ti inebria del dolce profumo del fieno, l'autunno meraviglia gli occhi coi colori caldi dei boschi e l'inverno…beh, sì … l'inverno si gela! Ma le stelle d'inverno sono bellissime.

La vita in Lessinia non è sempre facile se confrontata con la vita agiata di città, ma lassù i rapporti tra le persone sono aperti e sinceri.

Alle scuole superiori ho studiato Ragioneria, ma ben presto ho capito che non poteva essere quella la mia strada. Desideravo fare qualcosa che rendesse felici le persone, e questa non è il genere di attitudine che si richiede al proprio commercialista. Che fare? La risposta mi arrivò da Yahoo! Answers. Così abbandonai sul nascere qualsiasi prospettiva di studi economici per iscrivermi a Ingegneria Ambientale. Passando dal bilancio economico al bilancio ambientale di massa!

La decisione di avviami sulla strada dell' Ingegneria fu abbastanza strana e inusuale ma non me ne sono mai pentita. Dopo cinque anni tra triennale e magistrale, mi sono laureata all'Università di Padova con il Prof. Raffaello Cossu e la Prof.ssa Maria Cristina Lavagnolo ai quali devo il merito di avermi trasmesso due passioni: la gestione dei rifiuti solidi e i paesi in via di sviluppo. Queste due passioni sono alla base del mio lavoro di dottorato, condensato in questa tesi.

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FIRST PART

Thesis development

1. INTRODUCTION

1.1. Background and objectives

This thesis originated from a desire to explore the issue of solid waste, the appropriate management of which continues to represent a privilege for the few, in order to investigate alternative cost-effective solutions aimed at promoting access of the population worldwide to sustainable waste management systems, finding inspiration in the principles of the Blue Economy. The Blue Economy concept, introduced by Gunter Pauli in 2009, responds to basic needs finding solutions in what nature already offers, moving from environmental problems to opportunities of business and innovation.

The work had a particular focus on landfilling from a holistic point of view, investigating environmental, technical and economical sustainable solutions in terms of landfill management and emissions control. On the basis of the modern solid waste management (SWM) concepts, such as Zero Waste, Circular Economy (CE), 3Rs (Reduce, Reuse, Recycle), etc., landfilling is considered the least preferable option in SWM. Nevertheless, landfill continues to plays a fundamental role in providing a final sink for residues from CE, devoid of any economical or technical value. Moreover, landfilling continues to represent the only economically viable option to ensure a safe management of waste in Developing Countries (DCs), where the lack of both financial resources and technical skills limits the application of any other more complex technology. On the other hand, providing for the demonstrable environmental, technical and economical sustainability of sanitary landfill is of high concern, specifically when dealing with leachate treatment and management. Indeed, liquid emissions are a crucial issue for sustainability as they may last for extremely lengthy periods, usually exceeding the life span of the landfill physical barriers (liners, drainage systems, etc.).

1.2. Activities and outputs

The thesis work was developed over a three-year period according to the steps indicated in Figure 1.

In the first step, activities focused on the study and gaining a better understanding of the need for a global approach to waste management, with the application of identical concepts and knowledge throughout the world and envisaging appropriate and sustainable technical solutions, not only in environmental terms but also in economic (they should be low cost) and technical terms (they should easy to construct, operate and maintain). Further to carrying out literature reviews and taking part in a series of International Conferences where waste management in DCs was discussed in detail, a field stage abroad, on the Ivory Coast, proved of fundamental importance for the development of this first step. Living fully immersed in the local reality of a developing country promoted a full realization of the relevance of the SWM issue in DCs and the importance of trying to find effective solutions.

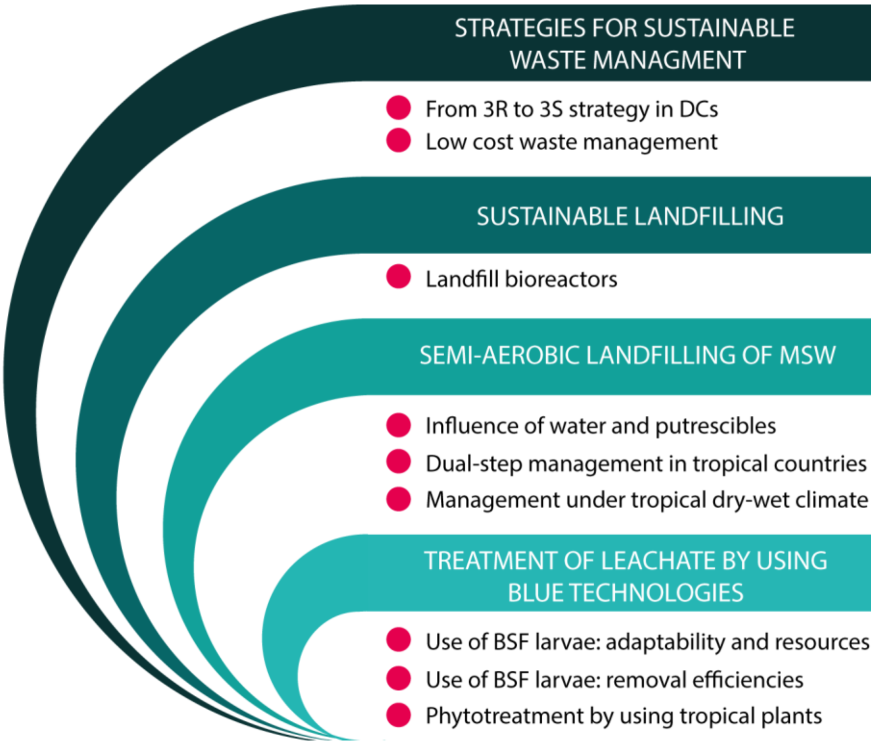


Figure 1. Scheme of thesis development.

The activity on the Ivory Cost was developed in the context of a cooperation and development project in the city of Agnibilèkrou (Côte d'Ivoire), with financial support of the "Valdese Church". The project underpinned the setting up of the concept of a 3S strategy (Sanitisation, Sustainable landfilling and Subsistence economy), proposed by Prof. Maria Cristina Lavagnolo (University of Padova) as a preliminary strategy for assuring a sustainable SWM system in all cases when conditions are not favorable for the direct application of 3R or Circular Economy concepts. Agnibilèkrou (69.174 inhabitants) is affected by severe problems related to waste management, a limited financial and economic scenario, together with an urgent need for action focused specifically on health and environmental protection, thus making the 3S strategy a potentially valuable first approach for the design of a SWM system.

During the stage a survey relating to in-situ data collection on waste quality and quantity was carried out; an analysis of possible collection and disposal systems for the identification and planning of an appropriate waste management system was performed.

Outputs generated by the activities undertaken have been reported on in two Editorials published by the scientific journal Detritus:

- Lavagnolo, M.C., Grossule, V., 2018. From 3R to 3S: An appropriate strategy for Developing Countries. Detritus, Volume 04, 1-3. doi:10.31025/2611-4135/2018.13749 (Paper I)
- Cossu, R., Grossule, V., Lavagnolo, M.C., 2019. Sustainable low-cost waste management: learning from airlines. *Detritus*, Volume 06, 1–3. doi: 10.31025/2611-4135/2019.13818 (Paper II)

In the second step, the sustainability of landfills was studied and analyzed by considering the tools which could be implemented to control long-term emissions in the case of Municipal Solid Waste (MSW) landfilling.

Research activities were focused on the comprehensive study of bioreactor landfills, comparing (using literature data) lab scale applications of different types of bioreactors, and evaluating the advantages and disadvantages. Having conducted a qualitative analysis of the main types of bioreactor landfills, landfill sustainability was quantified using a first order kinetic model for the COD and ammonia removal processes.

The following publications were produced as a result of these activities:

- Grossule, V., Morello, L., Cossu, R., Lavagnolo, M.C., 2018. Bioreactor landfills: comparison and kinetics of the different systems. *Detritus*, Volume 03, 100–113. doi: 10.31025/2611-4135/2018.13703. (Paper III)
- Cossu, R., Grossule, V., 2018. Landfill bioreactors. In Cossu, R.; Stegmann, R. Solid Waste Landfilling, Concepts, Processes, Technology. Elsevier, 2018, ISBN: 9780128183366. (Paper IV)

Amongst the different sustainable landfill alternatives, semi-aerobic landfill represented a viable option meeting environmental, technical and economical sustainability requirements. The semi-aerobic method is based on a specific landfill design which promotes the passive aeration of waste mass by means of a temperature difference between the landfill and external ambient. It aims at reproducing an aerobic environment within the waste mass accelerating stabilisation, but avoiding the typical operational costs associated with forced air injection or biogas management.

During the third step of the thesis work, semi-aerobic landfills were studied in detail in order to identify innovative solutions to optimise the design and management of the system under different situations. Incidence of the main factors controlling the stabilisation processes, such as water availability and putrescible organic content in waste (which may fluctuate considerably according to geographical position and socio-economic condition), were evaluated experimentally on a lab scale. Semi-aerobic landfilling was subsequently studied under tropical climate, the most diffused type of climate in numerous DCs. Rainfall seasonality of the tropical climate may significantly affect the correct functioning of the semi-aerobic method: a lack of moisture during the dry season and heavy rainfalls during the wet season could negatively affect both the degradation process, and landfill emissions. An innovative dual step management of semi-aerobic landfilling has been suggested, consisting in the storage of excess leachate during the wet season, which is then recirculated during the dry season in order to enhance biodegradation activity and perform an in-situ leachate treatment.

Finally, a study on optimisation of the system under tropical wet-dry weather concluded this step of the thesis work from which the following papers originated:

- Grossule, V., Lavagnolo, M.C., 2019. Lab tests on semi-aerobic landfilling of MSW under varying conditions of water availability and putrescible waste content. Submitted to Journal of Environmental Management (19/9/2019) (Paper V)
- Lavagnolo, M.C., Grossule, V., Raga, R., 2018. Innovative dual-step management of semi-aerobic landfill in a tropical climate. Waste Manag. 1–10. doi:10.1016/j.wasman.2018.01.017 (Paper VI)
- Grossule, V., Lavagnolo, M.C., 2019. Optimised management of semi-aerobic landfilling under tropical wet-dry conditions. Submitted to Detritus Journal (19/9/2019) (Paper VII)

The fourth step of research activities was inspired by a need to identify cost-effective solutions to solve the key issue in landfilling sustainability: leachate treatment. An innovative alternative potential solution based on exploiting the versatility and voracity of Black soldier fly (BSF) larvae was investigated. The adaptability of larvae to leachate and the quality of the biomass rich in fats and proteins were initially assessed. Additionally, the potential of proteins and fats to be conveniently converted into commercial resources, such as animal feed and biodiesel was evaluated. The system was then further tested to evaluate treatment performance using different solid substrates to support larvae growth. During this fourth step, for three months at the beginning of the 2019, a research stage was specifically organised at the KUET University, Bangladesh to investigate the potential of mangroves for use in the phytotreatment of landfill leachate, exploiting the high resistance to salinity of these plants. A preliminary study has been carried out using as a comparison other tropical plant species such as Canna indica. The research is still ongoing.

The following papers originated from the fourth step of activities:

- Grossule, V., Lavagnolo, M.C., 2019. The treatment of leachate using Black Soldier Fly (BSF) larvae: adaptability and resource recovery testing. Submitted to Journal of Environmental management. Accepted. (Paper VIII)
- Grossule, V., Vanin, S., Lavagnolo, M.C., 2019. Potential treatment of leachate by Hermetia Illucens (diptera, stratyomyidae) larvae: performance under different feeding conditions. Submitted to Waste Management and Research. Accepted. (Paper IX)

In the following section the main outputs of the thesis work will be presented.

2. STRATEGIES FOR SUSTAINABLE SOLID WASTE MANAGEMENT

2.1. General aspects

Environmental pollution is largely determined by emissions originating from human activities as the result of emissions in a gaseous, liquid or solid form. To this regard Solid Waste Management plays a highly important role. Emissions might originate from littering, waste incineration, landfilling, biological treatment, manure, sludge and compost application on land, recycling processes, mining, waste treatment, accidents, etc.

In accordance with the law of Lavoisier, materials cannot be lost - they can only be transformed. On this basis therefore, all released compounds will be distributed throughout the environment by water, air and wind, and may be biologically degraded or physically/chemically converted. This is why the increasing diffusion of contaminants in the anthroposphere represents today a major environmental issue.

Nowadays, a sustainable and environmentally-sound waste management system should satisfy the following requirements (Cossu, 2009):

- Minimisation of waste production;
- Efficient service of collection and disposal;
- Optimisation of material resource recovery;
- Minimisation of GHG emissions;
- Reduction of landfilled waste volumes;
- Optimisation of energy balance (reduction of energy consumption/waste to energy options);
- Reduction of emissions;
- Monitoring of toxicological effects and minimization of health risks, environmental sustainability.

Despite the aims and objectives of a modern waste management strategy tend to align and coincide throughout all corners of the world, there is a wide inhomogeneous scenario in global waste treatment.

In the field of waste management all countries have access to more or less the same tools: separation, collection, landfilling, composting, anaerobic digestion, thermal treatment, mechanical and manual sorting. However, around the world a wide range of levels of technology and service efficiencies can be observed. Clearly, socio-economic conditions (such as financial resources, technical education, infrastructures, etc.) are the main issues at the basis of these differences, manifested not only between industrialised countries and developing countries (DCs) but also within the same administrative areas, as is the case of the European Community (World Bank, 2018; Eurostat, 2019).

However, many other factors contribute towards these differences, including: population density, waste quality, market for recycled waste fractions, specific local situations (climate, topography, infrastructure, land planning, culture, etc.), regulations, policies, etc.

This picture is further negatively complicated by the transfer of inappropriate technologies from one country to another. Traditionally (and still persisting today!), this issue was confined to developing countries where the implementation of advanced technologies designed in (and for) industrialised countries may prove inappropriate for various reasons (complexity, maintenance, lack of professional education and skilled technicians, operational costs, infrastructures, etc.), as widely highlighted in the literature. However, improper use of technologies is also encountered in industrialised countries. In this case, the main factors impeding the use of specific technologies include an inadequate maturity of the technology, a non-homogenous waste quality and operational costs (energy and staff), in addition to a series of regulatory and bureaucratic issues.

In numerical terms, more than 50% of global MSW production is still dumped or poorly landfilled, while the rest is treated using a series of different technologies (sanitary landfilling, recycling, anaerobic and/or aerobic stabilization, etc.) some of which may prove to be considerably complex and expensive.

Particularly in economically developing and transient countries waste management is frequently seen as a low priority, largely due to lack of financial resources, but also to a scarce environmental awareness amongst politicians and the population. These areas are generally characterized by a fast-growing population, high level of urbanization, lack of modern infrastructures, highly inhomogeneous level of education, inadequate public administration, and frequent political instability. Areas featuring these characteristics can be identified with the so-called "Low Income Countries" but also with areas potentially present in countries with a more favourable classification.

In these areas waste management is generally characterized by the following features:

- Disposal facilities represented substantially by open dumps or poorly engineered and managed landfills;
- Uncontrolled waste burning;
- Widespread littering, very low waste collection coverage and precarious waste transport vehicles;
- Recovery of valuable waste resources by the informal sector (informal recycling and scavenging).

Under these conditions, environmental and health issues are of high concern (quality of drinking water, air quality, degradation of the urban environment, surface and ground water pollution, GHG (greenhouse gas) emissions, spread of infectious diseases, hazards for the scavengers, etc.).

2.2. From 3R to 3S: an appropriate strategy for Developing Countries
(Paper I)

A strategic tool has been developed to address the requirements of waste management in areas with economic constraints.

When circumstances are premature for the application of the 3R concept as part of a Circular Economy strategy, a 3S (Sanitisation, Subsistence economy and Sustainable landfilling) strategy, proposed and based on the experiences in SWM in DCs by Maria Cristina Lavagnolo, should be implemented. The 3S approach, at variance with the 3R concept, is not perceived as a hierarchical structure, but rather is based equally on all three pillars:

- *Sanitisation* aims to improve the standards of living in the country, achieving basic rules of hygiene in waste management.
- *Subsistence Economy* is aimed at returning waste to the economy as a resource through the use of appropriate technologies, providing economic profits and new business opportunities and involving the informal sector activity in a remunerated and formalized way.
- *Sustainable Landfilling* is needed to safely dispose of residues devoid of any economical or technical value.

Sanitisation, Subsistence economy and Sustainable landfilling should be considered as complementary principles, the integration of which is strongly advocated. Sanitisation cannot be achieved in the absence of safe allocation of the collected waste. The recovery of valuable resources, which are removed from the main waste stream, reduces the volume and improves the quality of the disposed waste (e.g. treatment of food waste by means of composting or anaerobic digestion), thus promoting the landfill sustainability concept. Simultaneously, the safe disposal of worthless materials is ensured by Sustainable landfilling. Waste collection and organisation of the informal sector must be designed so as to achieve both sanitisation and recovery of valuable materials, thus supporting the local trade sector.

Sensitisation is the essential aspect for ensuring the successfulness of the whole strategy, as a sustainable SWM system should above all rely on the local human resources. Sanitisation, Subsistence economy and Sanitary landfilling must not disregard the sensitisation process of all the stakeholders, from the public administration to the citizens. The lack of awareness of the population and administrators leads to the absence of an active participation and to the inevitable failure of any attempt of implementing a sustainable SWM system. An educational program should be carried out during all the process, at different level (schools, public administration, workers, citizens, etc.) and by different media for reaching the greatest number of people (educational activities with children, local radio, social media by electronic devices, social events involving the community, seminars, etc.)

2.3. Sustainable low-cost waste management (Paper II)

Based on the previously illustrated discrepancy, between the inconsistent global WM scenario and the common views in modern WM strategies, the following needs should be addressed in order to progress from the fictitious to reality:

- Increase in access worldwide to an appropriate waste management system
- Pursuit of the aims and objectives of a modern waste management system by adopting affordable low cost solutions, with minimal expenditure of energy and material resources.

Possible options may be taken into account in pursuing these objectives:

a) Any decision in WM should be based on a thorough and updated knowledge of waste quality variation in space and time; incredibly, this aspect is often neglected, resulting in inappropriate solutions and related costs;
b) Flexible strategies linked to the local situation (e.g. refraining from conducting source segregation and separate collection of a specific fraction in the absence of an end user at a convenient distance);
c) Recycling programs should not defer to moralistic principles but should rather be based on urban mining concepts (recovery of resources should be reliable, realistic, affordable, with no demagoguery, economically and environmentally convenient);
d) Separate collection should not strive to achieve percentages in terms of amount of collected materials but rather in terms of quality of recycled material (collect less but of a better quality);
e) Organised involvement of the informal sector, associations, NGOs, etc. ;
f) Simple technologies of proven efficiency should be preferred;
g) Technologies should be suited to the specific local conditions;
h) The same technology should be implemented throughout a given geographical area or country with the aim of saving on maintenance costs (spare parts supply, staff training, etc.);
i) In some specific situations the acquisition of services provided by experienced enterprises might be preferred over the direct acquisition and operating of facilities;
j) The so-called “Blue solutions” should be applied wherever possible, based on the principle whereby there is no need to spend/invest more to protect the environment, but rather lessons should be learned from the environment and from what nature has already created in order to establish new business and social capital;
k) A holistic approach should be adopted in spreading resources among the different WM steps (collection, transport, treatment, disposal);
l) Integrated approach to WM technologies with no ideological preclusion (shrewd combination of recycling, landfilling and thermal treatment);

m) The convenience of material suppliers should be assessed in terms of transportation (zero km, repercussion on the community), use of resources (lower production of CO^2, renewable energy, possibility of constant supply) and economic impact;
n) Economic return should be ensured through synergies with other economic/social activities (informal sector, recycling, reuse, etc);
o) Particular focus should be placed on the recycling of putrescible fractions prior to landfilling. Biological stabilization of residual putrescibles by in situ treatment should be opted for over expensive mechanical-biological off-site pre-treatment;
p) Landfill technologies should aim to drastically reduce the abuse of expensive geosynthetics, by substituting these with equivalent low-cost products (natural materials, suitable residues, etc.) when conveniently available locally;
q) Following traditional biological treatment, there is no need to remove residual COD, mainly made up of humic substances, from the treated MSW leachate. Requirements to comply with discharge standards set below 150 mg/L for COD, generally based on Reverse Osmosis, should not necessarily be adopted;
r) Waste management should not be overregulated (as occurs increasingly in numerous industrialised countries) as this may represent an obstacle to a virtuous waste management strategy, in both economic and technical terms;
s) Regulations should be flexible, open to significant innovative scientific development and compatible with specific local situations;
t) Science-driven educational WM programs in schools and universities should be increased, accessible to all, including local administrators;
u) Standardised and simplified operational and maintenance manuals should be provided to all technical staff;
v) An organised reasonable involvement of stakeholders in taking decisions prior to implementation of WM strategies might avoid costly opposition and protests afterwards;
w) Communication tools aimed at contrasting potentially misleading fake news (possibly resulting in unnecessary opposition by the public and related costs) should be developed.

To conclude, low cost strategies do not necessarily imply a reduced performance in protecting the environment and the public health; they should however represent a cost-effective solution intended to extend access of the populations worldwide to sustainable waste management systems.

References

Cossu R. (2009). Driving forces in national waste management strategies, Waste Management 29, 2797-2798

Eurostat (2019) waste statistics. https://ec.europa.eu/eurostat/statistics explained/index.php/Waste_statistics (Accessed on the 15th, June, 2019).

World Bank (2018). What a Waste 2.0 : A Global Snapshot of Solid Waste Management to 2050. Urban Development; Washington, DC: World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/30317

3. SUSTAINABLE LANDFILLING

3.1. General aspects

On the base of the modern waste management (WM) concepts, such as Zero Waste, Circular Economy, 3Rs, etc., landfilling is considered the least preferable option in WM. Nevertheless landfill will continue to plays a fundamental role in future modern solid waste management systems, in providing a final sink for residues from CE and in ensuring a safe management of waste when landfill is the only economically viable option in WM.

One of the major issues in the landfilling of waste is compliance with environmental sustainability in terms of control of long-term emissions (gas and leachate) and compliance with Final Storage Quality (FSQ) of the landfill (Cossu and Pivato, 2018; Cossu and van der Sloot, 2014; Laner et al., 2012). FSQ is defined as a set of values of different parameters to be achieved within the span of one generation, representing an acceptable equilibrium between the landfill and the environment.

In order to achieve sustainability targets a combination of treatments (mechanical, chemical, biological and thermal) should be implemented throughout the different life phases of a landfill (prior to waste deposition, in situ during operations and during the post-care phase) aimed at stabilizing the waste and reducing the long-term mobility of contaminants.

Biological stabilization is the main target when dealing with Municipal Solid Waste (MSW), particularly as environmental impacts deriving from landfilling originate largely from putrescible fractions in the waste (emission of methane and CO2, emission of organic contaminants and ammonia nitrogen associated to leachate, odours, risks of fires, etc.).

In landfill, the control of degradable organics and related environmental impacts may be achieved by a series of options:

- Avoidance of putrescible fraction in landfilled waste (Separate collection)
- Pre-stabilisation of waste prior to landfilling (Thermal treatment, Mechanical Biological Treatment)
- In-situ treatment to enhance biodegradation during landfilling and/or the aftercare phase;
- A combination of the above listed options

In recent years, the term "Landfill Bioreactor" has been coined specifically to indicate a landfill in which different in-situ measures are undertaken to enhance biological degradation and increase removal of ammonia and recalcitrant organics. These measures may include leachate recirculation, introduction of water, and natural or forced aeration.

Improved control of biochemical kinetics, moisture content and redox conditions may result in a significant shortening of the aftercare phase and, consequently, in a quicker achieving of environmentally sustainable targets.

Advantages gained by enhancing biodegradation processes in Landfill Bioreactors (depending on the different bioreactor models) may include the following:

- Shortening of the aftercare phase
- Reduction of environmental impacts
- Reduction of aftercare costs
- Reduction of landfill owner's environmental liability
- Improvement of leachate quality
- Faster and time-specific biogas production
- Faster mechanical stabilisation of waste mass
- Increased waste settlement and density
- Less post closure operations required
- Removal of long-lasting compounds from traditional landfills (ammonia, recalcitrant organics, etc.)

Disadvantages (in line with type of bioreactor model) may include the following:

- Increased capital and /or management costs
- Higher complexity of construction
- Energy for aeration
- More complex management and monitoring programme
- Specific disadvantages may arise with leachate recirculation such as:
- Increased odour generation
- Risk of mechanical instability (particularly on slopes) during the operational phase due to higher moisture content
- Higher production of leachate

According to type of bioreactor, different methane generation yields and waste stabilization rates may be achieved.

The choice of a specific bioreactor landfill is regulated by the objectives to be pursued (i.e., energy recovery landfill gas, waste stabilisation, sustainability targets, etc.) as well as by economic issues (balance between capital and operational costs and long-term savings) and the specific site conditions (e.g., waste characteristics, climate and social/economic situation, regulations).

3.2. Landfill bioreactors (Paper III – Paper IV)

Objectives

Several bioreactor landfill types have been successfully applied with promising results at lab or pilot scale, although full-scale bioreactor landfills are still uncommon. Obstacles to a large diffusion of landfill bioreactors are the higher costs and the ongoing reluctance of regulators due to concerns related to short-term environmental impacts, low maturity of the technologies and to the technical skill of landfill operators in implementing advanced technologies (Reinhart et al., 2002). The aim of this work was to contribute to filling this knowledge gap by reviewing state-of-the-art bioreactor landfill research and elaborating data to quantify the different kinetics with the goal of increasing the knowledge of bioreactor performance and potential.

Activities and methodologies

Several lab-scale applications of different bioreactors reported in literature were analysed, compared, and an overview of different types provided. A possible classification of the bioreactors was proposed, grouping them according to the main bioreactor types in literature; for each bioreactor category advantages and disadvantages were discussed.

Qualitative analysis was provided according to a series of selected characteristics with relevance in opting for a specific bioreactor type such as methane production and energy recovery, biochemical kinetics velocity, nitrogen removal, technological complexity, and maintenance and leachate treatment costs.

Considering landfill sustainability, the ability for a bioreactor to achieve waste stabilization was quantified by mean of first-order removal kinetics of COD and ammonia, determined by the approximation of the overall removal process of the selected relevant contaminants.

Results and remarks

Bioreactors can be categorised as follows: anaerobic, aerobic, semi aerobic and hybrid (Figure 3.1.).

The anaerobic landfill bioreactor is the most common application of bioreactor systems where the biological degradation is enhanced by means of leachate recirculation. Anaerobic bioreactors improve the methane generation rate but do not produce a significant impact on ammonia removal, and degradation kinetics remain slow. Aerated reactors create an aerobic environment within the waste mass through forced air injection. They increase ammonia and COD removal kinetics up to 10-fold anaerobic ones, appearing as an effective alternative to the traditional anaerobic processes, although the need for forced ventilation systems, the complex operation and management, and the high energy consumption, with high operational and capital costs fail to render aerated landfill not always technically and economically feasible. Semi-aerobic landfill method is based on the passive aeration of the landfill, in which natural flow of the external air into the waste mass is moved through the leachate collection pipes by the temperature gradient between the inside and outside of the landfill (Theng et al., 2005). This method performance is situated midway between anaerobic and aerobic reactor performance, but with lower operational costs. For this reason, the semi-aerobic system is recognized as a cost–effective, low technology landfill system. This system can also be feasibly implemented in developing countries, where financial constraints and limited technical knowledge are generally the main reasons for inadequate disposal. Aerobic and semi-aerobic landfilling however do not enable the energetic exploitation of landfill gas. Hybrid bioreactors, which are operated under various combinations of aerobic and anaerobic conditions, achieve both energy recovery and/or faster waste stabilization. In particular aerated-anaerobic hybrid reactors are aimed at enhancing biogas generation, however this system will experience ammonia accumulation challenges, while facultative bioreactors combine both objectives, providing the best performance in terms of ammonia removal kinetics. In general, the best ammonia removal performance is achieved under hybrid conditions.

On the basis of the literature review, the following remarks have been drawn:

- Due to the need for more careful operational and construction requirements of bioreactor landfills, capital and operating costs are higher compared to those of traditional landfills; however, these costs will be compensated by future economic benefits from bioreactor landfills, including shorter aftercare, reduced leachate treatment costs, reduced long term environmental risks, longer active life of the landfill, and earlier reuse of the land (Berge et al., 2009; Read et al., 2001).
- Despite the good results obtained at lab-scale, full-scale testing should be carried out in order to assess the technical and economic feasibility of these systems.
- Results showed that the benefits obtained under lab-scale investigation are much higher compared to full-scale application, largely due to the optimum and homogeneous conditions reproduced under lab-scale situation (Kylefors et al., 2003; Ritzkowski and Stegmann, 2012). However, knowledge of the general behavior of each bioreactor typology at lab-scale, as provided by this work, allows the identification of best bioreactor solution on a full-scale, according to the objectives and in situ conditions.

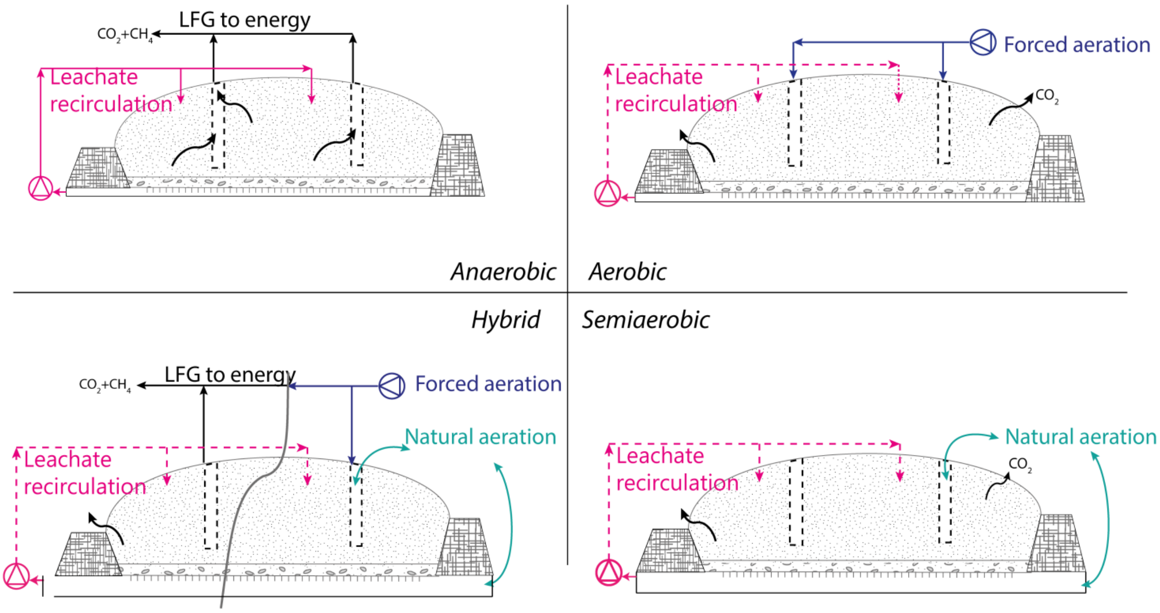


Figure 3.1. Scheme of the different bioreactors types.

References

Berge, N.D., Reinhart, D.R., Batarseh, E.S., 2009. An assessment of bioreactor landfill costs and benefits. Waste Manag. 29, 1558–1567. doi:10.1016/j.wasman.2008.12.010

Cossu, R., Pivato, A. Aftercare completition: final storage quality assessment. In Cossu, R.; Stegmann, R. Solid Waste Landfilling, Concepts, Processes, Technology. Elsevier, 2018, ISBN: 9780128183366.

Cossu, R; van der Sloot, H. Sustainable landfilling. CISA Publisher, 2014, ISBN 978-88-6265-005-2.

Kylefors, K., Andreas, L., Lagerkvist, A., 2003. A comparsion of small-scale, pilot scale and large -scale tests for predicting leaching behavioud of landfilled wastes. Waste Manag. 23, 45–59.

Laner, D., Crest, M., Scharff, H., Morris, J.W.F., Barlaz, M.A., 2012. A review of approaches for the long-term management of municipal solid waste landfills. Waste Manag. 32, 498–512. doi:10.1016/j.wasman.2011.11.010

Read, A.D., Hudgins, M., Phillips, P., 2001. Aerobic landfill test cells and their implications for sustainable waste disposal. Geogr. J. 167, 235–247. doi:10.1111/1475-4959.00021

Reinhart, D.R., Mccreanor, P.T., Townsend, T., 2002. Waste Management & Research The bioreactor landfill : Its status and future. Waste Manag. Res. 172–186. doi:10.1177/0734242X0202000209

Ritzkowski, M., Stegmann, R., 2012. Landfill aeration worldwide: Concepts, indications and findings. Waste Manag. 32, 1411–1419. doi:10.1016/j.wasman.2012.02.020

Theng, L.C., Matsufuji, Y., Mohd, N.H., 2005. Implementation of the semi-aerobic landfill system (Fukuoka method) in developing countries: A Malaysia cost analysis. Waste Manag. 25, 702–711. doi:10.1016/j.wasman.2005.01.008

4. SEMI-AEROBIC LANDFILLING OF MSW

4.1. General Aspects

As described earlier the implementation of aerobic processes in landfills may be achieved by means of either natural ventilation or forced aeration. The natural ventilation method is based on a simple physical principle: air flows into waste layers by means of a natural advection process generated by the difference in temperature between landfill layers (T_{LF}) and external ambient (T_{amb}) (Figure 4.1.). This difference is established when the landfilled waste contains putrescible organics and exothermic degradation reactions occur. Under aerobic conditions the heat released can increase the waste mass temperature by up to 50-70 °C. The movement of air is particularly enhanced in winter and during the night when the temperature differences are higher.

The semi-aerobic landfill system has been extensively studied in Japan since the early 1970s at the University of Fukuoka (Matsufuji et al., 1978, Hanashima *et al.,* 1981), hence becoming known as the “Fukuoka method”.

Semi-aerobic landfill systems, being based on a mechanism of natural air ventilation, promote, without using highly technological solutions, the presence of oxygen in the waste mass, thus accelerating waste stabilisation. Although semi-aerobic landfilling is characterised by a lower stabilization efficiency compared to aerobic systems, it represents a valuable solution for achieving sustainable landfilling, compromising between the technological complexity and high costs of aerobic systems and the long-term impacts generated by anaerobic systems. Accordingly, the semi-aerobic landfilling could be considered a cost–effective, low technology system suited to meet sustainability requirements.

From a structural point of view, a semi-aerobic landfill system consists of a network of horizontal pipes installed at the bottom of landfill sectors, and vertical venting pipes erected at specific intersections of the horizontal pipes. The perforated horizontal pipes not only collect and quickly drain off leachate generated in the waste layers but, as part of the network of pipelines, also promotes the circulation of air within the waste mass.

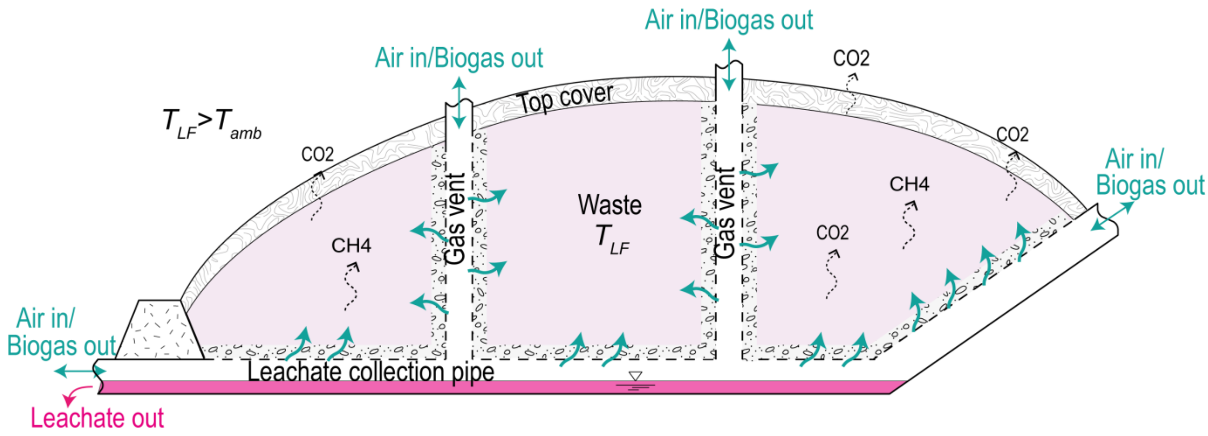
Organic compounds are degraded more effectively than under anaerobic conditions and ammonia is oxydised, generating leachate which is easier and more economical to manage. The generation of CH_4 and H_2S is significantly reduced, contributing towards the prevention of global warming (in a semi-aerobic process the proportion of CO_2 and CH_4 is approx. 4:1, much higher than the ratio 1:1 in an anaerobic landfill), (Matsufuji et al., 1997). Due to the impossibility in semi-aerobic systems of achieving aerobic conditions throughout the entire waste mass, both aerobic and anaerobic areas continue to coexist, enhancing denitrification of oxidized nitrogen compounds with subsequent release of N_2 gas.

The semi-aerobic processes described above can be improved by re-circulating leachate back into the landfill, with the advantage of further promoting the denitrification processes mentioned above, and potentially contributing towards trapping heavy metals.

Despite a series of full-scale applications both in Japan and abroad, semi-aerobic landfilling still needs to be further investigated in order to optimise performances under different operative conditions (e.g. climate, waste composition etc.) which may strongly be influenced by geographical position, economic resources, culture, etc.

In order to clarify some of these aspects three different experimental runs have been arranged within the thesis work. Testing was carried out at the LISA laboratory of the Voltabarozzo Research Centre at the University of Padova.

All the experiments were carried out using lab-scale cylindrical lysimeters in a thermal insulated room, with temperature values ranging between 18–30 °C in order to simulate the night/day cycle, which may significantly influence the temperature gradient between the waste mass and the external ambient temperature.



Fiure 4.1. Scheme of the semi-aerobic landfill.

4.2. Semi-aerobic landfilling under varying water availability and putrescibles content

(Paper V)

Objectives

The aim of this study was to investigate the stabilization performance and optimal control of semi-aerobic landfilling under inverse conditions of water availability (high and low) and content of putrescible waste fraction (high and low) as these parameters may strongly affect landfill stabilisation performance.

Water availability (rainfall infiltration, waste moisture, leachate recirculation, flushing, etc.) is fundamental for biodegradation processes and allows the removal of soluble non-degradable contaminants, however excessive water availability interferes with the advective air flow promoting anaerobic processes. The putrescible fraction in waste to be landfilled is related to several factors (seasonal variations, cultural practices, social and economic conditions, source segregation and separate collection, entity and type of waste pre-treatment) and is responsible for the main environmental impacts deriving from landfilling (methane and CO2 emissions, emissions of carbon and nitrogen contaminants in leachate, odours, risks of fires, etc.). The impacts are mitigated by promoting aerobic stabilisation processes in semi aerobic landfill, but high putrescible waste content might reduce the advective circulation of air enhancing anaerobic processes and negatively influencing the quality of gas released into the atmosphere.

Numerous aspects of semi-aerobic landfilling have been investigated (engineering features, vertical or horizontal piping, type of materials, fluid-dynamics, influence of morphology, etc.); however, from the point of view of the process, semi-aerobic landfilling has generally been considered a black box (Ahmadifar et al., 2016; Aziz et al., 2010; Hirata et al., 2012; Huang et al., 2008; Matsuto et al., 2015; Morello et al., 2017; Theng et al., 2005; Wu et al., 2017; Yang et al., 2012). The latter does not allow to explain the marked differences observed in the performance of full-scale semi aerobic landfills operating throughout the world. Although water availability and putrescible waste content are of major importance in controlling semi-aerobic landfill processes, no comparative systematic study has been conducted to date prior to our experimental research.

Activities and methodologies

The experimental activity was undertaken over a period of approx. 4 months using six purpose-designed lysimeters: two simulating wet conditions, two dry conditions, and two artificially controlled watering under dry conditions. In each pair of lysimeters one was filled with waste with a low putrescible content and the other with waste with a high putrescible content.

The performance of the different lab scale lysimeters was compared in terms of waste stabilization, leachate and gas quality. Concentrations of mobile ammonia and total organic carbon (TOC) in landfilled waste were modelled by means of first-order kinetics, and carbon and nitrogen mass balances were calculated.

Results and remarks

The best performance for the semi-aerobic process was achieved at a water availability in the range of 1.5-2.4 $kgH_2O/kgTS$, under the following two combinations: a) Waste with high putrescible content and no addition of external water; b) waste with low putrescible content and controlled watering.

In both cases the stability parameters proved quite satisfactory (Respiration index in 4 days, RI_4 = 12.25-12.87 mgO_2/gTS, BOD/COD ratio in leachate < 0.04-0.05).

On the basis of experimental results, the following conclusions were drawn:

- water availability and putrescible waste content have been confirmed as key factors in controlling performance of semi-aerobic landfilling;

- despite the limitations of the lab-scale operation, significant differences in performance were highlighted on varying these factors;
- the combination of high putrescible waste and high water availability resulted in anaerobic effects and limited waste stabilisation;
- with low putrescible waste, high water availability resulted in flushing effect and promoted high contaminant mobility. Low water availability halted the biodegradation processes;
- the best performance was achieved with water availability around 1.5-2.4 kgH_2O/kgTS (high putrescible waste with dry conditions and low putrescible waste with controlled water availability);
- with high putrescible waste, endogenous water (moisture) fully supported biodegradation processes and no water addition was required;
- the transfer of results from lab-scale to full-scale is limited by the site specific conditions, however the lab-scale results allowed to selectively discuss the influence of water availability and waste putrescible contents, yielding significant preliminary considerations.

4.3. Innovative dual-step management in a tropical climate (Paper VI)

Objectives

In line with the findings and conclusions obtained in the previous study, stabilization performance of semi-aerobic landfill is heavily influenced by water availability conditions and putrescible waste content. In particular, the results demonstrated that low water availability limits biodegradation processes when dealing with low putrescible content waste, while high water availability and high putrescible content waste results in anaerobic processes affecting the quality of biogas and leachate emissions. Proper management of water input proved to be an effective solution in improving landfill performance.

Tropical dry-wet climate poses significant challenges for a proper semi aerobic landfill management, being characterised by the alternation of dry (little or no precipitation) and wet seasons (heavy precipitations). In order to overcome the negative impacts of the rainfall seasonality on semi-aerobic landfill performance, this study aimed at investigating a dual step management of landfill: during the dry season the in-situ composting process was reproduced controlling water availability by means of leachate recirculation, whilst during the wet season a flushing simulating rainfall was applied and leachate stored (Figure 4.2.).

Activities and methodologies

A controlled dual-step management of semi- aerobic landfill was reproduced in eight bioreactors over a six-month period, simulating the alternation of two phases: composting phase during the dry season (0-96th day) and flushing phase during the wet

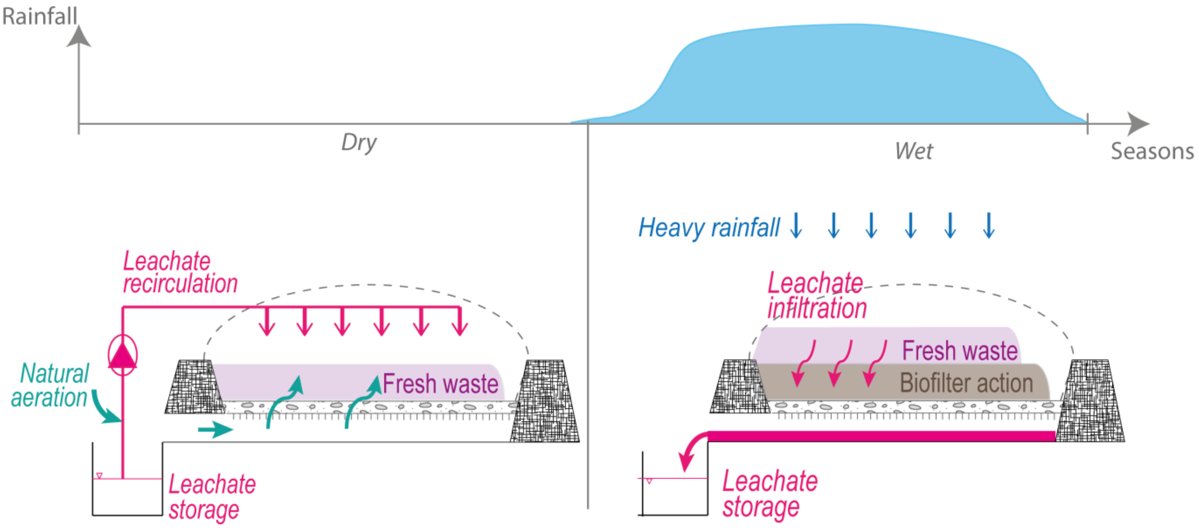


Figure 4.2. Scheme of the proposed innovative management of semi-aerobic landfill under dry-wet tropical climate.

season (97th-192th day). The eight landfill bioreactors were operated under two different process conditions: four under anaerobic conditions and four under semi-aerobic conditions; half of the reactors were filled with high putrescible content waste, half with low putrescible content.

The synergic effect of the subsequent phases (dry under controlled moistening and wet) in the semi-aerobic landfill was evaluated on the basis of both types of waste. The performance of the semi-aerobic reactors was compared with that of anaerobic reactors: waste stabilization, leachate and gas quality were studied and discussed in terms of degradation kinetics, ammonia removal, gasification enhancement, methane generation reduction, and Final Storage Quality (FSQ) achievement.

Results and remarks

As reported in the literature, semi-aerobic conditions promote a better stabilisation of organics, in particular, a dual-step management contributed to FSQ achievement over the one year period of simulation, achieving target values for BOD_5, COD, BOD_5/COD and ammonia in the final leachate, RI_4 in the solid samples.

Semi-aerobic stabilization kinetics were found to be 6 to 10-fold faster compared to anaerobic process, promoting higher carbon gasification levels with no methane production, and higher transformation of ammonia to nitrates.

Overall performance of the semi-aerobic lysimeters did not seem to be significantly influenced by the different initial organic content. During the first phase (characterised by relatively thin waste layer and controlled rain irrigation carried out by means of leachate recirculation, where possible), composting took place, thus enhancing waste stabilisation. In the second phase (characterised by flushing simulating the effect of rainfall in tropical areas), both biodegradation and flushing effect occurred in the removal of contaminants, and organic removal kinetics increased.

Conversely, anaerobic columns were affected by the presence of a diverse waste composition; indeed, particularly with the "O" waste, a lower pH caused by a higher degree of acidification, contributed both to carbon accumulation in the solid during the first dry phase, and to its release in leachate during the flushing period.

The innovative dual-step management strategy implies a “horizontal growth” of the landfill, implying a need for high space requirements and resulting in high leachate production, thus linked to higher landfill management costs. However, if space is not a limiting factor, the generation of leachate is fundamental in ensuring irrigation during the dry season and enhancing both leachate evaporation and treatability, thus reducing volumes and mitigating management costs.

4.4. Optimised management under tropical wet-dry conditions (Paper VII)

Objectives

Based on the findings and conclusions of the previous study, the dual-step management of semi-aerobic landfill under tropical dry-wet climate proved highly positive, leading to a more rapid and intense biological stabilisation of the waste mass compared with anaerobic conditions. However, benefits associated with the previously studied dual-step management compared to the simple management of the semi-aerobic landfill were not confirmed.

The aim of the present study was to investigate the performance of semi-aerobic landfill under tropical dry-wet climate conditions and to assess the potential benefits afforded by appropriate management of water input when operating the landfill by overlaying a new layer of waste in each climate season. In particular given the relevance of water availability, the initial phase of the semi-aerobic landfill under the given climate period (wet or dry) was specifically considered.

The following three paradigmatic conditions were studied:

- Initial phase during the dry season, without any external water addition;
- Initial phase during the dry season, with a controlled water addition;
- Initial phase during the wet season, with storage of leachate for subsequent recirculation during the dry phase.

These starting conditions were identical to those adopted in Paper V (§ 4.3.).

Activities and methodologies

Six lab scale lysimeters were operated in two phases reproducing a sequence of dry and wet tropical seasons: two with an initial dry phase, two with an initial dry phase under controlled watering and two with an initial wet phase, storing the leachate for subsequent recirculation during the dry phase. In each pair of lysimeters one was filled with waste with a low putrescible content and the other with waste with a high putrescible content. Following the initial phase, represented by the results presented in Paper V, a second phase was simulated by adding to the previously used lysimeters a second layer of fresh waste, under alternate climate conditions.

Solid, leachate and gas quality were monitored and stabilisation performances were assessed.

Results and remarks

On the basis of the above-reported results the following conclusive remarks can be drawn:

- Semi-aerobic landfilling is potentially heavily influenced by tropical wet-dry climate, due to the influence produced by water availability and different putrescible content of waste on natural advective air circulation.
- During the wet season flushing effect, in terms of mobility of contaminants, and anaerobic processes prevail over semi-aerobic conditions limiting natural air circulation.
- During the dry season, by ensuring a constantly balanced water availability through proportioning of putrescible waste content and external water addition, the circulation of natural air can be conveniently maintained.
- Previous studies (Grossule and Lavagnolo, 2019) have demonstrated that consistently balanced availability of water, both in terms of endogenous water naturally present in the putrescible fraction, and external water input (rainfall, leachate recirculation), promotes good natural air circulation while supporting aerobic degradation processes during the dry phase.
- When implementing semi-aerobic landfill under tropical dry-wet climate conditions, the overlaying of a new layer of waste in each climate season plays a fundamental role in ensuring good stabilisation. In particular, alternation of new waste layers together with rainfall seasonality, maintaining constant operational conditions throughout the entire climate season (wet or dry) for each individual layer will contribute towards enhancing stabilisation of the landfill bottom layer, which behaves as an internal attenuating biological filter for leachate produced during subsequent phases.

In conclusion, a semi-aerobic landfill operated under wet-dry climate conditions can be managed as a hybrid reactor, aerated throughout the dry season and flushed in anaerobic conditions in the wet season.

However, the positive results obtained in this preliminary investigation should be confirmed by further pilot studies in order to identify and define appropriate design parameters.

References

Ahmadifar, M., Sartaj, M., Abdallah, M., 2016. Investigating the performance of aerobic, semi-aerobic, and anaerobic bioreactor landfills for MSW management in developing countries. J. Mater. Cycles Waste Manag. 18, 703–714. doi:10.1007/s10163-015-0372-0

Aziz, S.Q., Aziz, H.A., Yusoff, M.S., Bashir, M.J.K., Umar, M., 2010. Leachate characterization in semi-aerobic and anaerobic sanitary landfills: A comparative study. J. Environ. Manage. 91, 2608–2614. doi:10.1016/j.jenvman.2010.07.042

Hanashima, M., Yamasaki, K., Kuroki, T., Onishi, K., 1981. Heat and gas flow analysis in semiaerobic landfill. J. Environ. Eng. Divis., Proc. Am. Soc. Civ. Eng. 107 (EE1), 1–9.

Hirata, O., Matsufuji, Y., Tachifuji, A., Yanase, R., 2012. Waste stabilization mechanism by a recirculatory semi-aerobic landfill with the aeration system. J. Mater. Cycles Waste Manag. 14, 47–51. doi:10.1007/s10163-011-0036-7

Huang, Q., Yang, Y., Pang, X., Wang, Q., 2008. Evolution on qualities of leachate and landfill gas in the semi-aerobic landfill. J. Environ. Sci. 20, 499–504. doi:10.1016/S1001-0742(08)62086-0

Matsufuji, Y., Hanashima, M., Nagano, S., 1978. Waste and landfill type. In: Proceedings of 33th Annual Conference of Japan Society of Civil Engineers, vol. 33, pp. 133-134.

Matsufuji, Y., Tanaka, A., Hanashima, M., 1997. Biodegradation process of municipal solid waste by semi-aerobic landfill type. In: Proceedings of the First Korean – Japan Joint International Symposium. Korea Society of Waste Management, pp. 87-98.

Matsuto, T., Zhang, X., Matsuo, T., Yamada, S., 2015. Onsite survey on the mechanism of passive aeration and air flow path in a semi-aerobic landfill. Waste Manag. 36, 204–212. doi:10.1016/j.wasman.2014.11.007

Morello, L., Raga, R., Lavagnolo, M.C., Pivato, A., Ali, M., Yue, D., Cossu, R., 2017. The S.An.A.® concept: Semi-aerobic, Anaerobic, Aerated bioreactor landfill. Waste Manag. doi:10.1016/j.wasman.2017.05.006

Theng, L.C., Matsufuji, Y., Mohd, N.H., 2005. Implementation of the semi-aerobic landfill system (Fukuoka method) in developing countries: A Malaysia cost analysis. Waste Manag. 25, 702–711. doi:10.1016/j.wasman.2005.01.008

Wu, X., Yue, B., Huang, Q., Wang, Q., Lin, Y., Zhang, W., Yan, Z., 2017. Spatio-temporal variation of landfill gas in pilot-scale semi-aerobic and anaerobic landfills over 5 years. J. Environ. Sci. (China) 54, 288–297. doi:10.1016/j.jes.2016.09.015

Yang, Y., Yue, B., Yang, Y., Huang, Q., 2012. Influence of semi-aerobic and anaerobic landfill operation with leachate recirculation on stabilization processes. Waste Manag. Res.

5. TREATMENT OF LANDFILL LEACHATE USING BLUE TECHNOLOGIES

5.1. General aspects

As already mentioned, sanitary landfilling continues to be the most-widely applied disposal method for MSW worldwide, particularly in DCs. One of the main operational problems in MSW landfilling is the management of leachate, both from an economic and technical point of view. Leachate is a strongly polluted wastewater containing a huge variety of components (mainly biodegradable organics, ammonia, salts, while metals typically in limited concentrations), which is formed by the rainfall infiltration through the landfilled waste mass. Leachate quality is the result of a combination of biological, chemical and physical processes, depending on specific waste composition and water regime (rainfall, water infiltration, leachate recirculation, etc.).

Quantity and quality of leachate vary dramatically in line with the development of the landfill volume and age, representing one of the major differences versus other traditional forms of sewage. This implies that a leachate treatment plant should be designed in a flexible way allowing progressive extension and adaptation of the treatment scheme.

With ever increasing quality standards set by the regulators with regards to the discharge of effluents into water bodies, the level of leachate treatment should consequently increase. Accordingly, in industrialized countries complex treatment processes, including precipitation, advanced biological oxidation units and reverse osmosis are frequently adopted, resulting in an approximate cost for leachate treatment of ± 20-40 €/m^3 (Stegmann, 2018). These costs are highly prohibitive for Developing Countries, and at times an issue also in more developed countries.

Consequently, there is growing interest internationally in developing, within the concept of the Circular Economy and Blue Economy, simple cost-effective technologies inspired by nature, aimed at the recovery of viable energy and material resources.

To this regard, in this thesis work two different proposals have been put forward and tested based on these principles:

- Biological aerobic stabilization using Black soldier fly (BSF) larvae
- Phytotreatment using tropical plants

The high versatility and voracity of Black soldier fly (BSF) larvae has been exploited for the purpose of treating a series of semisolid biowastes (e.g. kitchen waste, fish offal, coffee bean pulp, animal manure and human excreta) (Banks et al., 2014; Diener and Zurbrügg, 2011; Newton, 2004) and the benefits of using BSF larvae include: commercial value of the stabilized residue and production of biomass rich in fats and proteins, suitable both for biodiesel production and animal feeding. Leachate from MSW landfilling, traditionally characterised by a high biodegradable organic content, represents an unexplored source for BSF application, which would introduce a blue low cost solution, converting a problem into a resource recovery opportunity (Figure 5.1.). In the thesis two experimental runs have been carried out at the LISA laboratory of the Voltabarozzo Research Centre at the University of Padova, to test the adaptability of BSF larvae to leachate, to define removal efficiencies and to analyse the amount and quality of recoverable resources.

The phytotreatment of wastewaters exploits the combined action of plants, microorganisms (rhizosphere) and soil for pollutant stabilisation, extraction, degradation or volatilisation by means of biological, chemical or physical processes in plants or in the roots-soil system.

Phytotreatment has been applied, as an effective alternative to conventional wastewater treatment processes, to treat different types of wastewater, representing an effective low cost, and low management treatment option. In the case of landfill leachate, several freshwater wetland plants (e.g. Phragmites australis) have been successfully used; however excessive leachate loading and buildup of excess salt in the soil may result in failure of the system and dilution of high strength leachate is typically required (Jones et al., 2006).

In the presence of high concentrations of salts, nutrients and toxic pollutants, potentially present in leachate, particularly in developing countries with less stringent discharge standards, mangrove plants may represent a valuable alternative to freshwater wetland plants. The potential use of mangroves for the phytotreatment of landfill leachate has been investigated in a preliminary study, comparing another tropical plant such as Canna Indica. Experimental activities were carried out at KUET University, Civil department, Khulna, Bangladesh.

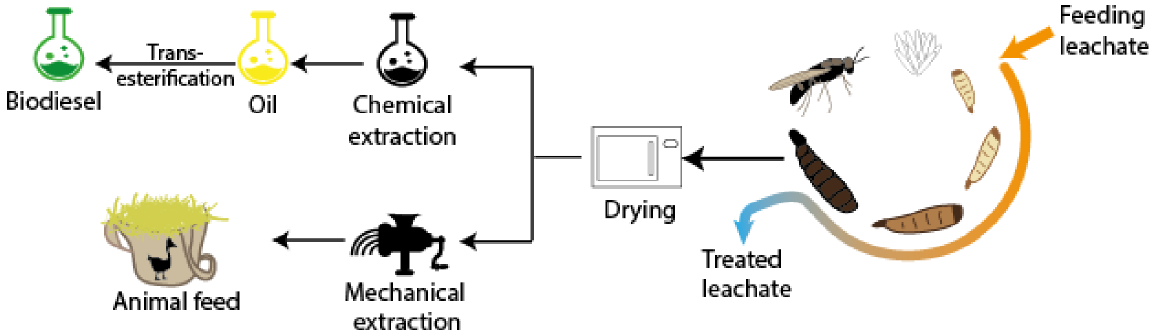


Figure 5.1. Schematic representation of BSF leachate treatment and resource recovery.

5.2. Use of BSF larvae in leachate treatment: Adaptability and resource recovery testing (Paper VIII)

Objectives

The research activity was aimed at investigating the adaptability of BSF larvae to leachate environment using different leachate concentrations (25%, 50%, 75%, 100%) and two different feeding substrates: liquid (pure leachate) and semi-solid (wheat bran mixed with leachate). Quality of BSF prepupal biomass was evaluated to identify the potential use as an alternative energy source in the production of biodiesel.

The use of BSF for leachate treatment represents to date an unexplored option, which could introduce a blue low cost solution in landfill technology, particularly appropriate in developing countries, where landfilling is still widely applied.

Activities and methodologies

An intense literature survey was undertaken on BSF larvae on larvae metabolism and application to biowaste.

The experimental activity was performed using six-day-old BSF larvae, housed in plastic boxes and supported with different substrates: Liquid and semisolid (mixture of liquid substrate -80%- and wheat bran -20%-). The liquid was a mixture of distilled water and four different percentages of leachate, 25%, 50%, 75%, and 100%.

The development of larvae, and consequently the quality and quantity of feeding, was monitored by measuring the following parameters: larval wet weight, prepupal wet weight, mortality of larvae, prepupation (percentage of prepupae formed throughout mean larval development time). Prepupal composition was evaluated in terms of crude protein and lipid content. Lipids were characterised for fatty acid profile.

Results and remarks

BSF larvae grow and develop while feeding on different substrates containing landfill leachate, with a semi-solid substrate performing better than a liquid one. In all tests, mortality was less than 50% and was mainly linked to food shortages: the higher the nutrient content in leachate, the higher the larval development, with no significant inhibitory effect ascribed to any toxicant in leachate. Regarding the lipids and proteins content in the prepupae biomass, values were within the range found in literature for BSF larvae fed on different biowaste (food waste, dairy manure) and profile of lipids proved that BSF prepupae biomass could be exploited as an alternative energy source in the production of biodiesel.

Further lab studies were deemed fundamental to investigate treatment efficiencies in terms of contaminants removal and substrate stabilisation and to test alternative solid substrates, selecting preferably residues, in order to render the semisolid feeding approach economically advantageous. In order to understand and solve engineering issues with a view to full-scale application, the following aspects should be further investigated:

- feasible and manageable systems for larvae rearing and prepupae harvesting;
- reactors shaping and optimisation of surface need;
- operation (leachate feeding, substrate arrangement and maintenance, etc.);
- economy of the system;
- relevance of any hygiene issues and social acceptance.

5.3. Use of BSF larvae in leachate treatment: Removal efficiencies (Paper IX)

Objectives

Based on the findings and conclusions of the previous study, leachate treatment efficiencies using H. illucens larvae (Black Soldier Fly-BSF) were investigated in terms of contaminant removal and substrate stabilisation by selecting residues as solid substrates to be mixed with leachate, in order to render semisolid feeding economically advantageous.

In particular, semisolid substrates were obtained by mixing leachate with three different solid materials: wheat bran, a biodegradable nutrient substrate traditionally used to feed BSF, brewers' spent grain, a biodegradable nutrient residue from the brewery industry, and sawdust, a low biodegradable residue from the wood industry.

Activities and methodologies

The experimental activity was performed using six-day-old BSF larvae housed in plastic boxes and fed with leachate using three different semisolid substrates obtained by mixing leachate with three different solid materials (wheat bran, brewers' spent grain and sawdust) until an 80% moisture content was achieved.

Larvae growth rate was monitored in terms of weight variation over time, mortality, time required by larvae to reach the prepupal stage (prepupation time) and prepupation percentage. The prepupal biomass composition was analysed in terms of crude protein, lipids and fatty acid profile. Treatment performance was evaluated by measuring the variation of Total Solids (TS), Total Organic Carbon (TOC) and nitrogen compounds in each semisolid substrate. Overall stabilisation was evaluated by measuring 7-days Respirometric index (RI_7).

Results and remarks

Larvae development and performance in removing contaminants were significantly different depending on the tested substrates. In particular, solid materials providing nutrients in addition to leachate displayed the best performance. Larvae supported by substrates with wheat bran and brewers' spent grain showed faster and greater growth and, lower mortality compared to those fed on sawdust, where leachate represented the main source of nutrients. Consequently, an insufficient load of nutrients in the sawdust substrate precluded larval pupation.

Larvae contribution to the overall removal of contaminants under the best operational conditions ranged between 10 and 15% for TOC, and between 21 and 36% for nitrogen, with specific load of 210-230 mg TOC/larva and 14-19 mg N/larva. No significant removal of ammonia nitrogen by larvae metabolism was detected, although ammonia did not appear to exert toxic effects on larval development at the concentrations used.

The initial amount of TS, TOC and TN was spread into a final semisolid residue, prepupal biomass and gaseous emissions. The fraction remaining in the final semi-solid residue varied between 40 and 50%, depending on the considered parameter (TS, TOC, TN) and the typology of substrate. The fraction uptaken by larvae ranged around 10% for TOC and from 18 to 28% for TN. Lipid and protein concentrations in the prepupal biomass were 28-30% TS and 43-45%, respectively.

On the basis of experimental results, the following conclusions were drawn:

- The load of TOC and TN in sawdust substrate was insufficient to support larval development. In further studies, the concentration and amount of leachate should be increased when using solid materials with low nutrient content.
- Further research should be performed to define the role and fate of the different forms of nitrogen involved in the removal process.
- The relationship between specific contaminant load (e.g. mg TOC/larva or mg TOC/g substrate) and removal efficiencies should be investigated in order to identify the optimal load.
- BSF larvae applied to leachate treatment, although contributing in a limited manner to contaminant removal, might provide a significant source of proteins and lipids, suitable respectively for use in animal feeds and the production of biodiesel.
- For a full-scale application, a series of engineering problems should be further studied at pilot-scale and a BSF larvae unit should be combined with other treatment units in order to reach the required efficiencies to comply with legal discharge limits.
- Finally, future studies should investigate how the eventual presence in leachate of heavy metals and emerging contaminants may influence larval metabolism in terms of larval development, treatment efficiencies and quality of final material resources.

5.4. Phytotreatment of leachate using tropical plants

Objectives

Mangrove plants represent one of the most productive ecosystems along the tropical and subtropical coastlines subjected to tidal flushing

The main features of mangrove ecosystems are the following:

- High tolerance to a series of environmental stresses, including high salinity, waterlogging, alternating aerobic and anaerobic conditions, unstable substratum, high concentration of nutrients in wastewater, fresh water without tidal flushing conditions, etc. (Zhang et al., 2010; Wu et al., 2008).
- The huge demand of nutrients, due to their high productivity (Alongi et al., 2005).

- The capability to transfer oxygen from the aerial parts to roots, which, jointly with their extensive root system, creates a significant aerobic zone in the rhizosphere (Holguin et al., 2001).
- Tidal flushing provides alternatively aerobic/anaerobic conditions, favouring nitrification/denitrification processes (Tam et al., 2009).

All these features provide an effective environment for the treatment of different wastewaters, both in natural and constructed wetlands (Leung et al., 2016; Tam et al., 2009; Xu et al., 2015; Yang et al., 2008; Ye et al., 2001), however, their capacity in treating high-strength landfill leachate has never been tested to date. A preliminary study has been carried out to investigate the potential use of mangroves in the phytotreatment of landfill leachate, and compared with another tropical plant such as Canna indica.

Activities and methodologies

The experimental activity was carried out using ten plastic pots set up as vertical flow systems. The experiment consisted in two parallel tests of constructed wetland (CW): four pots were planted with *Heritiera fomes* Mangrove plants (M tests) and four with *Canna Indica* (C tests). Two pots were unplanted and used as controls to assess the individual role of the soil in the treatment process (MCU and CCU). Three M tests and three C tests were operated as triplicates and irrigated with diluted leachate (M1-M3 and C1-C3); one M test and one C test were irrigated exclusively with tap water and used as control to assess toxic effects on plants potentially ascribable to leachate. After an acclimation phase of one month with tap water irrigation, the experiment lasted for a further 2 months divided into 8 phases, corresponding to different leachate doses. Test set up and irrigation scheme is illustrated in figure 5.2.

The leachate dose was gradually increased from 50 to 400 mL leachate/day, performed by upward dose of 50 mL/day per week, in order to adapt plants to the increasing contaminant concentrations. Additional tap water was added according to the plant’s needs, achieving an overall hydraulic load between 1-2 L (water+leachate)/day. Irrigation was performed daily from the top to simulate the vertical flux and leachate was extracted weekly from the bottom through a valve, specifically fixed to each pot.

Each pot (40 cm top diameter, 30cm bottom diameter, 45cm height) was filled with filter media at the bottom (gravel, coarse sand, fine sand) to facilitate leachate extraction and with sandy soil at the top to support plants growth. Leachate was collected in a local open dump. The main parameters of tested soil and leachate are illustrated in Table 5.1.

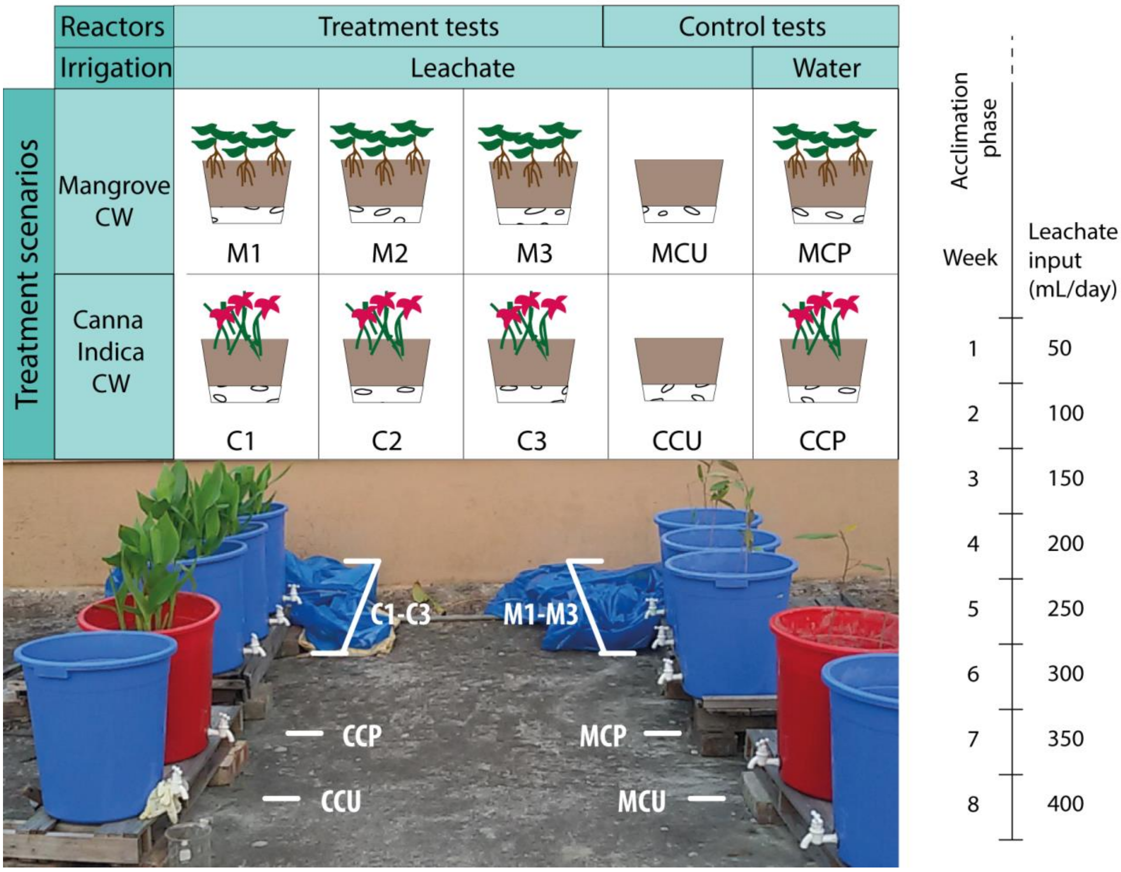


Figure 5.2. Scheme of the tests set up and irrigation.

Table 5.1. Characterisation of tested soil and leachate (TS: Total Solids).

SOIL		LEACHATE	
Parameters	Values	Parameters	Values
Porosity (e)	0.55	pH	9
Specific gravity (G_s)	2.6698	EC (mS/cm)	19.7
sand (2-0.02mm)	84%	TDS (mg/L)	20280
silt (0.02-0.002mm)	10%	COD (mgO_2/L)	3903
clay (<0.002mm)	6%	TKN (mgN/L)	1023
VS	4%(TS)	NH_4^+ (mgN/L)	874
Total organic carbon	<1%(TS)	NO_2 (mg/L)	4
Total nitrogen (mg/kg$_{SOIL}$)	18	NO_3 (mg/L)	58
Total phosphorous (mg/kg$_{SOIL}$)	277	PO_4 (mg/L)	42

Results and remarks

Both Mangrove and Canna Indica grew during the experiment under leachate feeding conditions without evidence of toxic effects to be ascribed to leachate. (Figure 5.3.)

Both ammonia and COD removal efficiencies did not significantly differ between the two species and when comparing the main tests (M1-M3; C1-C3) with the control tests unplanted under same leachate irrigation (MCU; CCU). On the contrary, contaminants concentrations in leachate released by planted control tests irrigated with water (MCP; CCP) achieved the lowest values, demonstrating the low content of leachable contaminants in soil. Contaminants removal efficiencies (to be ascribed to the combined action of plants, microorganisms –rhizosphere- and soil) increased when leachate loads increased moving from about 40% to 80% for Ammonia and from about 65% to 80% for COD, both with Mangrove and Canna Indica (Figure 5.4.).

On the basis of experimental results, the following remarks were drawn:

- Both species demonstrated good tolerance to leachate up to ammonia nitrogen and COD concentrations of 385mgN/L and 3800 mgO_2/L, corresponding to a daily load of 385mgN/day and 3800 mg O_2/day. Further study is required to define the maximum input load that can be tolerated by both species.
- The soil had a predominant role in the contaminants removal process. Further study should investigate the use of inert material (sand or gravel) as supporting material for plants.

Figure 5.3. Canna Indica and mangrove plants at the end of the test.

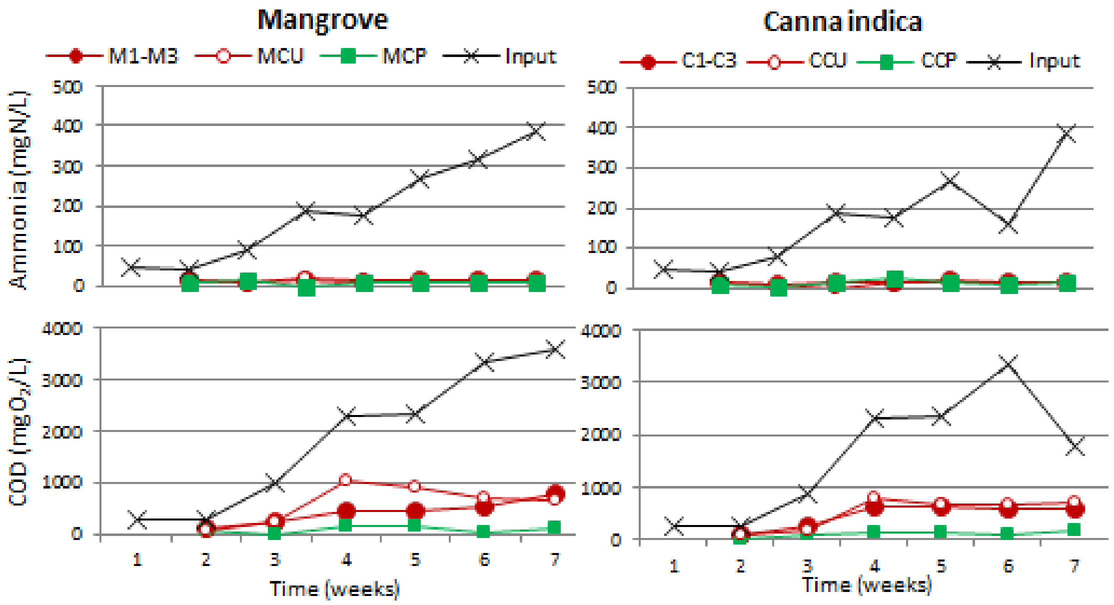


Figure 5.4. Ammonia and COD concentration from both Canna Indica and Mangrove tests measured in the feeding (Input), in the output from planted tests (M1-M3; C1-C3) and in the output of the control tests (planted: MCP,CCP; unplanted: MCU, CCU).

References

Alongi, D.M., Clough, B.F., Robertson, A.I., 2005. Nutrient-use efficiency in arid-zone forests of the mangroves Rhizophora stylosa and Avicennia marina. Aquatic Botany 82 (2), 121–131.

Banks, I.J., Gibson, W.T., Cameron, M.M., 2014. Growth rates of black soldier fly larvae fed on fresh human faeces and their implication for improving sanitation. Trop. Med. Int. Heal. 19, 14–22. doi:10.1111/tmi.12228

Diener, S., Zurbrügg, C., 2011. Black soldier fly larvae for organic waste treatment—prospects and constraints. Proc. … 52, 978–984.

Holguin, G., Vazquez, P., Bashan, Y., 2001. The role of sediment microorganisms in the productivity, conservation, and rehabilitation of mangrove ecosystems: an overview. Biol. Fert. Soils 33, 265–278.

Jones, D.L., Williamson, K.L., Owen, A.G., 2006. Phytoremediation of landfill leachate 26, 825–837. doi:10.1016/j.wasman.2005.06.014

Leung, J.Y.S., Cai, Q., Tam, N.F.Y., 2016. Comparing subsurface flow constructed wetlands with mangrove plants and freshwater wetland plants for removing nutrients and toxic pollutants. Ecol. Eng. 95, 129–137. doi:10.1016/j.ecoleng.2016.06.016

Newton, L., 2004. Using the black soldier fly, as a value added tool for the management of swine manure 36, 20–22.

Stegmann, R., 2018. Strategic issues in leachate management. In Cossu, R.; Stegmann, R. Solid Waste Landfilling, Concepts, Processes, Technology. Elsevier, 2018, ISBN: 9780128183366.

Tam, N.F.Y., Wong, A.H.Y., Wong, M.H., Wong, Y.S., 2009. Mass balance of nitrogen in constructed mangrove wetlands receiving ammonium-rich wastewater: Effects of tidal regime and carbon supply. Ecol. Eng. 35, 453–462. doi:10.1016/j.ecoleng.2008.05.011

Wu, Y., Chung, A., Tam, N.F.Y., Pi, N., Wong, M.H., 2008. Constructed mangrove wetland as secondary treatment system for municipal wastewater. Ecol. Eng. 34, 137–146. doi:10.1016/j.ecoleng.2008.07.010

Xu, Q., Tian, Y., Wang, S., Ko, J.H., 2015. A comparative study of leachate quality and biogas generation in simulated anaerobic and hybrid bioreactors. Waste Manag. 41, 94–100. doi:10.1016/j.wasman.2015.03.023

Yang, Q., Tam, N.F.Y., Wong, Y.S., Luan, T.G., Su, W.S., Lan, C.Y., Shin, P.K.S., Cheung, S.G., 2008. Potential use of mangroves as constructed wetland for municipal sewage treatment in Futian, Shenzhen, China. Mar. Pollut. Bull. 57, 735–743. doi:10.1016/j.marpolbul.2008.01.037

Ye, Y., Tam, N.F.Y., Wong, Y.S., 2001. Livestock wastewater treatment by a mangrove pot-cultivation system and the effect of salinity on the nutrient removal efficiency. Mar. Pollut. Bull. 42, 512–520. doi:10.1016/S0025-326X(00)00196-X

Zhang, J.E., Liu, J.L., Ouyang, Y., Liao, B.W., Zhao, B.L., 2010. Removal of nutrients and heavy metals from wastewater with mangrove Sonneratia apetala Buch-Ham. Ecol. Eng. 36, 807–812.

6. GENERAL CONCLUSIONS

Finding inspiration in the principles of the Blue Economy, this thesis work investigates alternative cost-effective solutions for extending the worldwide access to sustainable waste management systems.

Benefiting of an environmental sound SWM should be a universal human right even in those areas where economic and technical resources are restricted. Consequently, appropriate solutions should be low cost, simple in terms of design, construction and management, effective and sustainable, and should be included in a frame which promotes recovery and reuse of resources.

In any possible SWM strategy which respects these principles, landfilling plays a fundamental role either offering the opportunity to recover resources either closing the loop of the materials, which is important for controlling greenhouse gases emissions, the long term mobility of contaminants and the diffused pollution risks.

For this reason the work had a special focus on landfilling from a holistic point of view, investigating environmental, technical and economical sustainable solutions in terms of landfill management and emissions control.

A comprehensive study of the bioreactors landfills evaluated advantages and disadvantages of different types of bioreactors, providing a qualitative and quantitative comparison. Among the different sustainable landfill alternatives the semi-aerobic landfill resulted as a viable option for fulfilling the environmental, technical and economical sustainability requirements and innovative solutions have been investigated for optimising design and management under different situations.

The incidence of water availability and putrescible organic content in waste on semi aerobic landfill performance have been evaluated experimentally, on a lab scale. The study demonstrated the key role of these factors in controlling performance of semi-aerobic landfilling, in particular low water availability limits the biodegradation processes when dealing with low putrescible content waste, while high water availability and high putrescible content waste result in anaerobic processes affecting the quality of biogas and leachate emissions. Proper management of water input represents a fundamental tool in improving landfill performance.

To this regard the tropical dry-wet climate, the second most diffused climate worldwide, poses significant challenges for a proper semi-aerobic landfill management, being characterised by the alternating of dry (little or no precipitation) and wet seasons (heavy precipitations). An innovative dual step management has been suggested and investigated to overcome the issue of the rainfall seasonality, consisting in the storage of excess leachate during the wet season, which is then recirculated during the dry season in order to enhance the biodegradation activity and perform an in situ leachate treatment.

An important issue for the economic and technical sustainability of landfilling, is represented by leachate treatment, generally too complicate, too expensive and unsuitable to face long-term operational requirements. Within the concept of the Blue Economy, low-tech, cost-effective and sustainable technologies inspired by the nature might offer innovative solutions, such as the use of Black Soldier Fly (BSF) larvae. The first results proved that BSF are promising either in terms of treatment efficiencies and potential of resources recovery (proteins for animal feeding and fats for biodiesel production). Although the system was not effective on ammonia removal, a combination of BSF larvae with phytotreatment could promote a good control also of this parameter (Figure 6.1.). To this regards, the use of Mangrove in phytotreatment may offer the advantage of a high productivity, control of ammonia and huge tolerance to different stresses, such as high leachate salinity.

The potential use of mangroves for the phytotreatment of landfill leachate has been investigated in this thesis during a period of study at KUET University, Bangladesh, with encouraging results.

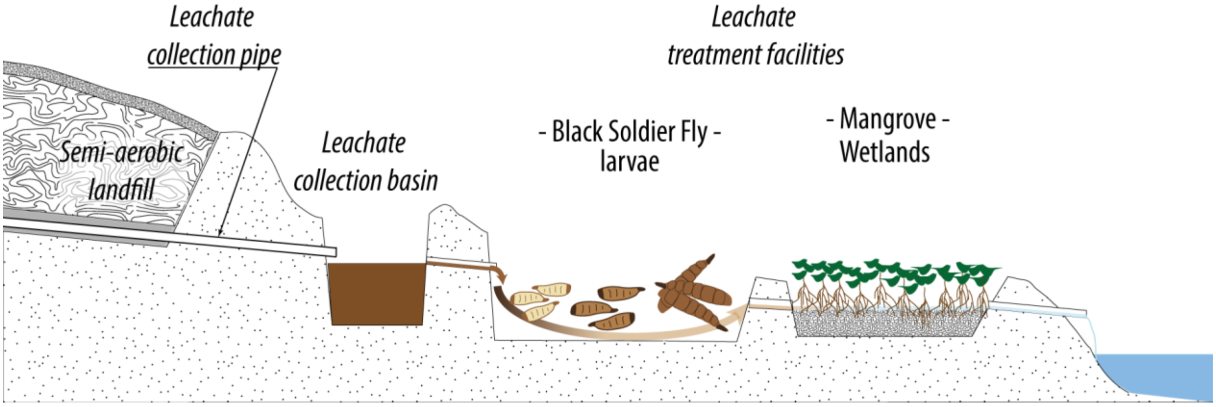


Figure 6.1. Scheme of the possible integration of the different studied technologies.

SECOND PART

List of publications

Paper I. From 3R to 3S: an appropriate strategy for developing countries

Lavagnolo, M.C., Grossule, V., 2018. From 3R to 3S: An appropriate strategy for Developing Countries. Detritus, Volume 04, 1-3. doi:10.31025/2611-4135/2018.13749

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CISA

Editorial

FROM 3R TO 3S: AN APPROPRIATE STRATEGY FOR DEVELOPING COUNTRIES

It is an acknowledged fact that the quality and generation rate of municipal solid waste (MSW) is largely linked to the lifestyle, welfare and cultural level of a society, with a production per capita ranging indicatively from 0.1 kg MSW/d in low income rural areas to 4.5 kg MSW/d in urbanized industrialised areas of the world (The World Bank, 2018). Social and economic development are even more crucial with regards to waste management strategies and related technologies, although a series of other factors may play an important role (availability of land and energy, climate conditions, education, public opinion attitude, etc.).

On an international level, the classification of countries with regard to their economic level of development remains an open issue, largely due to the difficulties in defining concepts such as poverty, financial constraints, and conditions of development. Not wishing to enter into a discussion on these aspects of classification, in this note the Authors focus on areas presenting jointly critical economic constraints and poor waste management systems. These areas are generally characterized by a fast-growing population, high level of urbanization, lack of modern infrastructures, highly inhomogeneous level of education, inadequate public administration, and frequent political instability. Areas featuring these characteristics can be identified with the so-called “Low Income Countries” but also with areas potentially present in countries with a more favourable classification.

In these areas waste management is generally characterized by the following features:

- Disposal facilities represented substantially by open dumps or poorly engineered and managed landfills;
- Uncontrolled waste burning;
- Widespread littering, very low waste collection coverage and precarious waste transport vehicles;
- Recovery of valuable waste resources by the informal sector (informal recycling and scavenging).

Under these conditions, environmental and health issues are of high concern (quality of drinking water, air quality, degradation of the urban environment, surface and ground water pollution, GHG (greenhouse gas) emissions, spread of infectious diseases, hazards for the scavengers, etc.).

Similar problems were also encountered in the past in wealthy, industrialized countries, although the situation has changed dramatically in recent decades due to the progressive increase of public awareness and perception of environmental issues, and scientific developments. These developments have focused prevalently on addressing a series of fundamental ecological issues (limited resources, climate change, widespread diffuse contamination, demographic growth, depletion of non-renewable energy sources, availability of land, etc.).

Nowadays, an environmentally-sound waste management system should satisfy the following requirements (Cossu, 2009a):

- Decrease in waste production;
- Efficient service of collection and disposal;
- Optimisation of material resource recovery;
- Minimisation of GHG emissions;
- Reduction of landfilled waste volumes;
- Optimisation of energy balance (reduction of energy consumption/waste to energy options);
- Reduction of emissions;
- Monitoring of toxicological effects and minimization of health risks, environmental sustainability.

These requirements should represent the conceptual guide for waste management in any corner of the world, irrespective of the level of economic development. Naturally, these requirements will need to be integrated into and evaluated in the various geographic contexts, taking into account economic, social and geomorphologic situations which may exert a strong influence on any choice.

The industrialized countries have attempted to meet the above-mentioned requirements by establishing a wide variety of approaches and technologies. Hierarchical Waste Management, zero-waste, Circular Economy, 3R (Reduce, Reuse, Recycle) are among the most popular concepts which currently contribute towards shaping national regulations. However, the practical application of these approaches has frequently been characterized by demagogueries, contradictory aspects, waste of economic resources, complicated and costly technologies, political speculation, misinformation of the public opinion, etc. (Cossu, 2009b, 2014, 2016, 2018).

Accordingly, the transfer of strategies and technologies from industrialized to developing countries should be carefully managed to avoid failures and mistakes and prevent export of outdated models or inappropriate or obsolete technologies.

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Transfer of proper management and technologies are generally hindered by several reasons:

- low education at different levels, resulting in unskilled technicians and widespread lack of environmental awareness;
- political instability with failure of long-term MSW management actions;
- MSW management is not always a high priority for local and national policy makers and planners;
- a scarce awareness of administrations with regard to the basic needs of the population and a lack of willingness to promote appropriate actions;
- ineffective institutional structures and pervasive corruption;
- inappropriate international funding and loans which support projects in the short-term, thus preventing the successful transfer of the project to the local authorities in the long-term;
- implementation of technologies of the highest standards, the operations of which are subsequently prevented due to lack of spare parts and/or well-trained personnel.

In line with the above considerations, when the circumstances are premature for the application of the 3R concept as part of a Circular Economy strategy, a 3S (Sanitisation, Subsistence economy and Sustainable landfilling) strategy should be implemented. The 3S approach, at variance with the 3R concept, is not perceived as a hierarchical structure, but rather is based equally on all three pillars (Figure 1).

Sanitisation aims to improve the standards of living in the country, achieving basic rules of hygiene in waste management.

In those countries in which people can count on a limited economical availability to support MSW tariffs, health and environmental protection constitutes a priority objective to be pursued beyond material and energy recovery. An inadequate waste disposal on the city streets entails a direct contact between wastes and the population. The population is therefore exposed to health issues including injury, diarrhoea, respiratory disorders and viral conditions, which are exacerbated by surface and groundwater contamination, air pollution from uncontrolled waste incineration, and soil contamination from leaching. The establishing of a stable waste collection system removes the waste from the residential areas, thus avoiding health issues. “Nothing is cheaper than not collecting solid waste” (Hoornweg et al., 1999).

Subsistence Economy is aimed at returning waste to the economy as a resource through the use of appropriate technologies, providing economic profits and new business opportunities and involving the informal sector activity in a remunerated and formalized way.

A robust and sustainable MSW management system should be designed and sized to meet local needs, at least over the medium-term. It should be resilient to political interferences and be flexible to further developments (e.g. market, technology, social). Custom-made technologies in line with social, cultural, economic and local requirements should be identified, being robust and well-proven, suited for management by local people.

Spontaneous recycling practices only occur when economically viable. Waste pickers worldwide are largely informal individual workers who are not supported by the government or included in insurance schemes or social welfare; they create an opportunity for self-employment in very difficult working conditions, strongly dependent on their capacity to sell collected material on a highly precarious market. In the presence of an informal sector, it is fundamental to involve these individuals in the operation of an MSW management system. The role of local authorities is critical in this context as solutions should be discussed and planned with the active involvement of the different stakeholders. Successful initiatives are represented by the organisation of informal recycler cooperatives (Gutberlet, 2015).

Sustainable Landfilling is needed to safely dispose of residues devoid of any economical or technical value.

Open dumps still constitute the most prevalent type of disposal facilities in developing countries, entailing a low level of technology and operational cost requirements. Open dumps are characterised by a lack of barriers for leachate containment and biogas control, uncontrolled waste discharge, presence of scavengers and uncontrolled waste burning to reduce the waste volume. This type of disposal results in environmental and health risks. Although awareness is increasing amongst both the public and politicians with regard to this dangerous situation, it is still insufficient and the achievement of sustainability remains a crucial challenge. Sustainable landfilling should be designed to reduce the emission potential in the long-term and to achieve an acceptable equilibrium with the environment within the span of one generation (30-40 years). In the presence of limited technical and economic situations, the following aspects should be integrated: low cost solutions in terms of development, operation and maintenance; simple, easily-implemented technologies, and maximum utilisation of natural resources and in situ materials (Lavagnolo M.C., 2018).

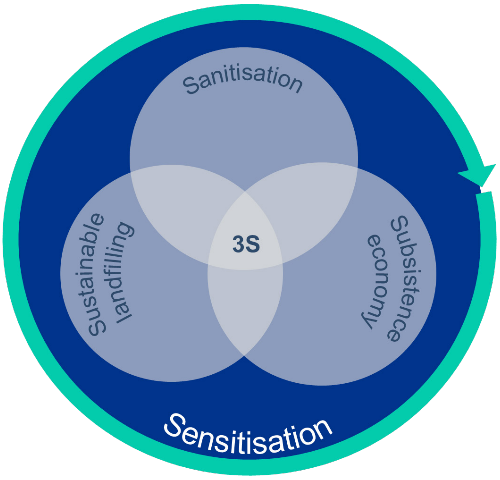

FIGURE 1: Graphical scheme of the 3S model proposed as a strategic tool to address the actual requirements of waste management in areas with economic constraints.

Sanitisation, Subsistence economy and Sustainable landfilling should be considered as complementary principles, the integration of which is strongly advocated. Sanitisation cannot be achieved in the absence of safe allocation of the collected waste. The recovery of valuable resources, which are removed from the main waste stream, reduces the volume and improves the quality of the disposed waste (e.g. treatment of food waste by means of composting or anaerobic digestion), thus promoting the landfill sustainability concept. Simultaneously, the safe disposal of worthless materials is ensured by Sustainable landfilling. Waste collection and organisation of the informal sector must be designed so as to achieve both sanitisation and recovery of valuable materials, thus supporting the local trade sector.

An essential tool for ensuring the successfullness of the whole 3S strategies is represented by the *Sensitisation* process of the local human resources.The lack of awareness of the stakeholders, mainly population and administrators, may lead to the absence of an active participation and to the inevitable failure of any attempt at implementing a sustainable SWM system. An educational program should be carried out throughout the entire process, at different levels (schools, public administration, workers, citizens, etc.) using all media supports in order to reach the highest number of people (educational activities with children, local radio, social media by electronic devices, social events involving the community, seminars, etc.) An example of a successful initiative is represented by the establishment of a literary cafè in Youndé (Cameroun) as a meeting point for the sharing of knowledge and points of view on sustainable waste management (Lavagnolo and Failli, 2018).

Low income countries are in an ideal position to advance the most modern ideas in waste management, particularly by learning from the mistakes of the "developed" world. Indeed, in the near future we might reach the paradoxical realisation that a rich country is in many ways poor and, vice versa, a poor country is in many ways rich.

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REFERENCES

Cossu, R., 2009a. Driving forces in national waste management strategies. Waste Manag. 29, 2797–2798. doi:10.1016/j.wasman.2009.08.002

Cossu R., 2009b. From triangles to cycles. Waste Management, 29, 2915–2917

Cossu R., 2014. Collection of recyclables does not need demagoguery. Waste Management , 34, 1561–1563

Cossu R., 2016. Back to Earth Sites: From "nasty and unsightly" landfilling to final sink and geological repository. Waste Management, 55, 1–2

Cossu R., 2018. Landfilling or biking? Detritus, 2, 1-2

Gutberlet, J., 2015. Cooperative urban mining in Brazil: Collective practices in selective household waste collection and recycling. Waste Manag. 45, 22–31. doi:10.1016/j.wasman.2015.06.023

Hoornweg, D., Thomas, L., Otten, L., 1999. Composting and its applicability in developing countries, urban waste management. Working Paper Series No. 8.

Lavagnolo M.C. (2018). Landfilling in developing Countries. In Cossu R., Stegmann R. "Solid Waste Landfilling", Elsevier Publisher (in press).

Lavagnolo M.C., Failli S. (2018). A literary Café in Yaoundé, Cameroun. Detritus, 1, I-III. doi:10.26403/detritus/2018.25

The World Bank, 2018. What a Waste 2.0. doi:10.1596/978-1-4648-1329-0

Paper II. Sustainable low-cost waste management: learning from airlines

Cossu, R., Grossule, V., Lavagnolo, M.C., 2019. Sustainable low-cost waste management: learning from airlines. Detritus, Volume 06, 1–3. doi: 10.31025/2611-4135/2019.13818

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Editorial

SUSTAINABLE LOW-COST WASTE MANAGEMENT: LEARNING FROM AIRLINES

Waste management around the world is characterised by a very wide range of levels of technology and service efficiencies. Clearly, socio-economic conditions (such as financial resources, technical education, infrastructures, etc.) are the main issues at the basis of these differences, manifested not only between industrialised countries and developing countries (DCs) but also within the same administrative areas, as is the case of the European Community (World Bank, 2018; Eurostat, 2019).

However, many other factors contribute towards these differences, including:

- Population density. This has a marked effect on waste quantities and, consequently, collection programs and volumes required for treatment and disposal of the waste. Indeed, the latter represents the main driving force for incineration as a prevailing waste management option in countries such as Japan, Singapore, Switzerland and many others, (Cossu, 2009).
- Waste quality. All decisions, any criteria, and recycling programmes in waste management are heavily based on this factor. Aspects such as presence of hazardous substances, their concentrations, purity of waste fractions might originate different solutions.
- Market for recycled waste fractions. This factor is closely linked to the industrial and socio-economic organization of the specific geographic area and to the local demand for products and services.
- Specific local situations (climate, topography, infrastructure, land planning, culture, etc.).
- Regulations. These may be of a varying nature (recommendation, address, prescription, etc.) and are capable of creating marked differences between one country and another.

This picture is further negatively complicated by the transfer of inappropriate technologies from one country to another. Traditionally (and still persisting today!), this issue was confined to developing countries where the implementation of advanced technologies designed in (and for) industrialised countries may prove inappropriate for various reasons (complexity, maintenance, lack of professional education and skilled technicians, operational costs, infrastructures, etc.), as widely highlighted in the literature (i.a. Grossule and Lavagnolo, 2018). However, improper use of technologies is also encountered in industrialised countries. In this case, the main factors impeding the use of specific technologies include an inadequate maturity of the technology, a non-homogenous waste quality and operational costs (energy and staff), in addition to a series of regulatory and bureaucratic issues. As an example, management problems experienced at several pyrolysis and gasification plants operated in Europe, including the lack of an adequate commissioning phase and survey of local conditions, are widely acknowledged.

Moreover, the transfer of inappropriate technologies may contribute towards creating so-called “Cathedrals in the desert”, i.e. oversized facilities which are disconnected from the local reality, uneconomical, useless and frequently totally abandoned.

In numerical terms, more than 50% of global MSW production is still dumped or poorly landfilled, while the rest is treated using a series of different technologies (sanitary landfilling, recycling, anaerobic and/or aerobic stabilization, etc.) (World Bank, 2018), some of which may prove to be considerably complex and expensive. It was Laila Iskandar, working with the poor Zabbaleen recycling communities in Cairo, who famously said that, “waste management is far too important to be left to engineers; they build facilities which look like 4-star hotels”.

Despite this inhomogeneous scenario in global waste treatment, the aims and objectives of a modern waste management strategy tend to align and coincide throughout all corners of the world.

This indeed represents the positive result achieved by an impressive growing globalization and consequent diffusion of culture and science, supported by the Internet, the media, conferences, scientific journals, common publishing targets in academic career, and exchange of scholars and students.

The aims and objectives of a modern waste management strategy can be summarized as follows:

- Industrial production with minimisation of waste generation by contrasting planned obsolescence, avoiding disposable goods and extending producer responsibility;
- Design and production of goods which promote reuse and facilitate recovery and recycling;
- Source segregation and reuse of waste fractions;
- Environmentally-sound waste collection programmes;
- Optimisation of consumption and recovery of energy and material resources from unavoidable waste;
- Sustainable management of recycling residues with

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control of contaminants and hazardous substances (this aspect is frequently underestimated in circular economy strategies);

- Adoption of a combination of technologies to synergise advantages (thermal treatment for combustibles, biological treatment for putrescibles, stabilization of mobile contaminants and sustainable landfill sinking);
- Control of short- and long-term emissions, prevention of diffuse emissions and control of greenhouse gasses (GHGs);
- Minimisation of health risks while paying strong attention to the public opinion and perception;
- Scientific monitoring of ecotoxicological effects arising from WM.

Based on the previously illustrated discrepancy between the inconsistent global WM scenario and the common views in modern WM strategies, in order to progress from the fictitious to reality, the following needs should be addressed:

- Increase in access worldwide to an appropriate waste management system;
- Pursuit of the aims and objectives of a modern waste management system by adopting affordable low cost solutions, with minimal expenditure of energy and material resources.

By successfully fulfilling these needs it may seem as though you are squaring the circle.

However…. airlines have already done something similar!

In the not so distant past, flying was a privilege reserved for the wealthy. The availability however of fast-moving transport solutions represented a common interest for an increasing number of individuals.

It could indeed be argued that an identical discrepancy is encountered in waste management globally!

Of course, nowadays a lot more people can afford to travel by plane at a reasonable cost in safe conditions. The way in which this has been achieved should be an inspiration for the waste management world, merely in terms of analogy. Consequently, indirect disadvantages linked to the fact that transport is the fastest growing source of greenhouse gas emissions in the world, and that airline travel is a major part of this increase, are not considered here.

An overview of the main reasons underlying this success, focusing mainly on European low cost airlines which have successfully developed budget flight models, is given in Table1.

All features are substantially aimed at saving time and cutting costs, while at the same time guaranteeing rigorous safety conditions.

Leaving behind the airline metaphor, the following list of possible options could be taken into account for the purpose of turning solid waste management into a low-cost efficient system:

a) Any decision in WM should be based on a thorough and updated knowledge of waste quality variation in space and time; incredibly, this aspect is often neglected, resulting in inappropriate solutions and related costs;
b) Flexible strategies linked to the local situation (e.g. refraining from conducting source segregation and separate collection of a specific fraction in the absence of an end user at a convenient distance);
c) Recycling programs should not defer to moralistic principles but should rather be based on urban mining concepts (recovery of resources should be reliable, realistic, affordable, with no demagoguery, economically and environmentally convenient);
d) Separate collection should not strive to achieve percentages in terms of amount of collected materials but rather in terms of quality of recycled material (collect less but of a better quality);
e) Organised involvement of the informal sector, associations, NGOs, etc.;
f) Simple technologies of proven efficiency should be preferred;
g) Technologies should be suited to the specific local conditions;
h) The same technology should be implemented throughout a given geographical area or country with the aim of saving on maintenance costs (spare parts supply, staff training, etc.);
i) In some specific situations the acquisition of services provided by experienced enterprises might be preferred over the direct acquisition and operating of facilities;
j) The so-called “Blue solutions” should be applied wherever possible, based on the principle whereby there is no need to spend/invest more to protect the environment, but rather lessons should be learned from the environment and from what nature has already created in order to establish new business and social capital;
k) A holistic approach should be adopted in spreading resources among the different WM steps (collection, transport, treatment, disposal);
l) Integrated approach to WM technologies with no ideological preclusion (shrewd combination of recycling, landfilling and thermal treatment) ;
m) The convenience of material suppliers should be assessed in terms of transportation (zero km, repercussion on the community), use of resources (lower production of CO^2, renewable energy, possibility of constant supply) and economic impact;
n) Economic return should be ensured through synergies with other economic/social activities (informal sector, recycling, reuse, etc);
o) Particular focus should be placed on the recycling of putrescible fractions prior to landfilling. Biological stabilization of residual putrescibles by in situ treatment should be opted for over expensive mechanical-biological off-site pre-treatment;
p) Landfill technologies should aim to drastically reduce the abuse of expensive geosynthetics, by substituting these with equivalent low-cost products (natural materials, suitable residues, etc.) when conveniently available locally;
q) Following traditional biological treatment, there is no need to remove residual COD, mainly made up of humic substances, from the treated MSW leachate. Requirements to comply with discharge standards set below

TABLE 1: Overview of common features in low cost airline models and in the perspective of a low cost waste management system. LCC= Low cost carrier.

Features	Adopted measures by LCC	Potential measures in WM
No luxury or high cost items	• No video entertainment, thus no TV set and no operation of a central audio or video station	a), b), c), f), g), k), l), o), p), q), r)
Wise spending strategies	• Well-proportioned fleet • Bulk buying of same model of aircraft • No frills on board	a), b), c), d), g), h), k), l), m), o), p), r), s), v), w)
Simplified and standardized technical solutions	Same reliable and well proven aircraft models: • Easy management and maintenance (professional staff are trained on the same vehicle) • More convenient supply and storage of spare-parts • Increased crew flexibility	c), f), j), h), o), q), t), u)
Simplified operation	• Non-reclining seats (cheaper to buy and maintain • No back pockets (less time for cleaning)	d), f), i), h), m), q), r), s), t)
Staff saving	• Young motivated staff • Simplified training scheme (same aircraft model) • Multi-tasking staff	e), h), i), k), n), t), u)
Extra revenue generation	• No free on-board services • Some companies offer lottery tickets • Separate fees for checked-in luggage and extra bags on board • Payment for seat reservation	b), d), e), j), n)
Siting	Small airports: • Low fees • High negotiation power	h), g), k), m), o), s), v), w)
Energy saving	Young aircraft fleets • Baggage weight restrictions	c), d), j), m), q)
Intense use of the facilities	• Aircraft are used almost non-stop with rapid changeover times • Aircrafts return to the home hangar • Overnight maintenance	h), i), o), u), k)
Minimum overhead	• Fuel bought in favourable market periods • Direct online booking only	j), m), n), p)
Time management	• Every effort is made to reduce operation time • On time flights promote the company image	b), h), i), m), o), p), t), u), v), w)
Safety	• High safety records (money saving and good image)	i), j), m), t), u), v), w)

150 mg/L for COD, generally based on Reverse Osmosis, should not necessarily be adopted;

r) Waste management should not be overregulated (as occurs increasingly in numerous industrialised countries) as this may represent an obstacle to a virtuous waste management strategy, in both economic and technical terms;

s) Regulations should be flexible, open to significant innovative scientific development and compatible with specific local situations;

t) Science-driven educational WM programs in schools and universities should be increased, accessible to all, including local administrators;

u) Standardised and simplified operational and maintenance manuals should be provided to all technical staff;

v) An organised reasonable involvement of stakeholders in taking decisions prior to implementation of WM strategies might avoid costly opposition and protests afterwards;

w) Communication tools aimed at contrasting potentially misleading fake news (possibly resulting in unnecessary opposition by the public and related costs) should be developed.

To conclude, low cost strategies do not necessarily imply a reduced performance in protecting the environment and the public health; they should however represent a cost-effective solution intended to extend access of the populations worldwide to sustainable waste management systems.

Squaring the circle? Prepare for take-off!!!

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REFERENCES

Cossu R. (2009). Driving forces in national waste management strategies, Waste Management 29, 2797-2798

Eurostat (2019) waste statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics (Accessed on the 15th, June, 2019).

Grossule V., Lavagnolo M.C. (2018). From 3R to 3S: an appropriate strategy for developing countries. Detritus, 4, 1-3. https://doi.org/10.31025/2611-4135/2018.13749 © Cisa Publisher. Open access article under CC BY-NC-ND license

Kaza S., Yao L. C., Bhada-Tata P., Van Woerden F. (2018). What a Waste 2.0 : A Global Snapshot of Solid Waste Management to 2050. Urban Development; Washington, DC: World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/30317

Paper III. Bioreactor landfills: comparison and kinetics of the different systems

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BIOREACTOR LANDFILLS: COMPARISON AND KINETICS OF THE DIFFERENT SYSTEMS

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ABSTRACT

The need for more sustainable landfilling has increased interest in bioreactor landfills as a suitable tool for optimising degradation processes. Bioreactors can be categorised as follows: anaerobic, aerobic, semi aerobic and hybrid. The choice of a specific bioreactor can be strongly influenced by the desired treatment objectives (i.e., energy recovery, increased rate of waste stabilisation, washing) as well as by the specific site conditions (e.g., waste characteristics, climate and social/economic situation, regulations). However, the increased rate of waste stabilisation should be the primary driving principle in the bioreactor landfill design (Cossu, 2010). Full-scale bioreactor landfills are still uncommon and one of the reasons is the perception that the effectiveness of this technology is not well demonstrated. This paper aims to contribute to filling this knowledge gap by analysing and comparing the lab scale applications of different types of bioreactors available in the literature and providing a survey of the different methods by considering their respective advantages and disadvantages. Qualitative analysis of the main types of bioreactor landfills is provided according to a few selected characteristics (i.e. energy recovery, biochemical kinetics, technological complexity, costs). Considering landfill sustainability, the discussion is primarily focused on the quantification of the stabilisation capability of the different bioreactors which is calculated in terms of COD and ammonia removal kinetics. The results demonstrate that the optimisation of COD removal kinetics is the highest in aerated bioreactors, while ammonia removal kinetics is maximum in hybrid bioreactors (i.e., 6 and 10 times higher, respectively, compared to the anaerobic bioreactors).

1. INTRODUCTION

Although recent legislation tends to limit landfilling as much as possible, it will continue to play a key role in future modern solid waste management systems (Cossu, 2012). Even with circular economy thinking, the zero-waste concept cannot currently be realistically achieved and a final disposal step is needed for residues that cannot be technically or economically exploited. Landfilling assumes the role of providing a final sink to close the loop in the material cycle in order to isolate, from the environment, concentrated residual waste that are no longer usable. In particular sustainable landfilling has been introduced as a system that should be operated in such a way to minimise the emissions potential by achieving waste stabilisation as quickly as possible in order to preserve the next generations from potential environmental risks and remediation costs.

From an environmental and health point of view, the most problematic issue dealt with in a landfill system is the putrescible fraction of waste. This fraction is responsible for the main long-term impacts, including methane and carbon dioxide emissions (contributing to the greenhouse effects and ozone depletion) and leachate emissions resulting in surface and groundwater pollution as well as soil pollution. In order to achieve the sustainability requirements, several strategies can be adopted to control the effects caused by the landfilling of biodegradable waste. These control strategies can be implemented before landfilling by means of the diversion of the putrescible fraction from the waste stream going to the landfill (separate collection), thermal or mechanical/biological pre-treatment and washing of the waste, and during the operational and/or aftercare phases by using in-situ treatments approaches.

Among the other solutions, the need for the implementation of innovative landfill management techniques has increased the interest in bioreactor landfills as a viable in-situ treatment tool (Cossu, 2012; Reinhart et al., 2002).

A bioreactor landfill is typically defined as a system purposely planned and operated for the in-situ treatment

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of degradable waste with the aim of enhancing conversion processes. The possible in-situ measures include injection of air and/or water, leachate recirculation, and other combinations of in-situ treatments. These treatments create a more suitable environment for degradation processes by controlling biochemical kinetics, nitrification, moisture content, pH, redox conditions, and gas emissions.

Moisture control particularly supports the metabolic processes, nutrients transport, microorganisms movement, and dilutes high concentration of inhibitors, while air injection speeds up the biodegradation processes and allows for the removal of nitrogen compounds (Cossu et al., 2003; Ritzkowski and Stegmann, 2013).

Bioreactor landfills can have several advantages over conventional landfills, from both an economic and environmental point of view:

- Reduce environmental impacts, by improving leachate quality and controlling landfill gas (LFG) emissions;
- The aftercare time is generally shorter due to the increased stabilisation rates therefore reducing aftercare costs and returning the site for different uses in a shorter timeframe;
- The leachate treatment is cheaper, since the in-situ treatment enhances leachate quality;
- The landfill gas (LFG) generation in an anaerobic bioreactor is enhanced;
- Refuse settlement and density are increased while less post-closure care operations are necessary (Berge et al., 2005; Omar and Rohani, 2015; Price et al., 2003; Warith, 2002).

On the other hand, a bioreactor landfill can have some disadvantages such as increased odours, physical instability of the waste mass due to the increase in moisture. Moreover, the need for aeration and/or leachate recirculation may increase capital and management costs.

According to the process, landfill bioreactors can be divided into four main types: anaerobic, aerobic, semi aerobic and hybrid. The hybrid bioreactor is a sequence of aerobic and anaerobic conditions (EPA, 2018a; Omar and Rohani, 2015).

Landfill bioreactors were mostly operated under anaerobic conditions (Price et al., 2003; Valencia et al., 2011; Vigneron et al., 2007) improving the methane generation rate, leachate quality, and reducing the period needed for long term maintenance and monitoring through recirculation, compared to traditional anaerobic landfills (Christensen, 2011). However, ammonia accumulation in leachate and the landfill body still remains one of the main challenges in anaerobic bioreactors. Furthermore, the anaerobic degradation process is still very slow.

According to the sustainable landfilling concept, the aerobic process is considered to be a better alternative to the traditional anaerobic landfills (Nikolaou et al., 2009; Read et al., 2001). Nevertheless, aerobic landfills are not always technically and economically feasible due to the need for forced ventilation systems, complex operation and management, and large energy consumption which translates to high operating and capital costs (Slezak et al., 2015). In order to overcome the cost disadvantage of forced aerated systems, the semi-aerobic landfill could be considered as an alternative solution to the aerated system (forced aeration). The semi-aerobic landfill aims to achieve aerobisation of the waste mass with a proper engineering design in which the ambient air naturally flows into the waste mass through leachate collection pipes, moved by the temperature gradient between the inside and outside of the landfill (Hanashima et al., 1981; Theng et al., 2005). Although developed at the Fukuoka University more than 20 years ago, this method is not widely spread around the world but field tested in Japan and in different on-going pilot projects in Italy, Pakistan, Iran, Nepal, Thailand, Malaysia, China, Vietnam, Samoa, and Mexico (Ministry of the Environment (Japan), 2018; JICA, 2004).

A limiting factor of aerobic bioreactors is the potential for complete inhibition of methane generation leading to the absence of any energy recovery. More recent developments have been shown in hybrid bioreactors, which are operated under various combinations of aerobic and anaerobic conditions (He et al., 2011; Long et al., 2009b; Sun et al., 2014; Xu et al., 2014). In a hybrid system, aerobic and anaerobic conditions can be purposely alternated to enhance the methane production for energy recovery and to achieve relatively faster waste stabilisation, facilitate conditions for nitrification and denitrification, improve leachate quality, reduce treatment costs (Berge et al., 2009), and potentially fulfil sustainability requirements. Bioreactor landfills are in some cases more economically advantageous than a traditional landfill (Berge et al., 2009; Hater et al., 2001; Theng et al., 2005), when accounting for landfill space recovery and a reduction in the post-closure care period (Anex et al., 1996).

A bioreactor landfill can also be operated as a flushing bioreactor. In a flushing bioreactor a large volume of water is applied in order to wash-out soluble waste constituents and accelerate waste stabilisation processes (Christensen et al., 2011). The magnitude of the flushing process is defined by the liquid to solid (L/S) ratio and according to Walker et al. (1997) the passage of approximately 4.6 times the bed volume of fluid is required to reduce leachate concentrations by two orders of magnitude, corresponding to a L/S ratio of ~3 m^3/t (Hupe et al., 2003; Christensen, 2011). However, the flushing process is strongly influenced by the solubility of various compounds in leachate (ammonia (NH_4), chemical oxygen demand (COD), Na, and Cl) (Christensen et al., 2011). Overall costs for this type of bioreactor may be two to four times higher than a conventional landfill (Karnik and Perry, 1997; Reinhart et al., 2002). Moreover the hydrodynamics of a landfill limits in time the potentialities of the flushing process. The high-water quantity addition increases the density of the waste, the hydraulic conductivity decreases and the short-circuiting phenomena tends to dominate with a limited portion of bulky waste subjected to water flow (Karnik and Parry, 1997; Walker et al., 1997).

The choice of the bioreactor landfill type is driven by the specific treatment objective to be achieved (e.g., energy recovery from landfill gas and/or leachate quality improvement) as well as by specific site conditions, such as waste characteristics, climate, and the social/economic situation. However, the sustainable landfill concept should be the driving principle in the bioreactor landfill design in order to assure the capability of achieving faster waste stabilisation (Cossu, 2010).

Several bioreactor landfill types have been successfully applied with promising results at lab or pilot scale, but full scale bioreactor landfills are still uncommon. The reasons for the lack of full scale systems are on one hand the regulatory constrains and on the other the technical complexity and cost investment associated with poorly demonstrated processes (Reinhart et al., 2002). This paper aims to review the state of the art bioreactor landfill research and elaborating on data to quantify the different kinetics with the goal of increasing the knowledge of bioreactors performances and potentialities.

Several literature lab-scale applications of different bioreactors have been analysed, compared, and an overview of different types is provided. The paper proposes a possible classification of the bioreactors, grouping them according to the main bioreactor types in literature, in order to simplify the bioreactors discussion. Advantages and disadvantages are discussed for each bioreactor category, although specific bioreactor performance should be considered individually. A qualitative analysis is then provided that takes into account some selected characteristics that are useful for the deciding on a specific bioreactor type such as methane production and energy recovery, biochemical kinetics velocity, nitrogen removal, technological complexity, and maintenance and leachate treatment costs. The ability for a bioreactor to achieve waste stabilization was quantified by the authors by mean of first-order kinetics which was determined by the approximation of the overall removal process of the selected relevant contaminants.

2. DATA COLLECTION AND ELABORATION METHODOLOGY

To provide an overall qualitative analysis of the different bioreactors types lab-, pilot- and full-scale applications of landfill bioreactors were considered. In order to quantify the stabilization performance and sustainability of the different systems, further and much more specific elaboration has performed based on lab-scale applications. Results from these studies have been published since 2005.

Variation kinetics of organic and nitrogen concentrations in leachate have been selected as criteria for the evaluation of the bioreactor stabilization performance (Ritzkowski et al., 2006) through the approximation of the combination of all the different processes involved in the stabilization of the bioreactor (e.g., biodegradation, flushing, volatilisation, etc.) in order to determine the overall first-order kinetics. These first-order kinetics were used for representing the removal process of the considered contaminants.

First-order kinetics (Heimovaara et al., 2014) for COD and ammonia conversion processes was performed by extrapolating the concentration values from graphs through the use of dedicated Matlab code and calibrating the following first-order kinetic equation:

$$C_t = C_{peak} * e^{-kt}$$

where:

C_t = concentration of considered contaminant at time t [mg/L];
C_{peak} = peak concentration [mg/L];
k = kinetic constant [d^{-1}];
t = time of process [d]

This equation is a strong approximation for a complete landfill simulation test (Fellner et al., 2009; Morello et al., 2017), but is acceptable for a qualitative discussion of the results of the investigated lab-scale tests. The concentration are clearly influenced by the water addition, but information about L/S ratio or water input were not clearly expressed in most of the cited papers. Starting from the data collection of the gas composition of the different bioreactors types, data elaboration has been performed in order to provide a graphical representation of the typical quality of the gases generated under different process conditions.

3. DISCUSSION

The results obtained from the leachate and gas literature data elaboration are presented in Table 1 and Figure 1. Peak and final concentrations (C_{peak} and C_{end}) of the considered contaminants in leachate are summarized in Table 1 for each analysed case study including the Putrescible Organic Fraction (POF) content of the studied waste. The C_{peak} has been considered as the beginning of the contaminant removal process, while the fraction of time required to reach the C_{peak} has been defined as Lag phase and has been indicated as the fraction of the whole experiment. COD and ammonia first-order kinetics have been calibrated to represent the contaminants removal process. In case where ammonia removal processes were not present, the related kinetics were not calculated.

Figure 1 summarises the typical composition of landfill gases under anaerobic, semi-aerobic, and aerobic conditions.

According to the U.S. EPA (2018), the contribution of landfills to the total non-CO_2 GHGs emissions will count for approximately 7% of the total GHGs emissions worldwide by 2030. The quality improvement of landfill gas represents a current challenge to limit the impact of landfills on climate change. The GHGs from landfill consist of primarily CO_2 and CH_4, along with several other trace gaseous components, such as non-methane volatile organic compounds (NMVOCs), nitrous oxide (N_2O), nitrogen oxides (NOx), and carbon monoxide (CO). But only CH_4 is counted towards a landfill's contribution to the GHG emissions (IPPC, 2006), being the most significant among the other emissions. In this study, the improvement of landfill gas quality performed by the landfill bioreactors has been considered only in terms of CH_4 reductions. Nitrous oxide emissions can become an issue when bioreactor landfills are implemented, since both leachate recirculation (Price et al., 2003; Vigneron et al., 2007; Watzinger et al., 2005)

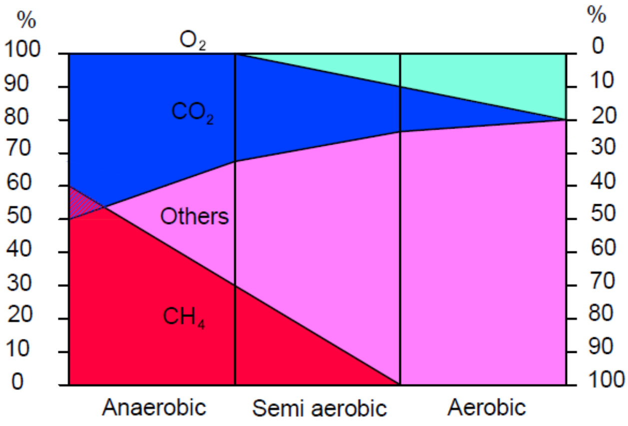

FIGURE 1: Composition of landfill gases in anaerobic, semi-aerobic and aerobic lab-scale bioreactors (Graph adapted using data from Ahmadifar et al. (2016), Borglin et al. (2004), Cossu et al. (2016, 2003), de Abreu et al. (2005); Erses et al. (2008), HUANG et al. (2008), Huo et al. (2008), Kim (2005), Nikolaou et al. (2008), Shao et al. (2008), Slezak et al. (2015), Sutthasil et al. (2014), Yang et al. (2012)).

and aeration (Berge et al., 2006; Powell et al., 2006; Tsujimoto et al., 1994) may induce N_2O production. N_2O production can result both from partial nitrification and partial denitrification (Mummey et al., 1994; Venterea and Rolston, 2000). Particularly, depending on the concentration of oxygen, the presence of oxygen during denitrification or oxygen below optimal levels during nitrification may result in the production of N2O (Berge et al., 2006; Khalil et al., 2004). A detailed study on the effects of the combination of the leachate recirculation and landfill aeration has been carry out by He et al. (2011). This study demonstrated the occurrence of N_2O under different leachate recirculation and aeration conditions. However, results showed that the conversion of the total nitrogen added to columns into N_2O occurred at a maximum of 0.18% and the significant reduction in nitrogen mass was mainly due to the production of N_2. Moreover, although some N_2O has been detected in several lab scale tests, the complete reduction of N_2O to N_2 can be expected within a full-scale landfill, due to the longer retention time of the gas (Price et al., 2003). Landfill N2O is considered globally negligible, although these emissions may need to be considered locally in case of aerobic/semi-aerobic bioreactor landfill.

3.1 Anaerobic bioreactor landfills

The anaerobic landfill bioreactor is the most common application of bioreactor systems where the biological degradation is enhanced by means of leachate recirculation and has been applied since the 80s at several landfills in USA (Reinhart et al., 2002). The literature review of several lab-scale tests identified the peculiarities which are typical in all anaerobic bioreactors, regardless of the differences in the putrescible waste content. In particular the maximization of carbon removal occurs when methanogenesis starts. Once methane gas production increases, the concentrations of COD, five-day biochemical oxygen demand (BOD_5), and volatile fatty acids (VFAs) decrease and a subsequent rise in pH to the ranges of 6.8-8 is observed. The BOD_5/COD ratio decreases from 0.8-0.4 to 0.4-0.1. The typical gas composition during the methanogenic phase shows between 30-60% CH_4 and 30-50% CO_2 (v/v) (Figure 1). These values are consistent with interstitial gas concentration in full-scale landfill bioreactors during the stable methanogenic phase (Raga and Cossu, 2014; Ritzkowski and Stegmann, 2007).

The main benefits associated with anaerobic bioreactors are both the increase in methane generation and the improvement of leachate quality compared to traditional landfills (Filipkowska, 2008; Read et al., 2001; Sanphoti et al., 2006). Sanphoti et al. (2006) compared the cumulative methane generation in anaerobic bioreactor with a traditional landfill. Anaerobic bioreactors with and without water addition generated 17 L_{CH4}/kg_{TS} and 54.9 L_{CH4}/kg_{TS}, respectively, while only 9 L_{CH4}/kg_{TS} was produced in a traditional landfill simulation.

Despite the proven advantages associated with the anaerobic bioreactor compared to the traditional landfill, anaerobic bioreactors represent the least preferable option compared to the other bioreactor types when considering the concept of sustainability. The slow anaerobic degradation is confirmed by the lower COD and ammonia removal kinetics compared to other bioreactors (Table 1) which leads to contaminant emissions lasting for several decades in case of landfill gas and even for centuries in case of leachate (Rich et al., 2008; Ritzkowski et al., 2006). In particular the treatment of nitrogen in leachate remains to be the major challenge in aftercare, which is limitedly removed by flushing processes. Moreover leachate recirculation can even enhance ammonification, resulting in an increased ammonia concentration compared to traditional landfills (Berge et al., 2006; Long et al., 2009a; Price et al., 2003). This increase often causes the partial or complete inhibition of methane production, increases the costs for leachate treatment, and may create a significant long-term impact (Cossu et al., 2016).

Slow degradation rates and ammonia persistence puts the anaerobic bioreactor far from meeting sustainability requirements, threatens the public health and the environment over the long term and increases the costs associated with aftercare (Berge et al., 2006; Giannis et al., 2008; Read et al., 2001). Moreover, considering that a robust gas collection system is required in order to achieve a high collection efficiency, this infrastructure is not always technically and economically feasible in particular in developing countries (Sutthasil et al., 2014).

3.2 Aerated bioreactor landfills

Bioreactor landfills can be treated aerobically by injecting air in order to create an aerobic environment within the waste mass and to promote the growth of aerobic microorganisms. According to Ritzkowski and Stegmann (2012), different technologies and strategies have been developed for in-situ aeration, such as high pressure aeration, low pressure aeration, and active aeration with or without off-gas extraction.

One of the first experiments on aerobic stabilization of municipal solid waste (MSW) was carried out by Stessel and Murphy (1992) to define the optimum air injection and

TABLE 1: Description of the sample (with respect to the year of the provider change).

Parameters	POF % wet weight	ANAEROBIC					AEROBIC					SEMI AEROBIC					HYBRID					REFERENCE
		C_{peak} (g/L)	C_{end} (g/L)	Lag phase %	Test duration (d)	k ·10^{-2} (d^{-1})	C_{peak} (g/L)	C_{end} (g/L)	Lag phase %	Test duration (d)	k ·10^{-2} (d^{-1})	C_{peak} (g/L)	C_{end} (g/L)	Lag phase %	Test duration (d)	k ·10^{-2} (d^{-1})	C_{peak} (g/L)	C_{end} (g/L)	Lag phase %	Test duration (d)	k ·10^{-2} (d^{-1})	
COD	80	64900	5300	33	160	1.46	44800	3840	3	160	4.5	56000	5000	6	110	1.57						Ahmadifar et al. (2015)
	44	94000	1600	13	500	0.98	68500	5000	0	250	1.59											Sinan Bilgili et al.. (2007)
	14	77000	3000	24	305	1.15											74364	1844	12	307	2.09(1)	Cossu et al. (2015)
					305												98000	2458	3	307	1.19(1)	Cossu et al. (2015)
	14	1942	500	15	310	1.79											2423	50	8	310	3.2(2)	de Abreu et al. (2005)
	25	68000	2550	15	271	0.85						54000	1000	9	271	1.45						He et al. (2012)
	70	86068	15600	15	370	0.46						82600	2270	15	370	1.9						Huo et al. (2008)
	15	79000	42050	4	690	0.1	70000	5880	15	335	0.85											Kim et al. (2005)
	60	60000	4000	8	260	1.17	42700	1160	0	260	6.51											Nikolaou et al. (2009)
	70	90200	79200	51	132	0.36											57300	3800	18	132	2.92(2)	Shou-liang et al. (2008)
	28	30000	2020	13	195	1.35	14920	460	5	195	2.34											Slezak et al. (2015)
	45	67520	900	10	630	0.5	19237	664	4	378	4.82											Erses et al. (2008)
	55	84300	75000	50	300	0.16											62000	7100	5	300	1.63(2)	Xu et al. (2014)
	30*	11100	700	5	900	0.29						9700	260	4	900	0.64						Yang et al. (2011)
MEAN						0.82					5.1					1.39					2.21	
SD						0.55					4.13					0.54					0.85	
N-NH_4	44	2100	1050	39	500	0.27	1700	120	26	250	3.06											Bilgili et al. (2007)
	14	155	80	8	310	0.39											304	24	8	310	3.01(2)	de Abreu et al. (2005)
	49	1340	1040	67	100	0.79											1040	120	31	100	6.22(2)	He et al. (2007)
	25	2800	1750	42	271	0.36						2100	700	42	271	0.95						He et al. (2012)
	70	2950	2490	25	370	0.06						3198	22	16	370	3.81						Huo et al. (2008)
	60	625	55	12	260	0.89	410	2	24	100	3.2											Nikolaou et al. (2009)
	60	1900	1840	18	200		1440	330	18	200	1.5	1300	22	30	200	1.27						Shao et al. (2008)
	70	3025	2550	60	132	0.3											1590	120	23	132	2.5(2)	Shou-liang et al. (2008)
	45	1064	638	42	630	0.14	407	5	10	378	1.47											Erses et al. (2008)
	30*	1580	510	9	900	0.19						1270	50	2	900	0.38						Yang et al. (2011)
MEAN						0.38					2.31					1.6					3.91	
SD						0.28					0.95					1.52					2.02	

** Estimated value. (1)Hybrid aerobic-anaerobic. (2)Hybrid facultative.*

leachate recirculation rate for degradation. Faster stabilization and improved settlement were demonstrated (Stessel and Murphy, 1992).

The positive effects of aeration on waste stabilization have been confirmed by several studies by comparing anaerobic and aerobic conditions (Table 1). Despite variation in the POF, lab-tests revealed similar results in terms of stabilization performance with higher carbon and nitrogen removal kinetics and/or shorter lag phase compared to anaerobic conditions. Aeration also lowered the leachate carbon and nitrogen values and achieved a final BOD_5/COD ratio between 0.02-0.003 (Table 1). Volatile organic acids production decreased by limiting the anaerobic fermentation processes and resulted in pH ranges between 6-8 after the initial acidic phase.

Although the aerobisation (establishment of aerobic conditions) of the waste mass prevents methane generation and thus energy recovery, there are several advantages compared to the anaerobic bioreactor landfill, which can be summarised as follows:

- Acceleration of the degradation processes in the landfill due to the higher biochemical aerobic degradation kinetics, reducing the long-term emission potential as well as the post closure management costs. In addition to faster settlement of the landfill, the site can be used for other uses in shorter time period (Yuen et al., 1999, Read, 2001);
- Higher waste settlement that generates additional landfill capacity
- Reduction of leachate volumes and enhanced remediation of recalcitrant carbon molecules and nitrogen compounds, improving the leachate quality resulting in the subsequent financial savings for secondary treatment;
- Reduction of CH_4 generation and increased carbon gasification dominated by CO_2;
- Reduction of odours generally produced from anaerobic degradation, such as hydrogen sulphide and volatile acids (Jacobs et al., 2003).

Among others, nitrogen removal is one of the most significant benefit of an aerobic system. In anaerobic landfills, nitrogen removal from leachate, in form of ammonia ion, is generally performed ex situ using costly and complex treatment plants. In order to avoid these costs, in-situ techniques have become an attractive solution and to date the most used alternative is the aeration of the waste mass to facilitate nitrification-denitrification processes (Berge et al., 2006; Shao et al. 2008). Although air injection will theoretically inhibit the denitrification process, the complete aerobisation of the waste mass is never achieved in the field. Therefore anaerobic and anoxic areas still exist inside the landfill and both processes can take place simultaneously even under low biodegradable matter conditions (Berge et al., 2006; Giannis et al., 2008; Ritzkowski, 2011; Ritzkowski and Stegmann, 2005, 2003; Shao et al., 2008). Air stripping and volatilisation can also occur since these processes are favoured by higher pH levels and temperatures reached in an aerobic system and can also be facilitated through the gas flow associated with air injection (Berge et al., 2005).

The forced air flow and the temperature rising up to more than 60°C results in a high evaporation of water and in a low quantity of leachate (Berge et al., 2005; Read et al., 2001).

Recirculation still represents an additional in situ leachate treatment tool to improve stabilization performance (Sinan Bilgili et al., 2007). In particular, the increased frequency of leachate recirculation accelerates the stabilization rate of waste, even if too much recirculation leads to saturation, ponding, and acidic conditions (Šan and Onay, 2001). Slezak et al. (2015) observed that the higher recirculation rate, increased the reduction of carbon and nitrogen parameters in leachate over a shorter time period but O_2 diffusion was limited leading to lower waste stabilization.

Aeration rates and modes influence the degradation performance differently. Slezak et al. (2010) compared stabilization performance of four aerobic lysimeters with different aeration rates obtaining similar changes in leachate parameters and demonstrated that above the minimum aeration requirements the increased rates do not provide any additional benefits. Intermittent aeration has been demonstrated to be much more effective than continuous aeration (Cossu et al., 2016; Morello et al., 2017); however optimum aeration rate is strongly influenced by oxygen consumption, which varies according to waste composition, age, and operating parameters.

Fate of metals in aerobic and anaerobic landfill bioreactors was investigated by Kim et al. (2011). Apart from the initial acidic phase, heavy metals mobility was reduced under aerobic conditions due to the high pH and positive redox conditions, affecting solubility and sorption properties. Metals were retained in the waste by sorption, carbonate precipitation, and hydroxide precipitation (Borglin et al., 2004; Giannis et al., 2008).

Typical composition of off gases reported in lab scale tests consists of 10-20% O_2 and 0-20% CO_2 (Figure 1). Methane generation is almost completely inhibited under aerobic conditions and mostly CO_2 is produced (Mertoglu et al., 2006; Slezak et al., 2015). On one hand aerobic conditions impede energy recovery while on the other environmental impacts are limited when biogas collection and control is not technically or economically feasible and uncontrolled emissions are expected. Ritzkowski and Stegmann (2007) demonstrated that in situ aeration could avoid more than 72% of the total GHG emissions occurring under anaerobic conditions.

Since the faster waste stabilization under aerobic conditions, carbon gasification is enhanced. Slezak et al. (2015) compared CO_2 and CH_4 gasification from anaerobic and aerobic lysimeters. The results showed that carbon gas released from aerobic lysimeters was about 5 times higher than that the one from anaerobic ones.

Potential disadvantages, which limit the use of this technology are the risks associated with the drying of the waste mass due to the high temperatures which may limit the highly sensitive nitrogen removal biological processes and may create an elevated temperature or fire potential. However, limited methane production, proper moisture content, and waste pre-treatment can overcome these problems (Berge et al., 2005). The high costs due to the energy requirements for compressed air injection may be limited by the appropriate selection of operating parameters, including aeration and recirculation rates, providing optimum conditions for waste decomposition, and minimizing energy consumption (Rich et al., 2008). According to the hypothetical cost model developed by Read et al. (2001), aerobic landfills could be a cost-effective solution when considering the potential recovery of valuable materials from the site, even if the operational costs and the regulatory requirements of closed landfills represents an obstacle for the full-scale development of aerobic landfills (Read et al. 2001).

Forced aeration is nowadays mostly used for remediating old anaerobic landfill, instead of being only a designed option for active landfill management. This is because aeration of old landfills represents a feasible solution to biologically stabilize waste, reduce nitrogen concentrations, and significantly control liquid emissions (Hrad et al., 2013; Ritzkowski and Stegmann, 2005, 2003). Moreover, the aeration of the landfill mass is a fundamental pre-treatment for landfill mining procedures (Raga and Cossu, 2014; Ritzkowski and Stegmann, 2012). In remediation, this technology is generally preferred over flushing: although on one hand flushing has been demonstrated to be the most effective approach (Bolyard and Reinhart, 2015), on the other hand it requires large volumes of water, off-site leachate treatment costs, and is not always technically or economically feasible (Ritzkowski et al., 2006).

Combination of both flushing and aeration processes however, have been suggested as alternative landfill management approaches by Cossu et al. (2003). PAF model was proposed as a combination of mechanical-biological Pre-treatment with Aeration and Flushing to exploit the advantages of the individual options. PAF and flushing reactors were compared to the traditional anaerobic, semi aerobic, and aerated landfills. Among the others, flushing bioreactors revealed faster kinetics and lower concentration values for carbon and nitrogen control parameters, even if the aerobic reactor presented lower residual carbon in the final solids and greater gasification. Gas generation is limited in flushing reactors since the washing of waste tends to remove the soluble biodegradable substance available to gasification (Cossu et al., 2003; Purcell et al., 1997).

3.3 Semi aerobic bioreactor landfills

The semi-aerobic system has been developed in Japan by Hanashima (1961). This system could be considered as a lower cost alternative solution to the aerobic landfill system, by providing the same benefits but lowering the operational costs by avoiding the direct air injection. Aerobic bacteria activity is improved by the natural flow of the external air into the waste mass through the leachate collection pipes, moved by the temperature gradient between the inside and outside of the landfill (Theng et al., 2005). The movement of air is particularly enhanced in winter and during the night when the temperature differences are higher. Hirata et al. (2012) observed that aerobic bacteria count in semi-aerobic systems were higher compared to anaerobic bacteria, demonstrating the effectiveness of the semi-aerobic system in the aerobisation of the waste mass.

Reproducing the aerobic process, the semi-aerobic system achieves the same benefits described for the aerated bioreactor landfill which has been proved by several lab-scale studies as well as by large-scale applications.

According to the data elaboration presented in Table 1, results show that regardless of the differences in the POF fraction of waste, the semi-aerobic system is able to achieve a much higher organic matter stabilization than the anaerobic system. The COD and ammonia concentrations in the leachate are always lower under semi-aerobic conditions, achieving higher removal kinetics. In particular, ammonia oxidation was achieved by creating aerobic conditions, while the simultaneous presence of anaerobic, anoxic, and aerobic zones within the waste mass creates conditions for denitrification of the nitrate. Shao et al. (2008) obtained higher efficiency under semi-aerobic conditions rather than in fully aerobic bioreactor since denitrification was limited due to the persistent presence of oxygen.

Despite the capability of the semi-aerobic system to partially simulate aerobic conditions, aerated bioreactors remain the best performing systems in terms of COD concentrations, degradation rates, and removal efficiencies (Table 1) (Ahmadifar et al., 2015).

A benefit of the aerobisation of the waste mass is the higher gasification occurring under semi-aerobic conditions dominated by CO_2 (Figure 1). According to Matsufuji et al. (1996) the proportion of gas to leaching emissions was 3:2 from the semi-aerobic lysimeter and 1:4 from anaerobic lysimeters. Similar results were obtained by Shimaoka et al. (2000) with a ratio of 4:1 and 2:3 under semi-aerobic and anaerobic conditions, respectively. Lavagnolo et al. (2018) achieved up to a 60% initial carbon gasification under semi-aerobic conditions compared to only 20% in anaerobic reactors.

Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006) estimates that the degradation process within a semi aerobic waste mass is supposed to occur simultaneously under anaerobic and aerobic conditions in line with the heterogeneity of the waste mass. According to this, the biogas composition in a semi-aerobic landfill is described by a CH_4/CO_2 ratio of 0.48 (Jeong et al., 2015). This value seems to align well with the majority of the values reported in the literature. The average methane concentration in the semi-aerobic process mostly ranges between 0-30% (v/v) with CO_2 and O_2 at 10-30% (v/v) and 0-20% (v/v), respectively (Figure 1).

3.4 Hybrid bioreactors

Hybrid bioreactors are conceptually based on the principle of combining a sequence of aerobic and anaerobic conditions with the purpose of achieving the benefits from both conditions in order to maximise the potential of bioreactors in terms of sustainability and/or methane generation. In particular methane production and energy recovery are maximized during the anaerobic phase while during the aerobic phase the nitrification-denitrification processes are enhanced for complete removal of nitrogen from landfill. Overall waste stabilization is achieved in a shorter period of time by improving the degradation of recalcitrant compounds such as lignin and aromatic substances

(Berge et al., 2006, 2005; He et al., 2011; Long et al., 2009b; Ritzkowski and Stegmann, 2013; Sun et al., 2013). A challenge with a Hybrid Bioreactor is the economic cost since continuous injection-extraction plants are expensive or alternatively require a biological leachate treatment plant. Consequently, this technology is applied for limited periods of time when traditional degradation processes cannot decrease the pollution any further (Berge et al., 2006).However, the high maintenance costs associated with air injection and leachate recirculation are generally covered by the increasing methane generation and/or by leachate treatments savings due to recirculation and aeration (Berge et al., 2009). Several different hybrid conditions have been tested at lab scale with promising results through combining various sequences of aerated and non-aerated phases, aeration modes (continuous or intermittent), and application (leachate aeration or in situ waste aeration).

3.4.1 Anaerobic-Aerobic sequencing

Long et al. (2009) proposed a hybrid bioreactor landfill sequencing the anaerobic and aerobic phases. At the end of the second phase, the system was able to achieve more than a 97% removal efficiency of COD and ammonia, nitrifying and denitrifying more than 70% of the initial content of nitrogen in the waste sample, produced methane for energy recovery, and dropped the main pollutants concentration to low levels (COD < 400 mg/L and ammonia < 20 mg/L). Aerobic conditions through air injection significantly improved the stabilization of the refuse, the readily biodegradable organic matter was mineralized during the initial anaerobic phase, and the hardly biodegradable organic matter was stabilized mainly during the aerobic phase. Ammonia was converted to NO_3^- and NO_2^- in ex-situ nitrification, while nitrate was reduced into nitrite and then to N_2 gas in in-situ denitrification. A simple example of the application of the hybrid bioreactor is the aeration of old landfills, in which the long lasting anaerobic process occurred over the lifetime of the landfill is followed by forced aeration. Forced aeration is an efficient technology applied worldwide for the remediation of persistent pollution (Ritzkowski and Stegmann, 2013). The same has been applied in some more recent landfills which were built as anaerobic bioreactors in order to achieve methane production leaving the possibility of applying in-situ aeration as a subsequent phase. This type of operation would convert this landfill to a Hybrid Bioreactor.

3.4.2 Aerobic-Anaerobic

When aerobic-anaerobic sequencing is applied completely in situ, aeration could be addressed to maximize the methane production by accelerating the initial acidogenic phase and anticipating optimum pH and VFA conditions for methanogenesis (Xu et al., 2014; Morello et al., 2017). Mali Sandip et al. (2012) showed that pre-aeration in combination with leachate recirculation and/or inoculum injection could increase the methane production by 25%. Similar results were obtained by Xu et al. (2014) using a lab scale hybrid bioreactor with intermitted air injection before a second anaerobic phase which achieved a higher methane production (about 32 L_{CH4}/kg_{TS}) and a higher consumption of organic compounds compared with a full anaerobic one in which methane production never started due to excessive acidity. Aeration frequencies, depth and rates strongly influence the methane production, the decomposition of organic carbon, and nitrification. Xu et al. (2015) operated two hybrid bioreactors with two different initial aeration frequencies (twice and 4 times per day) with same unit rate of 0.1 L/min/kg_{TS} until pH>7, obtaining similar trends in COD and ammonia values but higher methane generation in the case of low frequency aeration (85 L_{CH4}/kg_{TS} compared to 72 L_{CH4}/kg_{TS}). Cossu et al. (2015) tested aerobic-anaerobic hybrid bioreactors with continuous and intermittent aeration until optimum pH and VFA concentrations for methanogenesis were achieved. Both aeration modes were beneficial in accelerating waste stabilization and the acidogenic phase, however intermittent aeration until optimum pH values was more efficient in enhancing stabilization kinetics and methane generation (Table 1). According to Wu et al. (2014), aeration at the bottom layer achieved enhanced decomposition of organic carbon, while high air injection rates lead to effective simultaneous nitrification-denitrification. This combination accelerated waste decomposition but may limit methane generation. Despite the cited benefits of pre-aeration, it does not solve the problem of persistent nitrogen pollution in leachate and in all previous studies strong ammonification occurs during the first aerobic phase with positive trend in ammonia concentration which accumulated during the second anaerobic phase (Cossu et al., 2016; He et al., 2011; Morello et al., 2017; Xu et al., 2015, 2014). For this reason, S.An.A landfill model has been suggested, including a third final phase of post-aeration to drop down nitrogen indexes in leachate (Cossu et al., 2016; Morello et al., 2017). The Semiaerobic-Anaerobic-Aerobic (S.An.A) Landfill model is a hybrid system with an initial semi-aerobic phase to enhance the methane production occurring in the anaerobic step which is then followed by forced aeration for the abatement of the residual emissions. According to Morello et al. (2017) with this approach it was possible to achieve a methane potential 50% higher than that of a traditional anaerobic bioreactor which equates to an estimated reduction of aftercare by 25-35%.

A Mechanical Biological Pre-treatment (MBP) of waste before anaerobic landfilling could be regarded as a form of a hybrid bioreactor, with off-site forced aeration followed by in situ anaerobic reactions. MBP aims to achieve a quick stabilization of the waste and during landfilling the production of landfill gas might not be significant for energetic exploitation.

3.4.3 Facultative landfill

In order to overcome the challenge of ammonia accumulation under anaerobic conditions, an alternative solution consists of an external aerobic pre-treatment of leachate prior to recirculation in an anaerobic bioreactor, to allow for simultaneous nitrification and denitrification to occur in order to remove nitrogen compounds (Berge et al., 2005; de Abreu et al., 2005; Price et al., 2003; Zhong et al., 2009). This system aims at ensuring that the energy recovery due to methane production is maintained throughout the whole landfill by facilitating anaerobic conditions. In order to remediate nitrogen pollution in the leachate, the leachate is aerobically treated to nitrify the ammonia and then it is re-injected into the landfill to denitrify the produced nitrates. This system is also patented in the United States (US639895, 2002) by the name of a facultative landfill and has been tested at the lab scale by Price et al. (2003) in order to verify that the bioreactor is capable of denitrifying the nitrates produced during aerobic leachate treatment. The options available for ex situ leachate treatment are chemical-physical (ion-exchange, air stripping, chemical precipitation, reverse osmosis) and biological. Among the others, biological treatment is the most common since costs are limited compared to other processes (He et al., 2007). Several lab scale ex situ biological leachate nitrification options have been studied including the aerobic biofilter (Jokela et al., 2002), sequential anaerobic and air-lift loop sludge blanket reactors (He et al., 2007), continuous stirred tank reactor (Zhong et al., 2009), activated sludge reactor (Huo et al., 2008), fluidized bed reactors (de Abreu et al., 2005), and aerobic landfill reactor (Sun et al., 2017). All these studies demonstrate the capability of the facultative bioreactors to remove nitrogen through ex-situ nitrification of NH_4 to NO_2 and NO_3 and in-situ denitrification to convert nitrates to N_2 gas.

De Abreu et al. (2005) compared the performance of an anaerobic bioreactor with that of a facultative bioreactor with external aerobic biological leachate treatment consisting of an electrocoagulation/settling unit for metals removal and two fluidised bed reactors. According to Table 1 there are clear benefits in both COD and ammonia removal observed in the facultative bioreactor with higher removal kinetics (1.8-fold and 7.7-fold for the anaerobic column for COD and ammonia, respectively), achieving a final COD and NH_4 concentration much lower compared to the anaerobic bioreactors. Shou-liang et al. (2008) compared the performances of an anaerobic bioreactor with those of a facultative bioreactor. The latter consisted of a fresh waste landfill reactor for denitrification, a well decomposed waste landfill reactor for methanogenesis, and an aerobic-activated sludge reactor for nitrification. The obtained results showed the capability of the system to improve the methane generation and promote ammonia removal since nitrification and subsequent denitrification occurred with removal kinetics 8-folds higher than anaerobic conditions. The acidogenic phase was accelerated in the hybrid reactor with a higher methane concentration during the experimental period, while inhibiting methanogenesis in the anaerobic reactor due to the VFA accumulation and low pH level. He et al. (2007) studied the performance of a facultative reactor with an external leachate treatment consisting of a sequential up flow anaerobic sludge blanket reactor for organic matter removal and an air-lift loop sludge blanket reactor for nitrification. Even if the COD removal was quite similar to the control reactor, the ammonia removal was strongly enhanced with final NO_3 values of about 4 mg/L, suggesting the occurrence of denitrification. This kind of Hybrid Bioreactor is promising because it allows for the reduction in ammonia in the landfill without any aeration systems while ensuring methane recovery at the same. The downside of this process is the continued need for a biological leachate treatment plant.

The high concentration of nitrate produced in ex-situ nitrification may inhibit methanogenesis in a facultative bioreactor. For this reason, Sun et al. (2017) studied the use of ex situ simultaneous nitrification-denitrification in an aged refuse bioreactor for nitrification prior to in-situ denitrification, in order to enhance the methane production. Hirata et al. (2012) proposed the SeRA system (recirculatory semi-aerobic landfill) with ex situ leachate aeration in order to improve the semi-aerobic landfill performance by reducing the in situ oxygen demand, expanding the aerobic zone in the waste mass, and improving the nitrification denitrification process. SeRA achieved a similar TOC degradation performance compared to the aerobic lysimeter and an even better total nitrogen degradation performance confirmed by the higher gasification rates.

4. BIOREACTORS COMPARISON IN TERMS OF SUSTAINABILITY

A comparative qualitative analysis of bioreactor types are summarised in Table 2 based on selected characteristics, such as persistent emissions, technological complexity, maintenance costs, and leachate treatment costs.

Considering the prior need of achieving landfill sustainability, ammonia is generally recognized as the main long-term pollutant in leachate. Therefore almost all the bioreactor types involved some form of a nitrification-denitrification process with different methodologies. Even if the carbon and nitrogen emissions can be reduced efficiently, leachate can also be polluted by saline compounds and heavy metals, which are difficult to be removed biologically.

The performance of each type of bioreactor may highly depend on the-situ conditions, such as waste characteristics and climate, which should be taken into consideration beyond the objectives to be pursued (i.e. energy recovery, faster waste stabilization, washing of soluble compounds). For example, according to the recent European Regulations (EU, 2015), the reduction of the POF in landfilled waste and waste pre-treatment limit the practicability of bioreactors that are intended for energy recovery, while these bioreactors will surely have a central role in waste management outside of Europe (Reinhart et al., 2002). Moreover, the capability of bearing the costs and the technological complexity will strongly depend from country to country. Nevertheless, knowing the general behaviour in stabilization performance of each bioreactor type at the lab scale may help to identify the best bioreactor solution at field scale. The best performance would be based on the aim to fulfil the sustainability concepts according to the specific site objectives and in-situ conditions. For this reason, the quantification of the stabilization performance and thus the sustainability of the different systems has been carried out.

According to Berge et al. (2009), the main parameters that influence bioreactor economics are air space recovery, gas recovery for the subsequent energetic use, and savings resulting from reduced leachate treatment requirements. Therefore, faster biological stabilization provides a metric for measuring the successfulness of any landfill

TABLE 2: Qualitative analysis of different landfill bioreactor types compared to the traditional landfill.

Bioreactor Landfill Type	Objective		Biochemical Kinetics	Other Persistent Emissions	Technological complexity	Maintenance Costs*	Leachate treatment costs *
	Methane production & energy recovery	Nitrogen removal					
Traditional Landfill	Traditional Recovery	by leaching	slow	NH$_4^+$, Salinity, Heavy metals	Gas collection	Low	High
Anaerobic	Enhanced recovery	by leaching	Medium-slow	NH$_4^+$, Salinity, Heavy metals	Leachate recirculation, Gas collection	Leachate recirculation	Savings from leachate recirculation
Aerobic	No	Nitro-Denitro	fast	Salinity, Heavy metals	Leachate recirculation, Air Injection	Air injection, Leachate recirculation	Savings from leachate recirculation and aeration
Semi-aerobic	No	Partial Nitro-de-nitro	medium	Salinity, Heavy metals	Build to enhance natural convection	Sometimes Leachate recirculation	Savings from aeration
Hybrid	Enhanced recovery	Nitro-Denitro	fast (limited for NH$_4$ in aerated-anaerobic)	Salinity, Heavy metals (NH$_4^+$ in aerated-anaerobic)	Two stage aerobic-anaerobic or vice versa; Gas collection; ex situ treatment before reinjection	Air injection, Leachate recirculation	Savings from leachate recirculation and aeration, ex-situ treatment cost if present

** The costs are referred to the operational phase.*

bioreactor type, both by reducing leachate treatment costs and by assuring sustainability requirements are achieved. Stabilization criteria of landfills is still a debated topic in the scientific literature (Barlaz et al., 2002; Laner et al., 2012; Stegmann et al. 2003; Valencia et al., 2009) since the criteria are not absolute and site specific conditions significant influence the values. In order to evaluate the sustainability achievement and aftercare completion, several approaches have been proposed such as the compliance with Final Storage Quality (FSQ) which defines the target emission values that must be achieved, impact risk assessment approaches, and performance based systems (Laner et al,. 2012). All of these approaches require a site-specific assessment in order to take into consideration the potential of natural attenuation or vulnerabilities (Barlaz et al., 2002; Laner et al., 2012; Rich et al., 2008).

In this study first order removal kinetics of organic and nitrogen concentration in leachate have been selected as criteria for the evaluation of the bioreactor stabilization performance (Ritzkowski et al., 2006) of the investigated lab-scale tests (Table 1).

A general overview of the stabilization capability associated with the different bioreactor types were calculated by the mean values of the COD and ammonia removal kinetics and standard deviations. The latter ones are represented as bar errors in Figure 2 in order to describe the distribution of values. Although there are variations in the operational management in the different investigated case studies, including the recirculation rate, waste composition, L/S ratio, air injection and experimental period (Table 1), the obtained mean COD kinetics can represent the general behaviour of each bioreactor type, as demonstrated by the standard deviations. The benefits of aerobic conditions are evident in the maximization of the COD removal with an average COD removal kinetic of 0.051d^{-1}. Hybrid and semi-aerobic bioreactor performances are between the

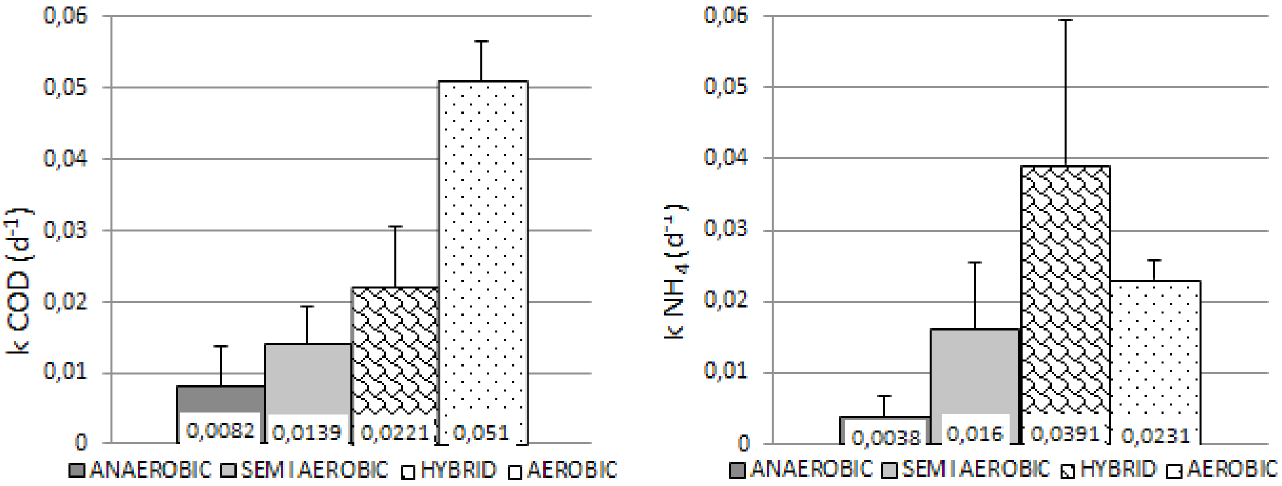

FIGURE 2: Mean values (numerically represented) and associated standard deviations (bar errors) of the COD and ammonia removal kinetics associate with each landfill bioreactor type starting from data collection and elaboration.(2012)).

results for anaerobic and aerobic conditions presenting a 0.0221 d^{-1} and 0.0139 d^{-1} average removal kinetics, respectively. Different results were obtained for ammonia removal kinetics in which hybrid bioreactors demonstrated better average value compared to the other bioreactors (0.0391 d^{-1}). The higher variability of the values around the mean makes these results carefully reliable since they are strongly influenced by the specific hybrid bioreactor application.

By the use of the mean COD and ammonia removal kinetics, it is possible to foresee and compare the stabilisation time for each bioreactor type. Considering the reference time (T) required under aerobic conditions to achieve a 95% contaminant removal (Figure 3), the time to achieve the same COD removal performance under hybrid, semi-aerobic, and anaerobic conditions increased by 2.3, 3.7, and 6.2-fold, respectively. In the case of ammonia removal, time is reduced by 0.7-fold under hybrid conditions, while time increased by 1.7 and 3.7-fold under semi-aerobic and anaerobic conditions, respectively. According to these results, the faster the stabilization, the shorter the aftercare time and the lower the post closure care costs.

5. CONCLUSIONS

Anaerobic bioreactors improve, by leachate recirculation, the methane generation rate and the leachate quality compared to the traditional anaerobic landfills. However, ammonia accumulation and slow degradation kinetics remain the main challenges in anaerobic bioreactors compared to the others, putting anaerobic bioreactors far from sustainability requirements. Aerobic reactors increased the ammonia and COD average removal kinetics up to 6 times more than under strictly anaerobic conditions and reduced the time required to achieve a 95% removal of COD and ammonia by 6.2- and 3.7-fold, respectively. Aeration appears to be an effective alternative to the traditional anaerobic processes, although the need for forced ventilation systems, the complex operation and management, and the large energy consumption, with high operational and capital costs, make the aerated landfill not always technically and economically feasible. A semi-aerobic landfill achieves a performance between the anaerobic and aerobic bioreactors but lowering the typical operational costs of aerated landfills by removing the need for direct air injection. For this reason, the semi-aerobic system is recognized as a cost–effective, low technology landfill system. This system can also be feasibly implemented in developing countries, where financial constraints and limited technical knowledge are generally the main reasons for inadequate disposal. A limiting factor of aerobic bioreactors is the complete inhibition of the methane generation, making any energy recovery impossible. Hybrid bioreactors, which are operated under various combinations of aerobic and anaerobic conditions, achieve both energy recovery and/or faster waste stabilization. In particular aerated-anaerobic hybrid reactors aim to enhance the biogas generation but this system will experience ammonia accumulation challenges, while facultative bioreactors combine both objectives which provides the best performance in terms of ammonia removal kinetics. In general, the best ammonia removal performance is achieved under hybrid conditions.

Due to the careful operation and construction requirements of bioreactor landfills, capital and operating costs would be greater compared to traditional landfills. However these costs will be recouped through future economy benefits from bioreactor landfills. In particular, the obtained results demonstrate the possibility of achieving shorter aftercare, reduced leachate treatment costs, reduced long term environmental risks, and an earlier reuse of the land. Detailed analysis of costs related to full-scale bioreactors is still a crucial aspect to be further investigated.

Moreover, the transfer from a lab-scale to full-scale bioreactor still remains a significant issue to be explored since much higher benefits are achieved under lab-scale investigation rather than at full-scale application due to the challenges with reproducing optimum and homogeneous conditions. However, knowing the general behavior of each bioreactor type at lab scale allows the identification of the best bioreactor solution at a larger scale according to the site specific objectives and in-situ conditions.

REFERENCES

Ahmadifar, M., Sartaj, M., Abdallah, M., 2016. Investigating the performance of aerobic, semi-aerobic, and anaerobic bioreactor landfills for MSW management in developing countries. J. Mater. Cycles Waste Manag. 18, 703–714. doi:10.1007/s10163-015-0372-0

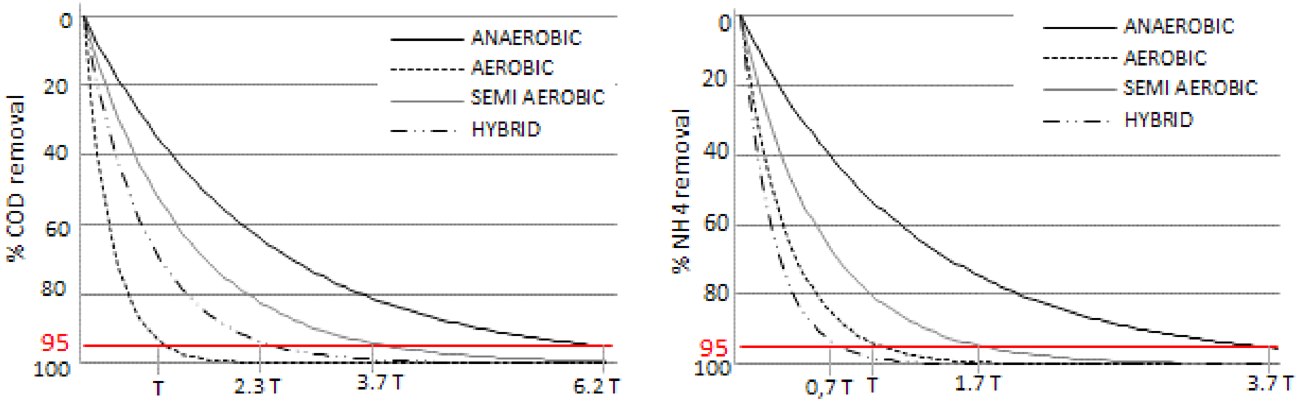

FIGURE 3: Variation of the percentage removal of COD and ammonia over time, according to the mean obtained removal kinetics. Reference time (T) is the time required to achieve a 95% removal under aerobic conditions.

Anex, R.P. (1996) Optimal Waste Decomposition- Landfill as Treatment Process. Journal of Environmental Engineering, ASCE, 122(11) 964–974.

Barlaz, M.A., Rooker, A.P., Kjeldsen, P., Gabr, M.A., Borden, R.C., 2002. Critical Evaluation of Factors Required To Terminate the Postclosure Monitoring Period at Solid Waste Landfills. Environ. Sci. Technol. 36, 3457-3464.

Berge, N.D., Reinhart, D.R., Batarseh, E.S., 2009. An assessment of bioreactor landfill costs and benefits. Waste Manag. 29, 1558–1567. doi:10.1016/j.wasman.2008.12.010

Berge, N.D., Reinhart, D.R., Dietz, J., Townsend, T., 2006. In situ ammonia removal in bioreactor landfill leachate. Waste Manag. 26, 334–343. doi:10.1016/j.wasman.2005.11.003

Berge, N.D., Reinhart, D.R., Townsend, T.G., 2005. The Fate of Nitrogen in Bioreactor Landfills. Crit. Rev. Environ. Sci. Technol. 35, 365–399. doi:10.1080/10643380590945003

Bolyard, S.C., Reinhart, D.R., 2015. Application of landfill treatment approaches for stabilization of municipal solid waste. Waste Manag. doi:10.1016/j.wasman.2016.01.024

Borglin, S.E., Hazen, T.C., Oldenburg, C.M., Zawislanski, P.T., 2004. Comparison of aerobic and anaerobic biotreatment of municipal solid waste. J. Air Waste Manag. Assoc. doi:10.1080/10473289.2004.10470951

Christensen, T.H., Manfredi, S., Knox, K, 2011. Landfilling: Reactor Landfills. In: Christensen, T.H. (Ed.), Solid Waste Technology and Management, vol. 2. Blackwell Publishing Ltd.

Cossu, R., 2012. The environmentally sustainable geological repository: The modern role of landfilling. Waste Manag. 32, 243–244. doi:10.1016/j.wasman.2011.11.005

Cossu, R., 2010. Technical evolution of landfilling. Waste Manag. 30, 947–948. doi:10.1016/j.wasman.2010.03.003

Cossu, R., Morello, L., Raga, R., Cerminara, G., 2016. Biogas production enhancement using semi-aerobic pre-aeration in a hybrid bioreactor landfill. Waste Manag. 55, 83–92. doi:10.1016/j.wasman.2015.10.025

Cossu, R., Raga, R., Rossetti, D., 2003. The PAF model: An integrated approach for landfill sustainability. Waste Manag. 23, 37–44. doi:10.1016/S0956-053X(02)00147-2

De Abreu, R., La Motta, E., McManis, K., 2005. Facultative landfill bioreactors (FLB): results of a pilot-scale study. Waste Containment Remediat., 1–13.

EPA, 2018a. Bioreactors. https://archive.epa.gov/epawaste/nonhaz/municipal/web/html/bioreactors.html. (Accessed on 5th March 2018)

EPA, 2018b. Global Mitigation of Non-CO2 Greenhouse Gases: Landfills. https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-mitigation-non-co2-greenhouse-gases-landfills (accessed on 5th August 2018)

Erses, A.S., Onay, T.T., Yenigun, O., 2008. Comparison of aerobic and anaerobic degradation of municipal solid waste in bioreactor landfills. Bioresour. Technol. 99, 5418–5426. doi:10.1016/j.biortech.2007.11.008

EU, Proposal of a Directive of the European Parliament and of the Council, 2015. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015PC0595.

Fellner, J., Döberl, G., Allgaier, G., Brunner, P.H., 2009. Comparing field investigations with laboratory models to predict landfill leachate emissions. Waste Manag. 29, 1844–1851. doi:10.1016/j.wasman.2008.12.022

Filipkowska, U., 2008. Effect of recirculation method on quality of landfill leachate and effectiveness of biogas production. Polish J. Environ. Stud. 17, 199–207.

Giannis, A., Makripodis, G., Simantiraki, F., Somara, M., Gidarakos, E., 2008. Monitoring operational and leachate characteristics of an aerobic simulated landfill bioreactor. Waste Manag. 28, 1346–1354. doi:10.1016/j.wasman.2007.06.024

Hanashima, M., Yamasaki, K., Kuroki, T., Onishi, K., 1981. Heat and gas flow analysis in semiaerobic landfill. J. Environ. Eng. Divis., Proc. Am. Soc. Civ. Eng. 107 (EE1), 1–9.

Hater, G.R., Young, K.E., Simpson, C., Harris, J.M., 2001. Economics of Eight Scenarios for Landfill Bioreactors as Compared to a Base Case Subtitle D Landfill. Waste Tech 2001, San Diego, CA, February.

Heimovaara, T.J., Cossu, R., van der Sloot, H.A., 2014. State of the art and perspectives for sustainable landfills. In: Cossu, R., van der Sloot, H.A. (Eds.), Sustainable Landfilling. CISA Publisher, ISBN 978-88-6265-005-2.

He, P., Yang, N., Gu, H., Zhang, H., Shao, L., 2011. N2O and NH3 emissions from a bioreactor landfill operated under limited aerobic degradation conditions. J. Environ. Sci. 23, 1011–1019. doi:10.1016/S1001-0742(10)60574-8

He, R., Liu, X. wen, Zhang, Z. jian, Shen, D. sheng, 2007. Characteristics of the bioreactor landfill system using an anaerobic-aerobic process for nitrogen removal. Bioresour. Technol. 98, 2526–2532. doi:10.1016/j.biortech.2006.09.013

He, Y., Guo, L., Gao, J., 2012. The Advantages and Mechanism of Semi-aerobic Landfill. Energy Procedia 17, 391–396. doi:10.1016/j.egypro.2012.02.111

Hirata, O., Matsufuji, Y., Tachifuji, A., Yanase, R., 2012. Waste stabilization mechanism by a recirculatory semi-aerobic landfill with the aeration system. J. Mater. Cycles Waste Manag. 14, 47–51. doi:10.1007/s10163-011-0036-7

Hrad, M., Gamperling, O., Huber-Humer, M., 2013. Comparison between lab- and full-scale applications of in situ aeration of an old landfill and assessment of long-term emission development after completion. Waste Manag. 33, 2061–2073. doi:10.1016/j.wasman.2013.01.027

HUANG, Q., YANG, Y., PANG, X., WANG, Q., 2008. Evolution on qualities of leachate and landfill gas in the semi-aerobic landfill. J. Environ. Sci. 20, 499–504. doi:10.1016/S1001-0742(08)62086-0

Huo, S.L., Xi, B.D., Yu, H.C., Fan, S.L., Jing, S., Liu, H.L., 2008. A laboratory simulation of in situ leachate treatment in semi-aerobic bioreactor landfill. Water SA 34, 133–140.

Hupe, K., Heyer, K. and Stegmann, R., 2003: Water infiltration for enhanced in situ stabilization. In: Proceedings Sardinia 2003, Ninth International Waste Management and Landfill Symposium, 6–10 October, Sardinia, Italy. Proceedings. CD-ROM, CISA – Environmental Sanitary Engineering Centre, Cagliari, Italy.

IPPC, 2006. IPPC Guidelines for National Greenhouse Gas Inventories. Volume 5: Waste. Chapter 3: Solid Waste Disposal. https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html (accessed 5 August 2018)

Jacobs, J., Scharff, H., Van Arkel, F., De Gier, C.W., 2003. Odour reduction by aeration of landfills: experience, operation and costs. In: Conference Proceedings, 9th International Waste Management and Landfill Symposium, Cagliari, Italy.

Jeong, S., Nam, A., Yi, S.M., Kim, J.Y., 2015. Field assessment of semi-aerobic condition and the methane correction factor for the semi-aerobic landfills provided by IPCC guidelines. Waste Manag. 36, 197–203. doi:10.1016/j.wasman.2014.10.020

JICA, 2004. Detailed design for development of semi-aerobic system pilot project at Sisdole landfill site (vol. I), Lalitpur, Nepal: East Consult. (P.) Ltd.

Jokela, J.P.Y., Kettunen, R.H., Sormunen, K.M., Rintala, J.A., 2002. Biological nitrogen removal from municipal landfill leachate: Low-cost nitrification in biofilters and laboratory scale in-situ denitrification. Water Res. 36, 4079–4087. doi:10.1016/S0043-1354(02)00129-X

Karnik, M. & C. Perry (1997) Cost Implications of Operating Landfills as Flushing Bioreactors. Proceedings from Sardinia 97, Sixth International Landfill Symposium, Volume I, S. Margherita di Pula, Cagliari, Italy, 13–17 October, 1997, Volume I, 419–426.

Khalil, K., Mary, B., Renault, P., 2004. Nitrous oxide production by nitrification and denitrification in soil aggregates as affected by O2concentration. Soil Biol. Biochem. 36, 687–699. doi:10.1016/j.soilbio.2004.01.004Kim H., 2005. Comparative studies of aerobic and anaerobic landfills using simulated landfill lysimeters. Doctoral dissertation. Retrieved from University of Florida Digital Collections. http://ufdc.ufl.edu//AA00025781/00001

Kim, H., Jang, Y.C., Townsend, T., 2011. The behavior and long-term fate of metals in simulated landfill bioreactors under aerobic and anaerobic conditions. J. Hazard. Mater. 194, 369–377. doi:10.1016/j.jhazmat.2011.07.119

Kylefors, K., Andreas, L., Lagerkvist, A., 2003. A comparsion of small-scale, pilot scale and large -scale tests for predicting leaching behavioud of landfilled wastes. Waste Manag. 23, 45–59.

Laner, D., Crest, M., Scharff, H., Morris, J.W.F., Barlaz, M.A., 2012. A review of approaches for the long-term management of municipal solid waste landfills. Waste Manag. 32, 498–512. doi:10.1016/j.wasman.2011.11.010

Lavagnolo MC, Grossule V, Raga R. Innovative dual-step management of semi-aerobic landfill in a tropical climate. Waste Manag [Internet]. 2018;1–10. Available from: https://doi.org/10.1016/j.wasman.2018.01.017

Long, Y., Hu, L. fang, Shen, D.S., 2009a. Nitrogen transformation in the hybrid bioreactor landfill. Bioresour. Technol. 100, 2527–2533. doi:10.1016/j.biortech.2008.11.036

Long, Y., Long, Y.Y., Liu, H.C., Shen, D.S., 2009b. Degradation of refuse in hybrid bioreactor landfill. Biomed. Environ. Sci. 22, 303–310. doi:10.1016/S0895-3988(09)60060-X

Mali Sandip, T., Khare Kanchan, C., Biradar Ashok, H., 2012. Enhancement of methane production and bio-stabilisation of municipal solid waste in anaerobic bioreactor landfill. Bioresour. Technol. 110, 10–17. doi:10.1016/j.biortech.2011.12.027

Matsufuji, Y., Kobayashi, H., Tanaka, A., Ando, S., Kawabata, T., Hanashima, M., 1996. Generation of greenhouse effect gases by different landfill types and methane gas control. In: Proceedings of 7th ISWA International Congress and Exhibition, Yokohama, Japan, pp. 230–237.

Mertoglu, B., Calli, B., Inanc, B., Ozturk, I., 2006. Evaluation of in situ ammonia removal in an aerated landfill bioreactor. Process Biochem. 41, 2359–2366. doi:10.1016/j.procbio.2006.06.014

Ministry of the Environment (Japan), 2018. http://www.env.go.jp/recycle/circul/venous_industry/index.html (Accessed on 6th June 2018)

Morello, L., Raga, R., Lavagnolo, M.C., Pivato, A., Ali, M., Yue, D., Cossu, R., 2017. The S.An.A.® concept: Semi-aerobic, Anaerobic, Aerated bioreactor landfill. Waste Manag. doi:10.1016/j.wasman.2017.05.006

Mummey, D.L., Smith, J.L., Bolton, H., 1994. Nitrous oxide flux from a shrub-steppe ecosystem: Sources and regulation. Soil Biol. Biochem. 26, 279–286. doi:10.1016/0038-0717(94)90168-6

Nikolaou, A., Giannis, A., Gidarakos, E., 2009. Comparison of aerobic and anaerobic degradation of municipal solid wastes in lab scale bioreactors. Proceedings of the 11th International Conference on Environmental Science and Technology. Chaina, Crete, Greece, 3-5 September 2009.

Omar, H., Rohani, S., 2015. Treatment of landfill waste, leachate and landfill gas: A review. Front. Chem. Sci. Eng. doi:10.1007/s11705-015-1501-y

Price, G.A., Barlaz, M.A., Hater, G.R., 2003. Nitrogen management in bioreactor landfills. Waste Manag. 23, 675–688. doi:10.1016/S0956-053X(03)00104-1

Powell, J., Jain, P., Kim, H., Townsend, T., Reinhart, D., 2006. Changes in landfill gas quality as a result of controlled air injection. Environ. Sci. Technol. 40, 1029–1034. doi:10.1021/es051114j

Price, G.A., Barlaz, M.A., Hater, G.R., 2003. Nitrogen management in bioreactor landfills. Waste Manag. 23, 675–688. doi:10.1016/S0956-053X(03)00104-1

Purcell, B.E., Sollars, C.J., Butler, A.P., 1997. Enhanced moisture movement in simulated landfill environments. In: Proceedings Sardinia 97, Sixth International Landfill Symposium, Vol. I, CISA, Cagliari, pp. 409–418.

Raga, R., Cossu, R., 2014. Landfill aeration in the framework of a reclamation project in Northern Italy. Waste Manag. 34, 683–691. doi:10.1016/j.wasman.2013.12.011

Read, A.D., Hudgins, M., Phillips, P., 2001. Aerobic landfill test cells and their implications for sustainable waste disposal. Geogr. J. 167, 235–247. doi:10.1111/1475-4959.00021

Reinhart, D.R., Mccreanor, P.T., Townsend, T., 2002. Waste Management & Research The bioreactor landfill : Its status and future. Waste Manag. Res. 172–186. doi:10.1177/0734242X0202000209

Rich, C., Gronow, J., Voulvoulis, N., 2008. The potential for aeration of MSW landfills to accelerate completion. Waste Manag. 28, 1039–1048. doi:10.1016/j.wasman.2007.03.022

Ritzkowski, M., 2011. How Does Landfill Aeration Impact on Leachate Composition ? Proceedings Sardinia 2011, Thirteenth International Waste Management and Landfill Symposium S. Margherita di Pula, Cagliari, Italy; 3 - 7 October 2011

Ritzkowski, M., Heyer, K.U., Stegmann, R., 2006. Fundamental processes and implications during in situ aeration of old landfills. Waste Manag. 26, 356–372. doi:10.1016/j.wasman.2005.11.009

Ritzkowski, M., Stegmann, R., 2013. Landfill aeration within the scope of post-closure care and its completion. Waste Manag. 33, 2074–2082. doi:10.1016/j.wasman.2013.02.004

Ritzkowski, M., Stegmann, R., 2012. Landfill aeration worldwide: Concepts, indications and findings. Waste Manag. 32, 1411–1419. doi:10.1016/j.wasman.2012.02.020

Ritzkowski, M., Stegmann, R., 2007. Controlling greenhouse gas emissions through landfill in situ aeration. Int. J. Greenh. Gas Control 1, 281–288. doi:10.1016/S1750-5836(07)00029-1

Ritzkowski, M., Stegmann, R., 2005. Mechanisms Affecting the Leachate Quality in the Course of Landfill in Situ Aeration. Proceedings Sardinia 2005, Tenth International Waste Management and Landfill Symposium. S. Margherita di Pula, Cagliari, Italy; 3 - 7 October 2005

Ritzkowski, M., Stegmann, R., 2003. Emission behaviour of aerated landfills : results of laboratory scale investigations. Proceedings Sardinia 2003, Ninth International Waste Management and Landfill Symposium. S. Margherita di Pula, Cagliari, Italy; 6 - 10 October 2003

Šan, I., Onay, T.T., 2001. Impact of various leachate recirculation regimes on municipal solid waste degradation. J. Hazard. Mater. 87, 259–271. doi:10.1016/S0304-3894(01)00290-4

Sanphoti, N., Towprayoon, S., Chaiprasert, P., Nopharatana, A., 2006. The effects of leachate recirculation with supplemental water addition on methane production and waste decomposition in a simulated tropical landfill. J. Environ. Manage. 81, 27–35. doi:10.1016/j.jenvman.2005.10.015

Shao, L.M., He, P.J., Li, G.J., 2008. In situ nitrogen removal from leachate by bioreactor landfill with limited aeration. Waste Manag. 28, 1000–1007. doi:10.1016/j.wasman.2007.02.028

Shimaoka T., Matsufuji Y., Hanashima M., 2000. Characteristic and Mechanism of Semi-Aerobic Landfill on Stabilization of Solid Waste. Intercontinental Landfill Research Symposium, 2000.

Shou-liang, H., Bei-dou, X., Hai-chan, Y., Shi-lei, F., Jing, S., Hong-liang, L., 2008. In situ simultaneous organics and nitrogen removal from recycled landfill leachate using an anaerobic-aerobic process. Bioresour. Technol. 99, 6456–6463. doi:10.1016/j.biortech.2007.11.047

Sinan Bilgili, M., Demir, A., Ince, M., Özkaya, B., 2007. Metal concentrations of simulated aerobic and anaerobic pilot scale landfill reactors. J. Hazard. Mater. 145, 186–194. doi:10.1016/j.jhazmat.2006.11.014

Slezak, R., Krzystek, L., Ledakowicz, S., 2015. Degradation of municipal solid waste in simulated landfill bioreactors under aerobic conditions. Waste Manag. 43. doi:10.1016/j.wasman.2015.06.017

Slezak, R., Krzystek, L., Ledakowicz, S., 2010. Simulation of aerobic landfill in laboratory scale lysimeters - effect of aeration rate. Chem. Pap. 64, 223–229. doi:10.2478/s11696-009-0113-8

Stegmann, R., Heyer, K.U., Hupe, K., Ritzkowski, M., 2003. Discussion of criteria for the completion of landfill aftercare. Paper presented at the Sardinia International Waste Management and Landfill Symposium, Sardinia, Italy.

Stessel, R.I., Murphy, R.J., 1992. A lysimeter study of the aerobic landfill concept. Waste Manag. Res. 10, 485–503. doi:10.1016/0734-242X(92)90089-4

Sun, F., Sun, B., Li, Q., Deng, X., Hu, J., Wu, W., 2014. Pilot-scale nitrogen removal from leachate by ex situ nitrification and in situ denitrification in a landfill bioreactor. Chemosphere 101. doi:10.1016/j.chemosphere.2013.12.030

Sun, X., Zhang, H., Cheng, Z., 2017. Use of bioreactor landfill for nitrogen removal to enhance methane production through ex situ simultaneous nitrification-denitrification and in situ denitrification. Waste Manag. 66, 97–102. doi:10.1016/j.wasman.2017.04.020

Sun, Y., Wang, Y.N., Sun, X., Wu, H., Zhang, H., 2013. Production characteristics of N2O during stabilization of municipal solid waste in an intermittent aerated semi-aerobic bioreactor landfill. Waste Manag. 33, 2729–2736. doi:10.1016/j.wasman.2013.08.013

Sutthasil, N., Chiemchaisri, C., Chiemchaisri, W., Wangyao, K., Towprayoon, S., Endo, K., Yamada, M., 2014. Comparison of Solid Waste Stabilization and Methane Emission from Aerobic and Semi-aerobic Landfills Operated in Tropical Conditions. Environ. Eng. Res. 19, 261–268.

Theng, L.C., Matsufuji, Y., Mohd, N.H., 2005. Implementation of the semi-aerobic landfill system (Fukuoka method) in developing countries: A Malaysia cost analysis. Waste Manag. 25, 702–711. doi:10.1016/j.wasman.2005.01.008

Tsujimoto, Y., Masuda, J., Fukuyama, J., Ito, H., 1994. N2o Emissions at Solid-Waste Disposal Sites in Osaka City. J. Air Waste Manage. Assoc. 44, 1313–1314. doi:10.1080/10473289.1994.10467327

US6398958 B1 2002. Gary R. Hater, Roger B. Green, Jeffrey M. Harris. Patent Facultative Landfill Bioreactor, Waste Management. Inc

Valencia, R., van der Zon, W., Woelders, H., Lubberding, H.J., Gijzen, H.J., 2009. Achieving “Final Storage Quality” of municipal solid waste in pilot scale bioreactor landfills. Waste Manag. 29, 78–85. doi:10.1016/j.wasman.2008.02.008

Valencia, R., Zon, W. van der, Woelders, H., Lubberding, H.J., Gijzen, H.J., 2011. Anammox: An option for ammonium removal in bioreactor landfills. Waste Manag. 31, 2287–2293. doi:10.1016/j.wasman.2011.06.012

Venterea, R.T., Rolston, D.E., 2000. Mechanisms and kinetics of nitric and nitrous oxide production during nitri ® cation in agricultural soil. Glob. Chang. Biol. 6, 303–316.

Vigneron, V., Ponthieu, M., Barina, G., Audic, J.M., Duquennoi, C., Mazéas, L., Bernet, N., Bouchez, T., 2007. Nitrate and nitrite injection during municipal solid waste anaerobic biodegradation. Waste Manag. 27, 778–791. doi:10.1016/j.wasman.2006.02.020

Walker, A.N., Beaven, R.P., Powrie, W., 1997. Overcoming problems in the development of a high rate flushing bioreactor landfill. In: Proceedings Sardinia 97, Sixth International Landfill Symposium, Vol. I, CISA, Cagliari, pp. 397–408.

Warith, M., 2002. Bioreactor landfills: Experimental and field results. Waste Manag. 22, 7–17. doi:10.1016/S0956-053X(01)00014-9

Watzinger, a, Reichenauer, T.G., Blum, W.E.H., Gerzabek, M.H., Zechmeister-Boltenstern, S., 2005. The Effect of Landfill Leachate Irrigation on Soil Gas Composition: Methane Oxidation and Nitrous Oxide Formation. Water, Air, Soil Pollut. 164, 295–313.

Wu, C., Shimaoka, T., Nakayama, H., Komiya, T., Chai, X., Hao, Y., 2014. Influence of aeration modes on leachate characteristic of landfills that adopt the aerobic-anaerobic landfill method. Waste Manag. 34, 101–111. doi:10.1016/j.wasman.2013.10.015

Xu, Q., Jin, X., Ma, Z., Tao, H., Ko, J.H., 2014. Methane production in simulated hybrid bioreactor landfill. Bioresour. Technol. 168, 92–96. doi:10.1016/j.biortech.2014.03.036

Xu, Q., Tian, Y., Wang, S., Ko, J.H., 2015. A comparative study of leachate quality and biogas generation in simulated anaerobic and hybrid bioreactors. Waste Manag. 41, 94–100. doi:10.1016/j.wasman.2015.03.023

Yang, Y., Yue, B., Yang, Y., Huang, Q., 2012. Influence of semi-aerobic and anaerobic landfill operation with leachate recirculation on stabilization processes. Waste Manag. Res. 30, 255–265. doi:10.1177/0734242X11413328

Yuen, S., Styles, J., Wang, Q., McMahon, T., 1999. Findings from a full-scale bioreactor landfill study in Australia. Proceedings Sardinia '99, 7th International Waste management and Landfill Symposium, Environmentla Sanitary Engineering Center (CISA), Cagiari, Italy.

Zeng, X.L., Ding, W.C., Long, T.R., Zhang, L.L., Lin, C.B., 2006. Influence of landfill structures on stabilization of fully recycled leachate. J. Cent. South Univ. Technol. (English Ed. 13, 321–324. doi:10.1007/s11771-006-0133-2

Zhong, Q., Li, D., Tao, Y., Wang, X., He, X., Zhang, J., Zhang, J., Guo, W., Wang, L., 2009. Nitrogen removal from landfill leachate via ex situ nitrification and sequential in situ denitrification. Waste Manag. 29, 1347–1353. doi:10.1016/j.wasman.2008.10.014

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14.3

LANDFILL BIOREACTORS

Raffaello Cossu and Valentina Grossule

INTRODUCTION

In landfill, the control of degradable organics and related environmental impacts may be achieved by a series of options:

- Avoidance of putrescible fraction in landfilled waste (separate collection);
- Prestabilization of waste prior to landfilling (thermal treatment, mechanical biological treatment, see Chapters 4.1 and 4.2);
- In situ treatment to enhance biodegradation during landfilling and/or the aftercare phase;
- A combination of the above listed options.

In recent years, the term “landfill bioreactor” has been coined specifically to indicate a landfill in which different in situ measures are undertaken to enhance biological degradation and increase removal of ammonia and recalcitrant organics. These measures may include leachate recirculation, introduction of water, and natural or forced aeration, as graphically represented in Fig. 14.3.1.

Improved control of biochemical kinetics, moisture content, and redox conditions may result in a significant shortening of the aftercare phase and consequently, in a quicker achieving of environmentally sustainable targets (Chapter 2.2).

Advantages gained by enhancing biodegradation processes in landfill bioreactors (depending on the different bioreactor models) may include the following:

- Shortening of the aftercare phase
- Reduction of environmental impacts
- Reduction of aftercare costs
- Reduction of landfill owner’s environmental liability
- Improvement of leachate quality
- Faster and time-specific biogas production
- Faster mechanical stabilization of waste mass
- Increased waste settlement and density
- Less postclosure operations required
- Removal of long-lasting compounds from traditional landfills (ammonia, recalcitrant organics, etc.)

Disadvantages (in line with type of bioreactor model) may include the following:

- Increased capital and/or management costs
- Higher complexity of construction

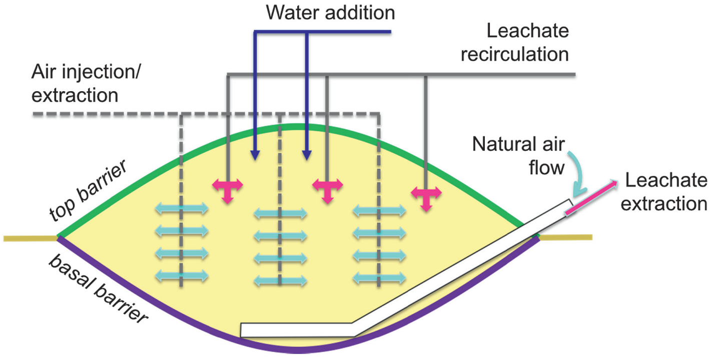

Figure 14.3.1 Scheme of the potential measures that may be adopted to enhance the biodegradation and removal of ammonia and recalcitrant organics in landfill bioreactors. Some potential theoretical measures (such as pH adjustment, sludge, or liquid waste addition) have not been mentioned.

- Energy for aeration
- More complex management and monitoring program
- Specific disadvantages may arise with leachate recirculation such as:
  - Increased odor generation
  - Risk of mechanical instability (particularly on slopes) during the operational phase due to higher moisture content
  - Higher production of leachate

According to type of bioreactor, different methane generation yields and waste stabilization rates may be achieved.

The choice of a specific bioreactor landfill is regulated by the objectives to be pursued (energy recovery landfill gas, waste stabilization, sustainability targets, etc.) and by economic issues (balance between capital and operational costs and long-term savings).

The way that each individual in situ measure affects the processes within the landfill is schematically represented in Fig. 14.3.2.

This chapter presents a series of different technologies capable of enhancing biodegradation in landfills with particular focus on hybrid bioreactors. Experiences, both on lab, pilot, and full scale, are described and outputs are discussed.

LANDFILL BIOREACTORS TYPOLOGIES

According to biodegradation conditions, landfill bioreactors can be subdivided into four main typologies: anaerobic, aerobic (aerated), semiaerobic, and hybrid, which consists in a sequence of aerobic and anaerobic conditions (Cossu et al., 2017).

The waste to be landfilled may either undergo biological pretreatment or not, to the extent of pretreatment being functional to the environmental sustainability targets.

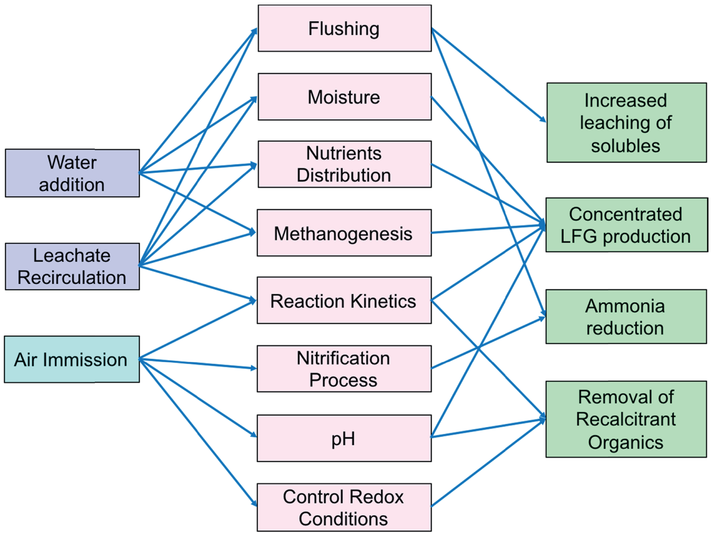

Figure 14.3.2 Graphical representation of how the most important measures that may be adopted in a landfill bioreactor can influence processes and consequent quality of emissions.

The main features of the four typologies of landfill bioreactors are graphically represented in Fig. 14.3.3.

Anaerobic Landfilling

In anaerobic landfilling, enhancement of the biodegradation process is obtained by increasing the leachate recirculation rate (Chapters 12.1 and 12.2). When the concept of landfill bioreactor was originally launched, this was the most popular model. It has been applied since the 80s in a series of landfills in the United States, Canada, Australia, and in Europe, mainly in France (i.e., Reinhart and Townsend, 1998; Pattison and Yuen, 2007; Rivière et al., 2011). This enhancement is reflected in leachate quality, with lower biochemical oxygen demand (BOD) and chemical oxygen demand (COD), when compared with traditional landfilling, and in an enhanced methane generation rate. Under anaerobic conditions ammonia is not significantly reduced. Some positive effects might be detected in relation with the flushing effect of leachate recirculation.

In some countries the regulators are reluctant to permit leachate recirculation due to concerns over an increased potential of environmental impacts and costs (Pattison and Yuen, 2007).

To overcome the problem of ammonia accumulation in anaerobic conditions, an alternative solution consists in external aerobic pretreatment of leachate prior to recirculation in the anaerobic bioreactor, to facilitate onset of both nitrification and denitrification processes and thus remove nitrogen compounds (De Abreu et al., 2005; Price et al., 2003; Berge et al., 2005; Zhong et al., 2009). The system aims to ensure the recovery of energy caused by methane production by maintaining the whole landfill in anaerobic conditions. To remediate nitrogen pollution in leachate, the latter is aerobically treated to nitrify n

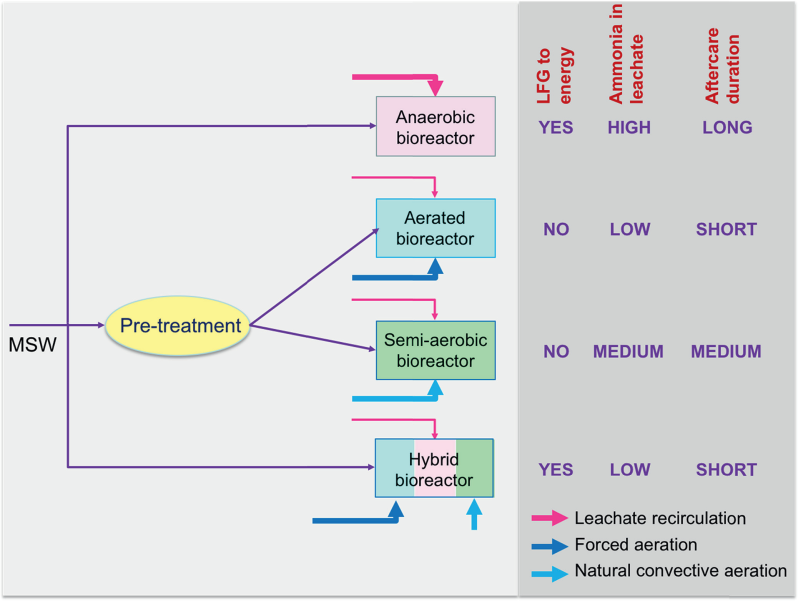

Figure 14.3.3 Scheme and general features of the different landfill bioreactor typologies.

and subsequently reinjected into the landfill to denitrify the produced nitrates. This system has also been patented in the United States (US639895, 2002) as a facultative landfill and has been tested in lab and full scale with positive results (Price et al., 2003).

Aerated Landfilling

Aerobic landfilling can be performed under forced or natural conditions: under forced conditions air is injected into the waste mass using several kinds of blower devices. In aerated landfilling, the waste should undergo preliminary pretreatment to reduce the biodegradable content and prevent a rapid increase in temperature.

A series of different technologies and strategies have been developed for use in situ aeration, including high-pressure aeration, low-pressure aeration, and active aeration with or without off-gas extraction (Ritzkowski and Stegmann, 2012; Chapter 16.2, this book).

Amongst others, nitrogen removal is one of the most significant benefits to be gained from an aerobic system (Berge et al., 2006; Shao et al., 2008). Although air injection might theoretically inhibit the denitrification process, complete aerobization of the waste mass is never achieved in a full-scale landfill, and anaerobic areas will still be present inside the landfill and both processes can take place simultaneously, even under scarcely biodegradable conditions (Berge et al., 2006; Shao et al., 2008; Ritzkowski and Stegmann, 2003, 2005; Ritzkowski, 2011; Giannis et al., 2008).

Leachate recirculation represents an additional in situ leachate treatment tool aimed at improving stabilization performance. In particular, increased frequency of leachate recirculation accelerates the stabilization rate of waste, although an excessive recirculation may result in saturation, ponding, and acidic conditions (Šan and Onay, 2001). Slezak et al. (2015) observed that the higher the recirculation rate, the higher and faster the reduction of carbon and nitrogen parameters in leachate, although O_2 diffusion was limited, thus leading to lower waste stabilization.

Kim et al. (2011) investigated the fate of metals in aerobic and anaerobic landfill bioreactors. With the exception of the initial acidic phase, the mobility of heavy metals is reduced under aerobic conditions due to high pH and positive redox conditions, affecting solubility and sorption properties of metals retained in waste by sorption, carbonate precipitation, and hydroxide precipitation (Borglin et al., 2004; Giannis et al., 2008).

Aeration rates and mode exert a varying influence on degradation performance: Slezak et al. (2010) compared stabilization performance in four aerobic lysimeters with different aeration rates, obtaining similar changes in leachate parameters, demonstrating that above the minimum aeration requirements, increased rates do not yield any additional benefit. Intermittent aeration has been demonstrated to be much more effective than continuous aeration (Cossu et al., 2015; Morello et al., 2017).

Nowadays, forced aeration is mainly applied in the remediation of old anaerobic landfills, rather than representing merely a design option for landfill management (Chapter 16.2). Moreover, aeration of landfill mass is a fundamental pretreatment for landfill mining procedures (Raga and Cossu, 2014; Ritzkowski and Stegmann, 2012).

Depending on the concentration of putrescibles in the waste (pretreated or non-pretreated waste), high temperatures may develop and waste moisture could be negatively affected (waste could dry out!). The process is energy consuming and could prove to be complex and expensive. Application of this process to a normal active landfill may create operational problems. The method is proposed and widely applied with a view to shortening aftercare time and in the remediation of old landfills (Chapter 16.2).

Semiaerobic Landfilling

The process involving natural aeration of landfills was initially proposed in Japan, in early seventies, by Hanashima at Fukuoka University (see Chapter 14.2). This system, referred to as semiaerobic landfilling or the "Fukuoka method," aims to achieve aerobization of waste mass with a proper engineering design in which ambient air naturally flows into the waste body through the leachate collection pipes, moved by the temperature gradient present inside and outside the landfill (Chapter 14.2). The semiaerobic system has been widely applied in Japan and, to a lesser extent, in many other countries. Through aerobic landfilling, BOD and COD concentrations decrease significantly; likewise, Total Kjeldhal Nitrogen (TKN) is also decreased due to the nitrification of ammonia. Methane production is low, with the exception of the initial phases. Leachate recirculation in aerobic landfills may be undertaken, although waste saturation should be carefully monitored to prevent potential obstacles in the circulation of air and extraction of the exhausted gas.

A combination of both mechanical biological pretreatement, flushing, and semiaerobic landfilling (PAF) has been suggested by Cossu et al. (2003). The results obtained with this combination have been very positive in terms of stabilization of the biomass and reduction of BOD, COD, and TKN in leachate.

Hybrid Landfilling

Hybrid landfill bioreactors are conceptually based on the principle of combining both aerobic and anaerobic processes by alternating over time aeration of the waste mass. The main purpose is to achieve the benefits yielded by the two systems (Cossu et al., 2017):

- Significant enhancement of biodegradation and shortening of aftercare time
- Leachate with lower concentrations of BOD and COD
- Nitrification of ammonia and denitrification
- Degradation of recalcitrant compounds such as lignin and aromatic substances
- Better control of pH during acidic enzymatic hydrolysis by early oxidation of the most putrescible substances.
- Quicker and more concentrated production of methane
- Enhancement of biogas generation

The immission of air could be implemented by means of either natural or forced aeration.

The sequencing of aerated and non-aerated phases, aeration mode (continuous or intermittent), and the duration of these characterizes the different schemes of hybrid bioreactors that have been proposed as summarized in Fig. 14.3.4.

Aerobic–Anaerobic Sequencing

The mechanical biological pretreatment of waste prior to anaerobic landfilling may be regarded as a kind of hybrid reactor, with off-site forced aeration followed by in situ anaerobic reactions. MBP is aimed at achieving rapid stabilization of the landfilled waste, although the resulting production of landfill gas may not be sufficient for energetic exploitation.

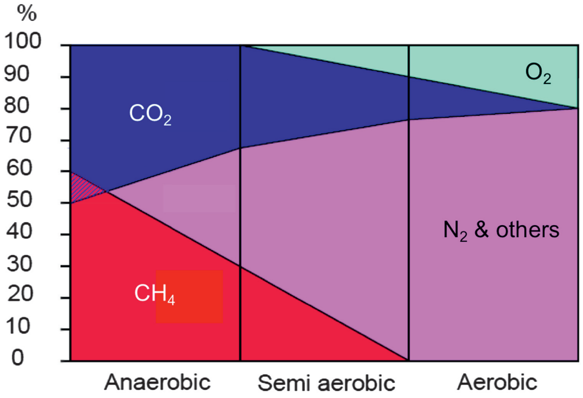

Figure 14.3.4 Composition of landfill gases in anaerobic, semiaerobic, and aerobic bioreactors (Grossule et al., 2018).

Aerobic—anaerobic sequencing may be applied completely in situ. However, in this case, preliminary aeration of the waste mass, rather than stabilizing the waste, would be mainly focused on accelerating the initial acidogenic phase, achieving optimum pH and VFA conditions for methanogenesis much earlier (Mali Sandip et al., 2012; Xu et al., 2014; Morello et al., 2017). Cossu et al. (2015) tested aerobic—anaerobic hybrid bioreactors with continuous and intermittent aeration up until an optimum pH and VFA concentration for methanogenesis was achieved. Both aeration modes were beneficial in accelerating waste stabilization and acidogenic phase, however, intermittent aeration up until optimum pH values was more efficient in enhancing stabilization kinetics and methane generation.

Anaerobic—Aerobic Sequencing

An example of double stage AN-AE is provided by application of the aeration technology to the remediation of old landfills, (Ritzkowski and Stegmann, 2012, Chapter 16.2). The lengthy duration of the anaerobic process over the life span of the landfill is followed by forced aeration. The same technology may also be applied to modern anaerobic landfills to shorten the aftercare phase, once the biogas generation has dropped to a level no longer viable for energy exploitation. Lab scale tests have shown that residual recalcitrant organics left over from the anaerobic phase are degraded under aerobic conditions (Long et al., 2009).

Aerobic—Anaerobic—Aerobic Sequencing

Three step sequencing promotes the best removal efficiency for ammonia (Repetti et al., 2013; Cossu et al., 2015; Morello et al., 2017).

A scheme proposed by Repetti et al. (2013), known as S.An.A, includes a first semiaerobic step followed by an anaerobic phase and subsequently forced aeration. Column tests were performed and the results obtained were quite encouraging (Morello et al., 2017).

This scheme may require the preliminary treatment of waste to reduce putrescibles content.

Other schemes could include the following:

- Preliminary forced aeration to remove readily degradable organics and enhance biogas generation
- Anaerobic phase for massive production of biogas
- Aerobic phase (semiaerobic or forced aeration) shorten the aftercare duration

Compared Performance

The composition of gas generated by the various bioreactor alternatives is represented in Fig. 14.3.5. Under anaerobic conditions, during the methanogenic phase, composition ranges typically around 60% CH_4 and 40% CO_2 (by vol.), with consequent CH_4/CO_2 ratio values in the range of 1.5. Values from lab-scale tests are consistent with full-scale landfill reactor interstitial gas concentration during stable methanogenic phase (Raga and Cossu, 2014; Ritzkowski and Stegmann, 2007). Under semiaerobic conditions, the CH_4/CO_2 ratio is around 0.48 (Jeong et al., 2015) with methane ranging between 0 and 30%, CO_2 from 10% to 30%, oxygen 0%—10%, with the remainder largely constituted by N2.

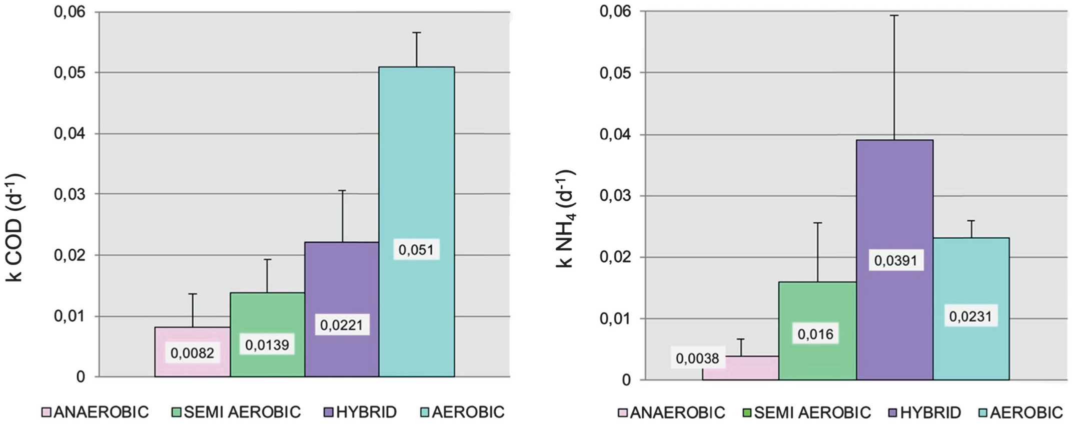

Figure 14.3.5 Mean values and associated standard deviations of ammonia and chemical oxygen demand (COD) removal kinetics associated with the individual landfill bioreactor typologies (Grossule et al., 2018).

Grossule et al. (2018) analyzed the results of several studies and experiences of enhanced degradation carried out using the various bioreactor landfill technologies. Assuming an overall first-order kinetics for the conversion (biodegradation, flushing, volatilization, etc.) of COD and $N{-}NH_4$ in leachate, they calculated the kinetics constant k and standard deviations for both parameters in relation to the different technologies (Fig. 14.3.5).

Despite the variety of operational conditions adopted in the studies (recirculation rate, waste composition, L/S ratio, air injection and experimental period, scale of the testing), all methods significantly reached similar conclusions, with values ranging around the mean value. The benefits yielded by aerobic conditions are evident in the maximization of COD removal with 0.051 day^{-1} average COD removal kinetic. The performance of hybrid and semi-aerobic bioreactors was situated midway between the anaerobic and aerobic reactors, displaying 0.0221 day^{-1} and 0.0139 day^{-1} average k values. On the contrary, for ammonia the best results were obtained with hybrid reactors ($k_{N\text{-}NH4} = 0.0391$ day^{-1}). The higher variability of values around the mean, however, renders these results particularly reliable as they were strongly influenced by the specific hybrid reactor application.

By calculating mean COD and ammonia removal kinetics, it is easy to predict and compare the required stabilization time for each bioreactor typology as representative average behavior. Considering the same starting point for COD and ammonia concentrations in reference to time (T) required under aerobic conditions to obtain 95% contaminant removal (Fig. 14.3.6), the time required to achieve the same rate of COD removal under hybrid, semiaerobic, and anaerobic conditions is increased by 2.3, 3.7 and 6.2-fold, respectively. In the case of ammonia removal, the time is reduced by 0.7-fold under hybrid conditions, whereas it increases by 1.7 and 3.7-fold under semiaerobic and anaerobic conditions, respectively.

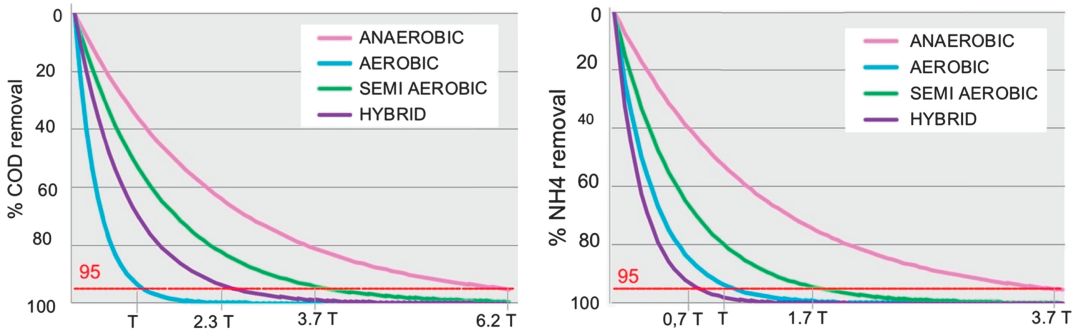

Figure 14.3.6 Variation of % chemical oxygen demand (COD) and % ammonia removal over time according to the mean removal kinetics in Fig. 14.3.5 versus time for the different bioreactor models. T is the assumed reference time corresponding to the time required to achieve 95% removal under aerobic (aerated) conditions. For both graphs, a common starting concentration was assumed for all models (Grossule et al., 2018).

To achieve a 95% removal of COD with an anaerobic landfill bioreactor, a period 6.2-fold higher than under aerobic conditions is required.

With regards to ammonia, hybrid reactors have displayed better performances than aerated bioreactors, achieving a 95% removal rate in a time below the reference time.

FINAL REMARKS

Landfill bioreactors, by implementing different in situ measures for the enhancement of biodegradation of putrescible waste, such as leachate recirculation and air immission, may elicit a significant shortening of the aftercare phase. Anaerobic bioreactors produce an improvement in methane generation rate but exert no relevant impact on ammonia accumulation, with degradation kinetics remaining slow. Aerated reactors increase ammonia and COD removal kinetics up to 10-fold those obtained under anaerobic conditions; they therefore represent an effective alternative to traditional anaerobic processes, although the need for forced ventilation systems, the complexity of operation and management, and high energy consumption associated with high operational and capital costs often fail to render aerated landfill a technically and economically feasible option. Semiaerobic landfill achieves a performance rate situated midway between that obtained by anaerobic and aerobic reactors, although with lower operational costs. Naturally, recourse to aerobic and semiaerobic landfills does not provide the possibility of energetic exploitation of landfill gas.

Hybrid bioreactors, operated under various combinations of aerobic and anaerobic conditions, may achieve energy recovery, fast waste stabilization, and significant removal of ammonia by means of a combination of nitrification–denitrification processes.

In view of the rigorous operational and construction requirements of bioreactor landfills, the required capital and operating costs are higher than those of traditional landfills. However, these increased costs will be compensated by the provision of future economic gains from bioreactor landfills, including a shorter aftercare period, reduced leachate treatment costs, reduced long-term environmental risks, longer active life of the landfill, earlier reuse of the land (Berge et al., 2009; Read et al., 2001).

Despite the successful results obtained at lab scale, full-scale testing should be undertaken in to assess the technical and economic feasibility of these systems.

Indeed, the widespread diffusion of landfill bioreactors is hindered by the above-stated high costs and continuing reluctance of regulators, who have expressed concern over the potential short-term environmental impacts, scarce maturity of the technologies, and the technical skill of landfill operators in implementing advanced technologies (Pattison and Yuen, 2007). Studies carried out to date have demonstrated that benefits achieved in lab-scale tests are much higher than those obtained in full-scale application, largely due to the reproduction of optimum homogeneous conditions in the laboratory (Ritzkowski and Stegmann, 2012; Kylefors et al., 2003). However, assessment of the general behavior of each type of bioreactor at lab scale will facilitate identification of the most appropriate bioreactor options to be used on a large scale, in line with the objectives established and in situ conditions.

References

Berge, N.D., Reinhart, D.R., Townsend, T.G., 2005. The fate of nitrogen in bioreactor landfills. Critical Reviews in Environmental Science and Technology 35, 365–399. https://doi.org/10.1080/10643380590945003.

Berge, N.D., Reinhart, D.R., Dietz, J., Townsend, T., 2006. In situ ammonia removal in bioreactor landfill leachate. Waste Management 26, 334–343. https://doi.org/10.1016/j.wasman.2005.11.003.

Berge, N.D., Reinhart, D.R., Batarseh, E.S., 2009. An assessment of bioreactor landfill costs and benefits. Waste Management 29, 1558–1567. https://doi.org/10.1016/j.wasman.2008.12.010.

Borglin, S.E., Hazen, T.C., Oldenburg, C.M., Zawislanski, P.T., 2004. Comparison of aerobic and anaerobic biotreatment of municipal solid waste. Journal of the Air & Waste Management Association. https://doi.org/10.1080/10473289.2004.10470951.

Cossu, R., Raga, R., Rossetti, D., 2003. The PAF model: an integrated approach for landfill sustainability. Waste Management 23, 37–44. https://doi.org/10.1016/S0956-053X(02)00147-2.

Cossu, R., Morello, L., Dongbei, Y., 2015. Hybrid bioreactor landfill: a review of the possible systems. In: Proceedings of Sardinia 2015. Fifteenth International Waste Management and Landfill Symposium, S. Margherita di Pula, Cagliari, Italy; 5–9 October 11.

Cossu, R., Lavagnolo, M.C., Morello, L., Pivato, A., Raga, R., Yue D., 2017. Role of semi-aerobic phase in hybrid landfilling: the S.AN.A method. In: Proceedings of Sardinia. Sixteenth International Waste Management and Landfill Symposium. S. Margherita di Pula, Cagliari, Italy; 2-6.

De Abreu, R., La Motta, E., McManis, K., 2005. Facultative landfill bioreactors (FLB): results of a pilot-scale study. Waste Containment Remediat 1–13.

Giannis, A., Makripodis, G., Simantiraki, F., Somara, M., Gidarakos, E., 2008. Monitoring operational and leachate characteristics of an aerobic simulated landfill bioreactor. Waste Management 28, 1346–1354. https://doi.org/10.1016/j.wasman.2007.06.024.

Grossule, V., Morello, L., Cossu, R., Lavagnolo, M.C., 2018. Bioreactor Landfills: comparison and kinetics of the different systems. Detritus, 03, 100–113. https://doi.org/10.31025/2611-4135/2018.13703.

Jeong, S., Nam, A., Yi, S.M., Kim, J.Y., 2015. Field assessment of semi-aerobic condition and the methane correction factor for the semi-aerobic landfills provided by IPCC guidelines. Waste Management 36, 197–203. https://doi.org/10.1016/j.wasman.2014.10.020.

Kim, H., Jang, Y.C., Townsend, T., 2011. The behavior and long-term fate of metals in simulated landfill bioreactors under aerobic and anaerobic conditions. Journal of Hazardous Materials 194, 369–377. https://doi.org/10.1016/j.jhazmat.2011.07.119.

Kylefors, K., Andreas, L., Lagerkvist, A., 2003. A comparison of small-scale, pilot scale and large -scale tests for predicting leaching behaviour of landfilled wastes. Waste Management 23, 45—59.

Long, Y., Long, Y.Y., Liu, H.C., Shen, D.S., 2009. Degradation of refuse in hybrid bioreactor landfill. Biomedical and Environmental Sciences: BES 22, 303—310. https://doi.org/10.1016/S0895-3988(09)60060-X.

Mali Sandip, T., Khare Kanchan, C., Biradar Ashok, H., 2012. Enhancement of methane production and bio-stabilisation of municipal solid waste in anaerobic bioreactor landfill. Bioresource Technology 110, 10—17. https://doi.org/10.1016/j.biortech.2011.12.027.

Morello, L., Raga, R., Lavagnolo, M.C., Pivato, A., Ali, M., Yue, D., Cossu, R., 2017. The S.An.A.® concept: semi-aerobic, Anaerobic, Aerated bioreactor landfill. Waste Management. https://doi.org/10.1016/j.wasman.2017.05.006.

Pattison, E.C., Yuen, S.T.S., 2007. Obstacles to progression of landfill bioreactor technology in Australia. In: Proceedings of International Solid Waste Association (ISWA) World Congress 2007, Amsterdam, 24—27 September 2007.

Price, G.A., Barlaz, M.A., Hater, G.R., 2003. Nitrogen management in bioreactor landfills. Waste Management 23, 675—688. https://doi.org/10.1016/S0956-053X(03)00104-1.

Raga, R., Cossu, R., 2014. Landfill aeration in the framework of a reclamation project in Northern Italy. Waste Management 34, 683—691. https://doi.org/10.1016/j.wasman.2013.12.011.

Read, A.D., Hudgins, M., Phillips, P., 2001. Aerobic landfill test cells and their implications for sustainable waste disposal. Geographical Journal 167, 235—247. https://doi.org/10.1111/1475-4959.00021.

Reinhart, D.R., Townsend, T.G., 1998. Landfill Bioreactor Design and Operation. Lewis Publishers, Boca Raton, FL, ISBN 1-56670-259-3, p. 189.

Repetti, R., Testolin, G., Cossu, R., Raga, R., 2013. Discarica S.AN.A?: Un sistema innovativo per la sostenibilità ambientale delle discariche. In: Proceedings Sardinia 2013. Fourteenth International Waste Management and Landfill Symposium, S. Margherita di Pula, Cagliari, Italy, 30 September—4 October 2013.

Ritzkowski, M., 2011. How does landfill aeration impact on leachate composition ?. In: Proceedings Sardinia 2011, Thirteenth International Waste Management and Landfill Symposium S. Margherita di Pula, Cagliari, Italy; 3—7 October 2011.

Ritzkowski, M., Stegmann, R., 2003. Emission behaviour of aerated landfills : results of laboratory scale investigations. In: Proceedings Sardinia 2003, Ninth International Waste Management and Landfill Symposium. S. Margherita di Pula, Cagliari, Italy; 6—10 October 2003.

Ritzkowski, M., Stegmann, R., 2005. Mechanisms affecting the leachate quality in the course of landfill in situ aeration. In: Proceedings Sardinia 2005, Tenth International Waste Management and Landfill Symposium. S. Margherita di Pula, Cagliari, Italy; 3—7 October 2005.

Ritzkowski, M., Stegmann, R., 2007. Controlling greenhouse gas emissions through landfill in situ aeration. International Journal of Greenhouse Gas Control 1, 281—288. https://doi.org/10.1016/S1750-5836(07)00029-1.

Ritzkowski, M., Stegmann, R., 2012. Landfill aeration worldwide: concepts, indications and findings. Waste Management 32, 1411—1419. https://doi.org/10.1016/j.wasman.2012.02.020.

Rivière, D., Vigneron, V., Baffaleuf, N., Le Lay, G., Guerbois, M., Rivero, J.C., 2011. Diagnostic of a French bioreactor landfill after 8.5 years of degradation. In: Proceedings Sardinia 2011, Thirteenth International Waste Management and Landfill S Ymposium. CISA Publisher, ISBN 978-88-6265-000-7.

Šan, I., Onay, T.T., 2001. Impact of various leachate recirculation regimes on municipal solid waste degradation. Journal of Hazardous Materials 87, 259—271. https://doi.org/10.1016/S0304-3894(01)00290-4.

Shao, L.M., He, P.J., Li, G.J., 2008. In situ nitrogen removal from leachate by bioreactor landfill with limited aeration. Waste Management 28, 1000—1007. https://doi.org/10.1016/j.wasman.2007.02.028.

Slezak, R., Krzystek, L., Ledakowicz, S., 2010. Simulation of aerobic landfill in laboratory scale lysimeters - effect of aeration rate. Chemical Papers 64, 223—229. https://doi.org/10.2478/s11696-009-0113-8.

Slezak, R., Krzystek, L., Ledakowicz, S., 2015. Degradation of municipal solid waste in simulated landfill bioreactors under aerobic conditions. Waste Management 43. https://doi.org/10.1016/j.wasman.2015.06.017.

US6398958 B1, 2002. Hater, G. R., Green, R. B., Harris, J. M. Patent Facultative Landfill Bioreactor. Waste Management Inc.

Xu, Q., Jin, X., Ma, Z., Tao, H., Ko, J.H., 2014. Methane production in simulated hybrid bioreactor landfill. Bioresource Technology 168, 92—96. https://doi.org/10.1016/j.biortech.2014.03.036.

Zhong, Q., Li, D., Tao, Y., Wang, X., He, X., Zhang, J., Zhang, J., Guo, W., Wang, L., 2009. Nitrogen removal from landfill leachate via ex situ nitrification and sequential in situ denitrification. Waste Management 29, 1347—1353. https://doi.org/10.1016/j.wasman.2008.10.014.

Paper V. Lab tests on semi-aerobic landfilling of MSW under varying conditions of water availability and putrescible waste content

Grossule, V., Lavagnolo, M.C., 2019. Lab tests on semi-aerobic landfilling of MSW under varying conditions of water availability and putrescible waste content. Submitted to Journal of Environmental Management (19/9/2019)

Lab tests on semi-aerobic landfilling of MSW under varying conditions of water availability and putrescible waste content

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Keywords: environmental sustainability, landfill bioreactor, long term emissions, semi aerobic landfilling

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ABSTRACT

The aim of this study was to investigate the stabilization performance and the optimal control of semi-aerobic landfilling under inverse conditions of water availability (high and low) and content of putrescible waste fraction (high and low). Six lysimeters were specifically set up: two simulating wet conditions, two dry conditions, and two artificially controlled watering under dry conditions. In each pair of lysimeters one was filled with waste with a low putrescible content and the other with waste with a high putrescible content. Quality and quantity of emissions were regularly monitored. Concentrations of mobile ammonia and total organic carbon (TOC) in landfilled waste were modelled by means of first-order kinetics, and carbon and nitrogen mass balances were calculated. The best performance for the semi-aerobic process was achieved at a water availability around 1.5-2.4 $kgH_2O/kgTS$, under the following two combinations: a) Waste with high putrescible content and no addition of external water; b) waste with low putrescible content and controlled watering.In both cases the stability parameters proved to be quite satisfactory (Respiration index in 4 days, RI_4 = 12.25-12.87 mgO_2/gTS, BOD/COD ratio in leachate < 0.04-0.05).

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1. INTRODUCTION

One of the major issues in the landfilling of waste is compliance with environmental sustainability in terms of control of long-term emissions (gas and leachate) and compliance with the Final Storage Quality (FSQ) of the landfill (Cossu and Pivato, 2018; Cossu and van der Sloot, 2014; Laner et al., 2012). FSQ is defined as a set of values of different parameters to be achieved within the span of one generation, representing an acceptable equilibrium between the landfill and the environment.

In order to achieve sustainability targets a combination of treatments (mechanical, chemical, biological and thermal) should be implemented throughout the different life phases of a landfill (prior to waste deposition, in situ during operations and during the post-care phase) aimed at stabilizing the waste and reducing the long-term mobility of contaminants.

Biological stabilization is the main target when dealing with Municipal Solid Waste (MSW), particularly as environmental impacts deriving from landfilling originate largely from putrescible fractions in the waste (emission of methane and CO_2, emission of organic contaminants and ammonia nitrogen associated to leachate, odours, risks of fires, etc.).

Biological stabilization may be achieved through appropriate pre-treatment (Mechanical Biological Pre-treatment) or by in-situ aeration of the landfilled waste through natural ventilation or forced aeration (Ritzkowski and Stegmann, 2012). The natural ventilation method, also known as semi-aerobic system or "Fukuoka method", was originally proposed and studied at the University of Fukuoka, Japan (Broun and Sattler, 2016; Hanashima et al., 1981). The method is based on a specific landfill design (network of vertical and horizontal pipes, granular media beds, etc.) which promotes air circulation through a difference of temperature between the waste mass and external environment (Matsufuji et al., 2018; Schwinge et al., 2004). Benefits to be gained from passive aeration of the waste mass have been confirmed by several studies (see Aziz et al., 2010; Grossule et al., 2018).

Specific in-situ conditions, such as climate conditions and waste composition, should be carefully considered, as they may strongly influence landfill stabilisation performance (Chanton et al., 2011; De La Cruz and Barlaz, 2010; Esteban-Altabella et al., 2017; Grossule et al., 2018; Levis and Barlaz, 2011). The main factors in controlling stabilization performance of the semi-aerobic method are: a) Water availability; b) Putrescible organic content in the landfilled waste; c) Temperature gradient between the waste mass and the external ambient.

Water availability (rainfall infiltration, waste moisture, leachate recirculation, flushing, etc.) plays a series of positive and negative roles in landfilling. It provides a fundamental reagent for the biodegradation process (enzymatic hydrolysis) and flushes soluble compounds from the waste mass, also allowing the removal of non-degradable contaminants; it reduces the free porosity of waste, slowing down or even blocking advective air flow.

The putrescible fraction in the waste drives the kinetics of biological degradation in terms of emission quality and bacterial growth. Bacterial growth may impair the porosity of the granular drainage media, often resulting in clogging phenomena. As a consequence, this would reduce the advective circulation of air, thus enhancing anaerobic processes. The generation of significant gas volumes with high methane content would negatively influence the overall quality of gas generated by the semi-aerobic system, since it is normally released untreated into the atmosphere. In addition, high moisture content of putrescible waste, may reduce permeability of the waste mass to gas, again resulting in a reduction of the advective circulation of air.

The presence of putrescible waste in MSW to be landfilled is related to several factors, including seasonal variations, cultural practices, social and economic conditions, source segregation and separate collection, entity and type of waste pre-treatment. Typically, high concentrations of putrescible wastes (kitchen waste, green waste, etc.) are present in wastes from developing countries (DCs) and from rural areas in industrial countries. Conversely, low concentrations may be encountered in countries where thermal waste treatment is widely adopted (e.g. Japan) or where source segregation of putrescible fraction or Mechanical Biological Pre-treatment is promoted (e.g. European countries), or where the percentage of kitchen and food residues in the waste is limited by different cultural practices (canned food, more packaging material, WEEE, etc.), or by use of kitchen shredders that divert food waste to the sewage network (e.g. United States).

Numerous aspects of semi-aerobic landfilling have been investigated to date, including engineering features, vertical or horizontal piping, type of materials, fluid-dynamics, and influence of morphology (Ahmadifar et al., 2016; Aziz et al., 2010; Hirata et al., 2012; Huang et al., 2008; Matsuto et al., 2015; Morello et al., 2017; Theng et al., 2005; Wu et al., 2017; Yang et al., 2012).

But from the point of view of the process, semi-aerobic landfilling has generally been considered a black box. This does not allow to explain the marked differences in the performance of full-scale semi aerobic landfills operating all over the world (Grossule et al., 2018; Matsufuji et al., 2018).

Although water availability and putrescible waste content are so important in controlling the semi-aerobic landfill processes a comparative systematic study has not to date been carried out.

The aim of this study was to investigate, in lab scale lysimeters, stabilization performance of semi-aerobic landfill under extreme conditions of these two factors which may be encountered with different climate and socio economic conditions. Contrary to a full-scale landfill, a lab scale plant will promote a better systematic control of the variables of interest (water availability, putrescible waste content), avoiding interferences from site specific conditions (depth, density, management, etc.).

The performance of the different lab scale lysimeters was compared in terms of waste stabilization, leachate and gas quality. A mass balance for carbon and nitrogen was calculated and the contaminants removal kinetics defined.

2. MATERIALS AND METHODS

2.1. Waste samples

Two different types of waste were tested, reproducing Municipal Solid Waste (MSW) with Low Putrescible (LP) and High Putrescible (HP) content.

LP waste was represented by the residues from MSW source segregation collected at the Legnago (Verona, North Italy) waste management facilities. Kitchen wastes in the residue corresponded to 9% wt wet. The sample was shredded to yield a homogeneous granulometry (≤ 6 cm).

HP waste was obtained by mixing LP waste with source segregated kitchen waste to achieve a 50 % (wet wt).

Main fractions (expressed by wet weight percentages) in LP waste were represented by undersieve (27%), paper (20%), plastic (18%), composites (10%), glass and inert (9%) and kitchen residues (9%). Wooden materials, textiles and metals were about 3%, 2% and 2% respectively. Total solids (TS), volatile solids (VS), Total organic carbon (TOC) and Respirometric Index at day 4 (RI_4) were respectively 56.9%, 72.7 %(TS), 34.5 gC/gTS, 38.4 mgO_2/gTS in LP waste and 39.5%, 84.4%(TS), 40.3 gC/gTS, 93.3 mgO_2/gTS in HP waste.

2.2. Equipment

The experiment was carried out in six cylindrical Plexiglass lysimeters (1 m height, inner diameter of 40 cm). Each column was equipped at the bottom with a slotted pipe (8 cm diameter), open to air.

A layer of 20 cm gravel (size 16-32 mm) was placed at the bottom of lysimeters to allow leachate drainage and facilitate air circulation. The columns were filled with 27 kg waste, reaching an approximate compaction of 0.5 kg/L. A 5 cm layer of the same sized gravel was placed on top of the waste to ensure a uniform water irrigation.

Gas sampling valves were fitted laterally, while leachate was collected at the bottom of each column. Columns were thermally insulated by a coating system made of polyethylene. Temperature in each column was monitored by using thermocouples (Thermo Systems TS100). A perforated plate placed at the top of each column allowed a uniform water irrigation (Figure 1).

The reactors operated in a thermally controlled room.

2.1. Methodology

Lysimeters were arranged in three pairs, simulating different water input conditions each: wet climate conditions (W columns), absence of precipitation under dry climate conditions (D columns) and controlled water input for appropriate moisture content (C columns). In each pair of lysimeters, one was filled with low putrescible waste (LP) and the other with high putrescible waste (HP).

A water irrigation rate of 3 L/d was adopted in W columns reproducing the water infiltration of an yearly mean precipitation of 1400 mm. This

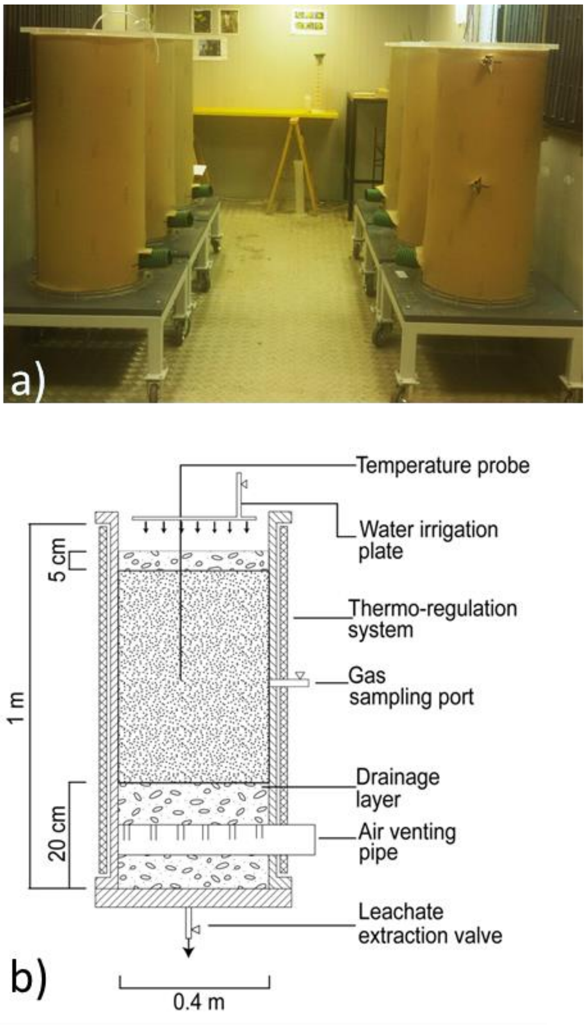


Figure 1. a) Semi-aerobic reactors set up; b) Construction scheme of individual reactors.

corresponded to a liquid to solids ratio (L/S) ranging between 20.7 and 14.4 L/kgTS in columns W-HP and W-LP respectively. No water was added to D columns, reproducing dry climate conditions. In C columns water input (0.25 L/d) was intended to reproduce an optimal value for biodegradation with a final L/S ratio of 2.2 and 1.6 L/kgTS in C-HP and C-LP columns, respectively, as suggested by Lavagnolo et al. (2018).

As the day and night cycle may significantly influence the temperature gradient between the waste mass and the external ambient temperature (which is governing the convective natural air circulation in semi-aerobic landfilling) the ambient temperature values in the testing room were varied and maintained between 18°C (night simulation) and 30°C (day simulation).

During the experimental test, solid, liquid, and gas samples were analysed according to International Standard Methods. Biogas concentrations of CO_2, CH_4 and O_2 were monitored by using Eco-Control LFG20 analyser.

At the beginning and at the end of the tests, waste was sampled from each reactor for measuring the following parameters: RI_4, Total Carbon (TC), TOC, Total Kjeldahl Nitrogen (TKN), TS and VS. TC and TOC on solid samples were determined using a TOC–VCSN Shimadzu Analyzer. RI_4 was measured by using a Sapromat respirometer (H+P Labortechnik, Germany).

pH, alkalinity, TS and VS, volatile fatty acids (VFA), chemical oxygen demand (COD), TC and TOC, five-day biochemical oxygen demand (BOD_5), nitrogen compounds (TKN, ammonia, nitrate, nitrite) and chlorides, were regularly analysed in leachates.

3. RESULTS AND DISCUSSION

3.1. Temperatures

In general, temperature values inside the waste mass were higher in “LP” columns (with respect to “HP” ones) and in dry conditions when considering the same waste type. This suggested that the higher the water availability the lower the temperature. In particular, at the beginning of the test D-LP and D-HP columns achieved the highest values, around 58°C and 45°C, respectively. High temperature values (up to 75 °C) have been observed by several studies on semi-aerobic landfills (i.a. Huang et al., 2008). More intense degradation processes in C-LP and D-HP columns resulted in temperature values remaining higher than ambient values for a longer period of time compared to the other columns.

3.2. Landfill gas composition

The concentration of the most significant LFG components (CH_4, CO_2 and O_2) are represented in the stacked area chart in Figure 2, jointly with the stability trend line and water availability (wa). Water availability can be defined as follows (Eq. 1):

$$wa = ew + L/S = u \cdot \frac{kg\ waste}{kg\ TS} + L/S \quad Eq\ (1)$$

Where:

wa: water availability (kgH_2O/kg TS)

ew: endogenous water (kgH_2O/kg TS) = $u \cdot \frac{kg\ waste}{kg\ TS}$

L/S: liquid (input water) over solid ratio (kgH_2O/kg TS) in a given time.

u: moisture in waste to be landfilled (kgH_2O/kgwaste).

At the beginning of the experiment, CO_2 concentration in all lysimeters was around 20-30% with very low oxygen concentration (below 5%) consequently to the aerobic conversion of the most readily-biodegradable fractions. On the contrary, in column D-LP, O_2 concentrations was higher (7-8%) as the low putrescible content and the low water availability (wa=0.8 kgH_2O/kgTS) reduced biodegradation and favoured air circulation by the increased free porosity.

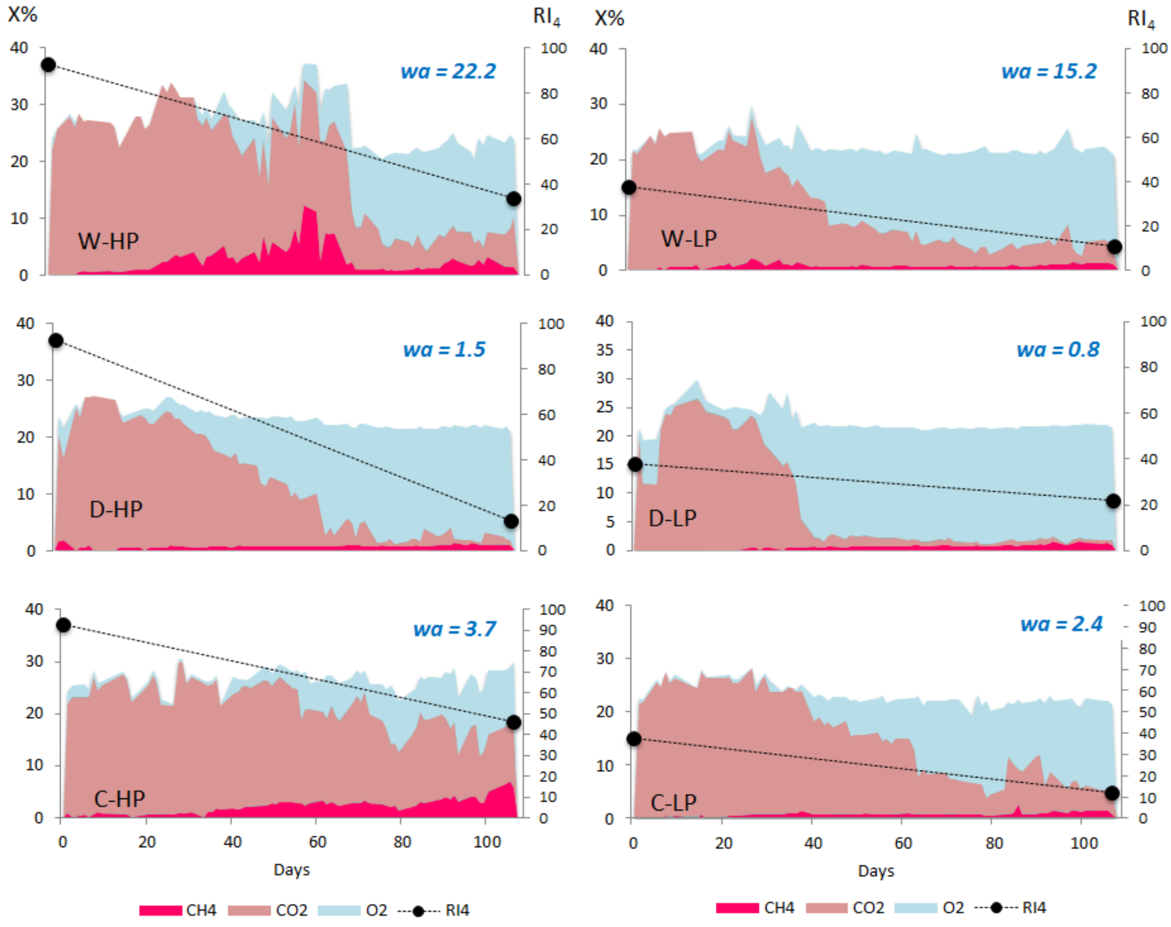


Figure 2. Landfill gas (LFG) composition (Stacked area chart) and waste stabilisation in the lysimeters, along the testing time. (X%: volumetric gas fractions, % v/v; RI4: 4 days Respirometric Index, mgO2/kgTS; wa: water availability, kgH2O/kgTS). Nitrogen gas is not represented. The line associated to RI4 is not representing the temporal trend of the parameter but it facilitates the reading of the charts. W=Wet conditions, D=Dry conditions, C=Controlled watering; HP=Waste with high putrescible content; LP=Waste with low putrescible content.

Generally methane generation started after 10-25 days and fluctuated according to the waste type and the water availability. Faster decrease in CO_2 concentrations was observed in columns filled with the lower putrescible fraction content (LP). When comparing columns filled with the same waste type, a more rapid CO_2 decrease was observed in D columns (low *wa* conditions). In D-HP column, CO_2 decrease was indicative of a fast waste stabilisation, yielding the lowest RI_4 value among "HP" columns (Figure 2). Conversely, the sudden CO_2 decrease observed in D-LP column was due to a lack of moisture which halted the biodegradation process, as confirmed by the highest RI_4 final value among "LP" columns (Figure 2). Waste stability improved in "LP" columns on increasing water availability. On the contrary, in "HP" columns a *wa* higher than 1.5 (columns W-HP, C-HP) resulted in a lower waste stabilisation (higher RI_4 values), leading to anaerobic conditions and to highest methane concentrations (up to 10%). Similar methane concentration was detected by Ahmadifar et al. (2016) using waste with 80% putrescible fraction. In both columns under wet conditions (W) the decrease of CO_2 was more evident than under controlled watering conditions (C) due to the considerably higher water availability, resulting in a higher flushing effect of degradable carbon (more in leachate, less in the gas). In all columns, biogas concentrations were comprised in the typical range found in literature, as summarised by Grossule et al. (2018).

3.3. *Leachate quality and quantity*

During the experiment, leachate production ranged between 83% *wa* (in wet column with "HP") and 15% *wa* (in dry column with HP) (Figure 3). No leachate production occurred in D-LP column.

Figure 3 illustrates, by using stacked area chart, the concentrations variation vs time of nitrogen fractions ($N\text{-}NH_4^+$, N Org, NO_2^- and NO_3) analysed in the leachate from the different columns. The water availability (*wa*) vs. time line is also represented.

Higher TKN concentrations occurred in "HP" columns. On comparing columns with the same waste type, the lowest concentrations of N Org and $N\text{-}NH_4^+$, and lack of NO_2^- and NO_3^- were observed in W columns due to the higher dilution effect and restricted oxidation induced by the higher water availability. Conversely, effective nitrification occurred in C columns and in D-HP. In particular, mainly oxidised nitrogen compounds were present in leachate of D-HP column. Final ammonia concentrations were 50, 25, 38, and 8 $mgN\text{-}NH_4^+/L$ in C-HP, C-LP, W-HP, and W-LP, respectively.

Figure 4 illustrates, in a logarithmic overlapped area, TOC and VFA concentrations vs. time, jointly with pH trend line. The effect of a more intense waste passive aeration in columns C is clearly reflected in pH values constantly above pH 7. On the contrary, the flushing effect in wet columns (W) caused predominantly acidic conditions (pH<7) with high VFA concentration (300-1000 $mgCH_3COOH$) and lower buffering alkalinity compared to C columns. Consistently with nitrogen compounds, lowest TOC and VFA concentrations and faster VFA reduction occurred: in low putrescible columns (LP) when comparing waste types; in D-HP and W columns when comparing water availability conditions. In latter case the main driving phenomenon was the flushing effect due to high water availability.

C-HP, C-LP, W-HP, and W-LP columns achieved a final TOC concentration of 865, 698, 85, and 57 mgC/L, respectively.

COD and BOD concentrations in leachate during the test period are illustrated in the stacked area chart of Figure 5, jointly with BOD/COD ratio trend. The above considerations on TOC and VFA trends also apply for BOD and COD in all columns.

3.4. *Flushing and biodegradation*

In the wet columns (W) the two main effects of water addition (i.e. waste biostabilization and flushing of contaminants) are combined. In order to selectively analyse their individual contribution to ammonia ($N\text{-}NH_4^+$) and TOC removal, column C was set up. Watering was

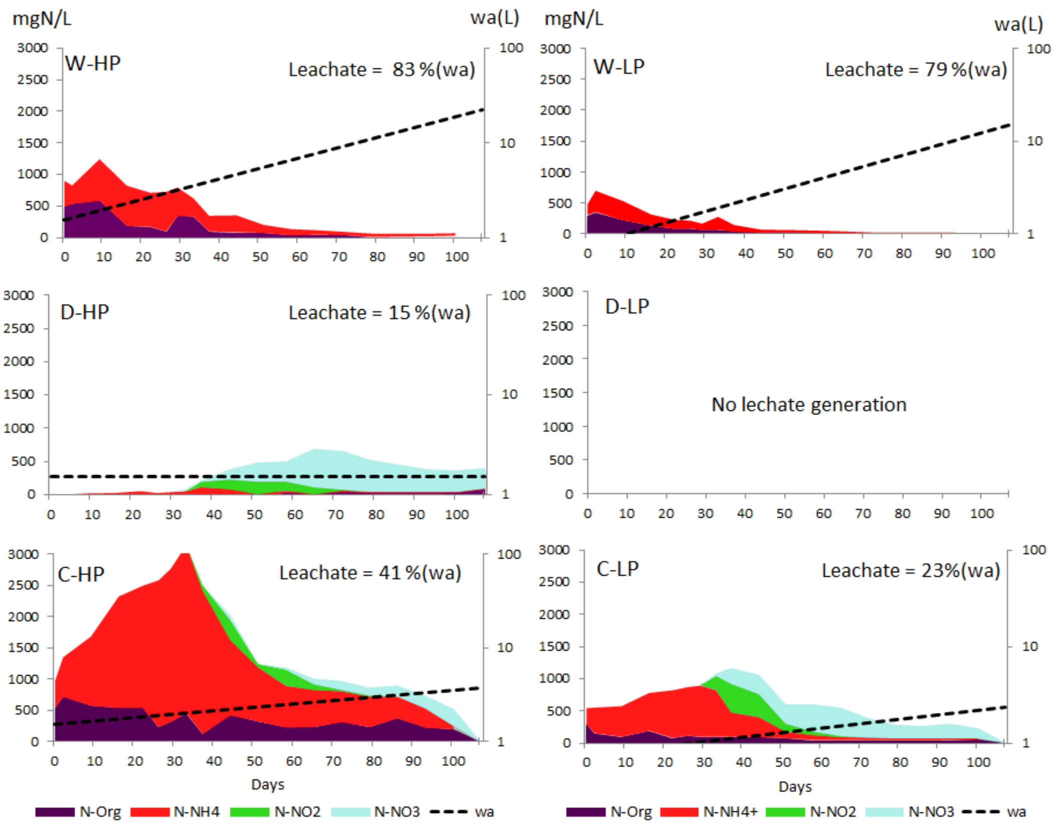


Figure 3. N-NH4+, N organic, NO2-, NO3- concentrations in leachate (Stacked area chart) vs. testing time measured for each individual lysimeter. wa (L)= water availability (endogenous water + water input), kgH2O/kgTS; Leachate= percentage of wa released as leachate. W=Wet conditions, D=Dry conditions, C=Controlled watering; HP=Waste with high putrescible content; LP=Waste with low putrescible content.

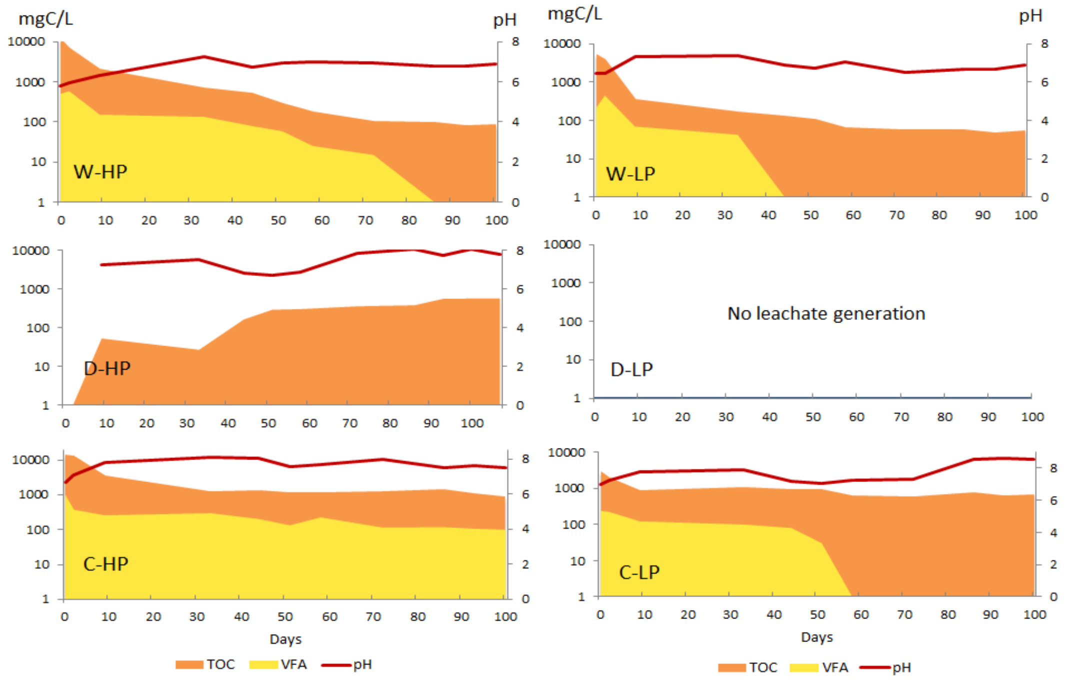


Figure 4. pH, VFA and TOC concentrations in leachate (overlapped area chart) vs. testing time, for the different lysimeters. W=Wet conditions, D=Dry conditions, C=Controlled watering; HP=Waste with high putrescible content; LP=Waste with low putrescible content.

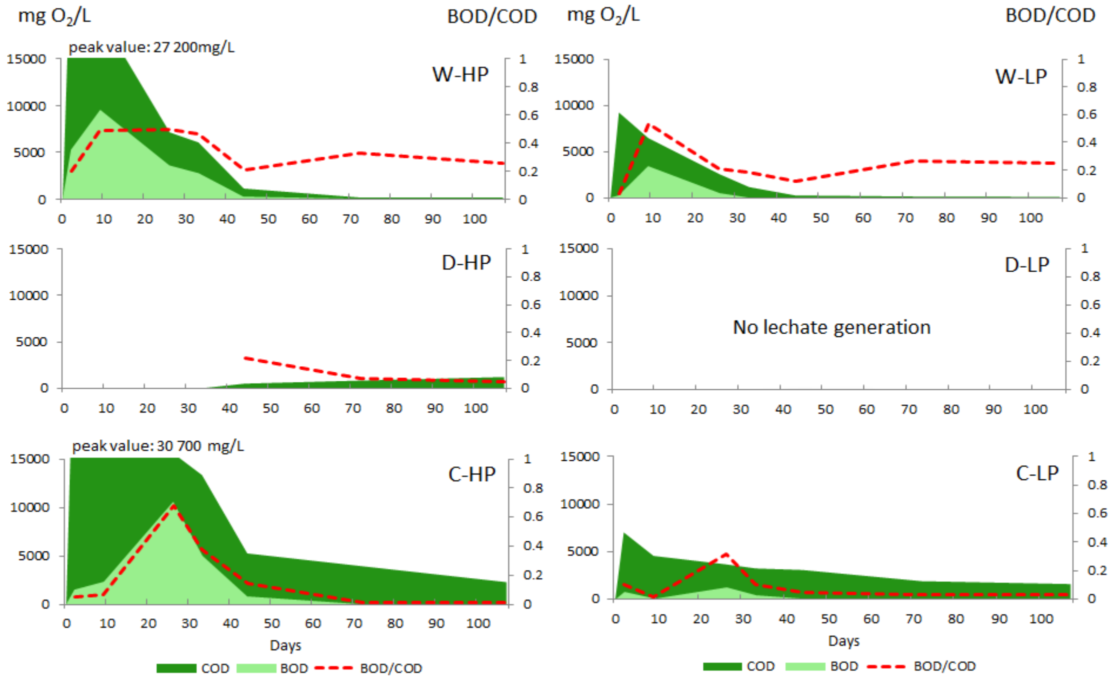


Figure 5. BOD/COD ratio, BOD and COD concentrations in leachate (overlapped area chart). testing time, for the different lysimeters. W=Wet conditions, D=Dry conditions, C=Controlled watering; HP=Waste with high putrescible content; LP=Waste with low putrescible content.

limited to the biodegradation water need, avoiding any significant flushing effect. Then N-NH_4^+ and TOC have been related to a conservative parameter such as chlorides. N-NH_4^+/Cl^- and TOC/Cl^- ratios were calculated throughout the testing period and are represented in Figure 6.

Time constant values indicate the dominant role of flushing in the removal process. Vice versa, a decrease implies a significant concurrent presence of biodegradation.

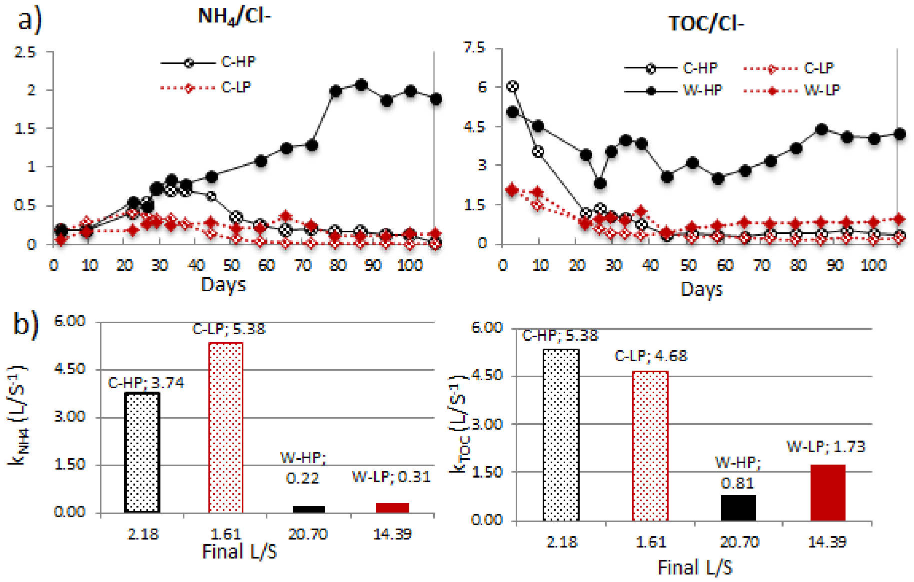


Figure 6. a) Variation of Ammonia/Chloride and TOC/Chloride ratios during the experiment. b) First-order kinetic constant (kTOC;kNH4) obtained from the calibration of first-order kinetic model under different watering conditions (L/S). W=Wet conditions, D=Dry conditions, C=Controlled watering; HP=Waste with high putrescible content; LP=Waste with low putrescible content.

The predominant role of flushing is evident in wet columns in agreement with previous studies by Lavagnolo et al. (2018).

n the case of putrescible waste (W-HP) the ratio N-NH_4^+/Cl^- increases due to the hydrolysis of organic nitrogen. Conversely, the descending trend of both ratios in C columns proved an enhancement of simultaneous biodegradation activity.

In order to quantify and compare the removal performance of both phenomena in the different lysimeters, a first-order kinetic model was calibrated and the concentration of mobile N-$NH4^+$ and TOC in landfilled waste was simulated.

As reference time in the first-order kinetic equation (Eq. 2) the ratio between liquid input and dry mass of solid waste (kg of water input/kg of TS in waste), which varied progressively over time, was assumed. Consequently, the integrated equation is as follows (Eq. 2):

$$C_{L/S} = C_0 * e^{-k\cdot\left(\frac{L}{S}\right)} \quad Eq\ (2)$$

Where:

C= concentration of mobile TOC and N-NH_4 in landfilled waste (g-mobile contaminant/g-TS)

$C_{L/S}$= C at L/S (g-mobile contaminant /g-TS)

C_0= C at the beginning of the removal process (g-mobile contaminant /g-TS)

L/S= Liquid-Solid ratio (L/S)

k = removal kinetics $(L/S)^{-1}$

The mobile contaminant was measured as dissolved TOC on N-NH_4 in leachate. The model was calibrated by minimising the mean square deviation of values measured and calculated. Model performance was assessed by verifying the degree of collinearity between modelled and observed load values by means of Pearson's correlation coefficient (r) (Moriasi et al., 2007), and significance level of the correlation provided with p_{value} and corrected for autocorrelation (Pyper and Peterman, 1998). The correlation was considered statistically significant ($p<0.05$).

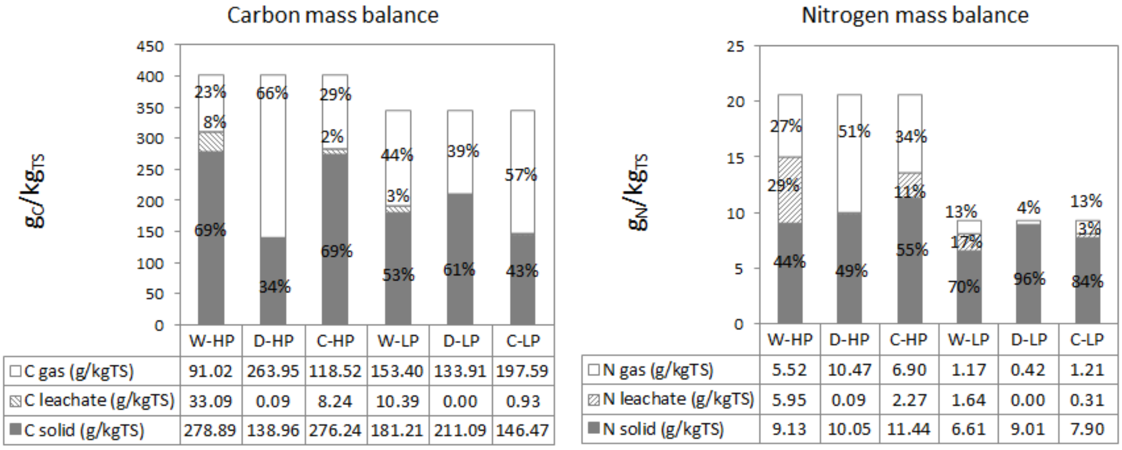
The first-order kinetic constants (k_{NH4+}, k_{TOC}) are illustrated in Figure 6. The significance of biodegradation in the removal process of contaminants for the columns with controlled watering is evident. Providing confirmation of previous observations, the kinetic constants for both N-NH_4^+ and TOC were respectively 17-fold and 3-6 fold higher in C columns compared to those operated under wet conditions (W).

3.5. *Waste characterisation and mass balance*

Input waste and final solid samples from each column were characterised to better evaluate stabilisation performance and the fate of contaminants in the different reactors operated under varying water availability and filled with different types of wastes. Considering the reactors filled with "HP" waste, the highest stabilisation performance was observed in the D-HP column, which achieved a final RI_4 of 12.87 mgO_2/gTS (Figure 2). Water availability (represented solely by endogenous water in the waste) was sufficient to promote optimum moisture conditions for biodegradation. Conversely, the *wa* achieved through controlled water input in C-HP column was excessive. A different behaviour was observed in the columns filled with "LP" waste, in which final RI_4 values demonstrated the limited stabilisation performance of the D-LP column due to lack of moisture. Improved results were achieved under controlled water inputs compared to the D-LP column through a *wa*=2.4 kgH_20/kgTS.

Mass balance for carbon and nitrogen was evaluated for each individual column (Figure 7). The initial content of carbon and nitrogen in the solid waste (N solid, C solid) and leachate (N leachate, C leachate) were measured. Carbon and nitrogen gasification (C gas, N gas) were taken as the difference between the total content of contaminants in the input and output.

Flushing effects in both W columns were confirmed by the high release of carbon and nitrogen into leachate, achieving transferral of up to 8% carbon and 29% nitrogen to leachate in the W-HP column, and removal of 3% carbon and 17% nitrogen through leaching in the W-LP column. The positive effect of controlled water input observed in the C-LP column, was confirmed by the highest nitrogen and carbon gasification. Approximately 57%



	W-HP	D-HP	C-HP	W-LP	D-LP	C-LP
☐ C gas (g/kgTS)	91.02	263.95	118.52	153.40	133.91	197.59
▨ C leachate (g/kgTS)	33.09	0.09	8.24	10.39	0.00	0.93
■ C solid (g/kgTS)	278.89	138.96	276.24	181.21	211.09	146.47

	W-HP	D-HP	C-HP	W-LP	D-LP	C-LP
☐ N gas (g/kgTS)	5.52	10.47	6.90	1.17	0.42	1.21
▨ N leachate (g/kgTS)	5.95	0.09	2.27	1.64	0.00	0.31
■ N solid (g/kgTS)	9.13	10.05	11.44	6.61	9.01	7.90

Figure 7. Total mass and percentage distribution of Carbon and Nitrogen in the different solid, liquid and gas phases, for each individual lysimeter. W=Wet conditions, D=Dry conditions, C=Controlled watering; HP=Waste with high putrescible content; LP=Waste with low putrescible content.

carbon and 13% nitrogen was transferred into the gas phase in the C-LP column with negligible loads in the leachate. Similarly, Lavagnolo et al. (2018) achieved up to 60% initial carbon gasification under comparable semi-aerobic conditions. Conversely only 39% carbon and 4% nitrogen were released as gas in the D-LP column.

3.6. Significance of the results for full scale applications

In semi-aerobic landfills, full-scale conditions may differ considerably from those adopted in the lab-scale testing of this study. In addition to the obvious difference in reactor volume, the following aspects should be taken into consideration: a) test units contained waste at a density of approx.. 500 kg/m^3, whereas densities in a full-scale landfill would be double this; b) a full-scale landfill may be considerably deeper (30m or more); c) the ratio between thickness of waste layers and diameter of the venting pipe is roughly 6:1 in the lab test, being generally much higher in a full-scale landfill; d) waste granulometry was smaller and more homogeneous in the lab-scale; e) drainage gravel size is much higher in full-scale landfill; f) values of L/S ratio exceeding 20 (as adopted in some tests) are hard to achieve at full scale; g) the quality of daily cover (no daily cover in the lab scale test). In view of these differences, water and air flow might of course be heavily restricted and may not be distributed throughout the entire waste mass.

These drawbacks could however be limited by implementing appropriate engineering options and operational procedures. The results of the lab-scale testing allowed to selectively discuss the influence of water availability and putrescible contents in the waste not in absolute but in relative terms.

A series of possible engineering and operational options for transferring the lab-scale results to full-scale applications are reported in Table 1. These options would be of course more effective once the main features of semi-aerobic landfilling (fluid-dynamics, drainage system, density, etc.) have been optimised. To date, there is a marked scarcity of reports in literature relating to poor performance or failure of full-scale semi-aerobic landfills.

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Table 1. Research feedback and potential operational/engineering hints for the different conditions adopted during the investigations

Landfill operation		Reference reactor	Research feedbacks	Operational/ engineering hints
Water availability	**Waste type**			
Wet climate	High putrescible	W-HP	The effect of anaerobiosis is particularly evident, due to the high water input and moisture content in landfilled waste.	Engineering top cover to reduce water infiltration. Storage of rain water for recirculation during the eventual dry season is suggested.
	Low putrescible	W-LP	High water availability does not negatively affect the process. On the contrary, the flushing effect promotes a high contaminant mobility, whilst waste with a low putrescible content provides porosity for air circulation. On the other hand, high leachate volumes are produced.	Top cover aimed at controlling hydrological balance and thus limiting leachate volumes.
Dry climate	High putrescible	D-HP	The water content of HP waste is sufficient to promote biodegradation with negligible leachate contribution to landfill emissions.	Leachate or fresh water recirculation may be supplied to control biodegradation according to the variation of putrescible fraction content.
	Low putrescible	D-LP	The total lack of water both in waste and naturally available through precipitation exerts a negative impact on the biodegradation process and contaminant flushing.	Top cover engineered for leachate and/or water recirculation to regulate water availability.
Controlled watering	High putrescible	C-HP	The amount of water was excessive for the biodegradation process and needs, resulting in anaerobiosis and partial flushing of contaminants.	Leachate or fresh water recirculation may be supplied to control biodegradation according to the variation of putrescible fraction content.
	Low putrescible	C-LP	Controlled forced watering was shown to be effective in controlling biodegradation process and contaminant flushing.	Top cover engineered for leachate and/or water recirculation to regulate water availability.

4. CONCLUSIONS

On the basis of experimental results, the following conclusive remarks can be drawn: a) water availability and putrescible waste content have been confirmed as key factors in controlling performance of semi-aerobic landfilling; b) despite the limitations of the lab-scale operation, significant differences in performance have been highlighted on varying these factors; c) the combination of high putrescible waste and high water availability resulted in anaerobic effects and limited waste stabilisation; d) with low putrescible waste, high water availability limited waste stabilisation and flushing effect promoted high contaminant mobility. Low water availability halted the biodegradation processes; e) the best performance was achieved with water availability around 1.5-2.4 $kgH_2O/kgTS$ (high putrescible waste with dry conditions and low putrescible waste with controlled water availability); f) with high putrescible waste, endogenous water (moisture) fully supported biodegradation processes and no water addition was required; g) the transfer of results from lab-scale to full-scale is limited by the site specific conditions, however the lab-scale results allowed to selectively discuss the influence of water availability and waste putrescible contents, yielding significant preliminary considerations.

REFERENCES

Ahmadifar, M., Sartaj, M., Abdallah, M., 2016. Investigating the performance of aerobic, semi-aerobic, and anaerobic bioreactor landfills for MSW management in developing countries. J. Mater. Cycles Waste Manag. 18, 703–714. doi:10.1007/s10163-015-0372-0

Al-Yaqout, A.F., Hamoda, M.F., 2003. Evaluation of landfill leachate in arid climate - A case study. Environ. Int. 29, 593–600. doi:10.1016/S0160-4120(03)00018-7

Aziz, S.Q., Aziz, H.A., Yusoff, M.S., Bashir, M.J.K., Umar, M., 2010. Leachate characterization in semi-aerobic and anaerobic sanitary landfills: A comparative study. J. Environ. Manage. 91, 2608–2614. doi:10.1016/j.jenvman.2010.07.042

Bogner, J., Pipatti, R., Hashimoto, S., Diaz, C., Mareckova, K., Diaz, L., Kjeldsen, P., Monni, S., Faaij, A., Qingxian, G., Tianzhu, Z., Mohammed, A.A., Sutamihardja, R.T.M., Gregory, R., 2008. Mitigation of global greenhouse gas emissions from waste: Conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. Working Group III (Mitigation). Waste Manag. Res. 26, 11–32. doi:10.1177/0734242X07088433

Bogner, J.E., Spokas, K.A., Burton, E.A., 1999. Temporal Variations in Greenhouse Gas Emissions at a Midlatitude Landfill. J. Environ. Qual. 28, 278–288. doi:10.2134/jeq1999.00472425002800010034x

Broun, R., Sattler, M., 2016. A comparison of greenhouse gas emissions and potential electricity recovery from conventional and bioreactor landfills. J. Clean. Prod. 112. doi:10.1016/j.jclepro.2015.10.010

Chanton, J., Abichou, T., Langford, C., Hater, G., Green, R., Goldsmith, D., Swan, N., 2011. Landfill methane oxidation across climate types in the U.S. Environ. Sci. Technol. 45, 313–319. doi:10.1021/es101915r

Cossu, R., Morello, L., Raga, R., Cerminara, G., 2016. Biogas production enhancement using semi-aerobic pre-aeration in a hybrid bioreactor landfill. Waste Manag. 55, 83–92. doi:10.1016/j.wasman.2015.10.025

Cossu, R., Pivato, A. Aftercare completion: final storage quality assessment. In Cossu, R.; Stegmann, R. Solid Waste Landfilling, Concepts, Processes, Technology. Elsevier, 2018, ISBN: 9780128183366.

Cossu, R., Stegmann, R. Solid Waste Landfilling, Concepts, Processes, Technology. Elsevier, 2018, ISBN: 9780128183366.

Cossu, R; van der Sloot, H. Sustainable landfilling. CISA Publisher, 2014, ISBN 978-88-6265-005-2.

D. N. Moriasi, J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, T. L. Veith, 2007. Model Evaluation Guidelines for

Systematic Quantification of Accuracy in Watershed Simulations. Trans. ASABE 50, 885–900. doi:10.13031/2013.23153

De La Cruz, F.B., Barlaz, M.A., 2010. Estimation of Waste Component Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data Supporting Information (SI) 44, 4722–4728. doi:10.1021/es100240r

Erses, A.S., Onay, T.T., Yenigun, O., 2008. Comparison of aerobic and anaerobic degradation of municipal solid waste in bioreactor landfills. Bioresour. Technol. 99, 5418–5426. doi:10.1016/j.biortech.2007.11.008

Esteban-Altabella, J., Colomer-Mendoza, F.J., Gallardo-Izquierdo, A., 2017. Simulation of the behavior of a refuse landfill on a laboratory scale. J. Environ. Manage. 204, 144–151. doi:10.1016/j.jenvman.2017.08.045

Grossule, V., Morello, L., Cossu, R., Lavagnolo, M.C., 2018. Bioreactor landfills : comparison and kinetics of the different systems, Detritus, 03, 100–113.

Hanashima, M., Yamasaki, K., Kuroki, T., Onishi, K, 1981. Heat and gas flow analysis in semiaerobic landfill. J. Environ. Eng. Divis., Proc. Am. Soc. Civ. Eng. 1981, 107 (EE1), 1–9.

Hirata, O., Matsufuji, Y., Tachifuji, A., Yanase, R., 2012. Waste stabilization mechanism by a recirculatory semi-aerobic landfill with the aeration system. J. Mater. Cycles Waste Manag. 14, 47–51. doi:10.1007/s10163-011-0036-7

HUANG, Q., YANG, Y., PANG, X., WANG, Q., 2008. Evolution on qualities of leachate and landfill gas in the semi-aerobic landfill. J. Environ. Sci. 20, 499–504. doi:10.1016/S1001-0742(08)62086-0

Klusman, R.W., Dick, C.J., 2000. Seasonal variability in CH. J. Air Waste Manag. Assoc. 50, 1632–1636. doi:10.1080/10473289.2000.10464201

Kylefors, K., Andreas, L., Lagerkvist, A., 2003. A comparsion of small-scale, pilot scale and large -scale tests for predicting leaching behavioud of landfilled wastes. Waste Manag. 23, 45–59.

Laner, D., Crest, M., Scharff, H., Morris, J.W.F., Barlaz, M.A., 2012. A review of approaches for the long-term management of municipal solid waste landfills. Waste Manag. 32, 498–512. doi:10.1016/j.wasman.2011.11.010

Lavagnolo, M.C., Grossule, V., Raga, R., 2018. Innovative dual-step management of semi-aerobic landfill in a tropical climate. Waste Manag. 1–10. doi:10.1016/j.wasman.2018.01.017

Levis, J.W., Barlaz, M.A., 2011. Is biodegradability a desirable attribute for discarded solid waste? Perspectives from a national landfill greenhouse gas inventory model. Environ. Sci. Technol. 45, 5470–5476. doi:10.1021/es200721s

Matsufuji, Y., Tanaka, A., Cossu, R., 2018. Semiaerobic landfilling. In Cossu, R., Stegmann, R. Solid Waste Landfilling, Concepts, Processes, Technology. Elsevier, 2018, ISBN: 9780128183366.

Matsuto, T., Zhang, X., Matsuo, T., Yamada, S., 2015. Onsite survey on the mechanism of passive aeration and air flow path in a semi-aerobic landfill. Waste Manag. 36, 204–212. doi:10.1016/j.wasman.2014.11.007

Morello, L., Raga, R., Lavagnolo, M.C., Pivato, A., Ali, M., Yue, D., Cossu, R., 2017. The S.An.A.® concept: Semi-aerobic, Anaerobic, Aerated bioreactor landfill. Waste Manag. doi:10.1016/j.wasman.2017.05.006

Pyper, B.J., Peterman, R.M., 1998. Comparison of methods to account for autocorrelation in correlation analyses of fish data. Can. J. Fish. Aquat. Sci. 55, 2127–2140. doi:10.1139/f98-201

Rafizul, I.M., Alamgir, M., 2012. Characterization and tropical seasonal variation of leachate: Results from landfill lysimeter studied. Waste Manag. 32, 2080–2095. doi:10.1016/j.wasman.2012.01.020

Ritzkowski, M., Stegmann, R., 2012. Landfill aeration worldwide: Concepts, indications and findings. Waste Manag. 32, 1411–1419. doi:10.1016/j.wasman.2012.02.020

Šan, I., Onay, T.T., 2001. Impact of various leachate recirculation regimes on municipal solid waste degradation. J. Hazard. Mater. 87, 259–271. doi:10.1016/S0304-3894(01)00290-4

Schwinge, J., Wiley, D.E., Fane, A.G., 2004. Novel spacer design improves observed flux. J. Memb. Sci. 229, 53–61. doi:10.1016/j.memsci.2003.09.015

Sinan Bilgili, M., Demir, A., Ince, M., Özkaya, B., 2007. Metal concentrations of simulated aerobic and anaerobic pilot scale landfill reactors. J. Hazard. Mater. 145, 186–194. doi:10.1016/j.jhazmat.2006.11.014

Tatsi, A.A., Zouboulis, A.I.U., 2002. A field investigation of the quantity and quality of.pdf.

Theng, L.C., Matsufuji, Y., Mohd, N.H., 2005. Implementation of the semi-aerobic landfill system (Fukuoka method) in developing countries: A Malaysia cost analysis. Waste Manag. 25, 702–711. doi:10.1016/j.wasman.2005.01.008

Wu, X., Yue, B., Huang, Q., Wang, Q., Lin, Y., Zhang, W., Yan, Z., 2017. Spatio-temporal variation of landfill gas in pilot-scale semi-aerobic and anaerobic landfills over 5 years. J. Environ. Sci. (China) 54, 288–297. doi:10.1016/j.jes.2016.09.015

Yang, Y., Yue, B., Yang, Y., Huang, Q., 2012. Influence of semi-aerobic and anaerobic landfill operation with leachate recirculation on stabilization processes. Waste Manag. Res. 30, 255–265. doi:10.1177/0734242X11413328

Paper VI. Innovative dual-step management of semi-aerobic landfill in a tropical climate

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Innovative dual-step management of semi-aerobic landfill in a tropical climate

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ABSTRACT

Despite concerted efforts to innovate the solid waste management (SWM) system, land disposal continues to represent the most widely used technology in the treatment of urban solid waste worldwide. On the other hand, landfilling is an unavoidable step in closing the material cycle, since final residues, although minimized, need to be safely disposed of and confined.

In recent years, the implementation of more sustainable landfilling aims to achieve the Final Storage Quality conditions as fast as possible. In particular, semi-aerobic landfill appears to represent an effective solution for use in the poorest economies due to lower management costs and shorter aftercare resulting from aerobic stabilisation of the waste. Nevertheless, the implementation of a semi-aerobic landfill in a tropical climate may affect the correct functioning of the plant: a lack of moisture during the dry season and heavy rainfalls during the wet season could negatively affect performance of both the degradation process, and of leachate and biogas management. This paper illustrates the results obtained through the experimentation of a potential dual-step management of semi-aerobic landfilling in a tropical climate in which composting process was reproduced during the dry season and subsequently flushing (high rainfall rate) during the wet period. Eight bioreactors specifically designed: four operated under anaerobic conditions and four under semi-aerobic conditions; half of the reactors were filled with high organic content waste, half with residual waste obtained following enhanced source segregation. The synergic effect of the subsequent phases (composting and flushing) in the semi-aerobic landfill was evaluated on the basis of both types of waste. Biogas production, leachate composition and waste stabilization were analysed during the trial and at the end of each step, and compared in view of the performance of anaerobic reactors. The results obtained underlined the effectiveness of the dual-step management evidencing how wastes reached a higher degree of stabilization and reference FSQ values for leachate were achieved over a one-year simulation period.

1. Introduction

One of the most urgent requirements in the modern solid waste management strategy is to define the future role of landfill. The EU Directives on solid waste management and the recent circular economy packages (EU, 2015; Ellen MacArthur Foundation, 2013) do not place sufficient emphasis on the need for a final sink to close the material loop (Cossu, 2009; Cossu et al., 2016). From the point of view of short- and long-term environmental impacts, it is important to define the performances over time of the landfill (Laner et al., 2012; Hrad, 2013; Heimovaara et al., 2014). Cossu (2009) suggested the design of a modern landfill aimed at achieving a Final Storage Quality (FSQ) in equilibrium with the environment over the span of one generation. Moreover, although FSQ has not yet been fully defined by the scientific community, a series of measures aimed at contributing towards sustainable landfilling have been implemented in affluent countries. As an example, in northern Italy in 2014, the first legislation on sustainable landfill introduced FSQ limits (D.G.R. 2461/14). However, although the huge development in technologies, the appropriate tools for sustainability implementation are still lacking in most of the cases, particularly in developing countries the effective design of a sustainable landfill remains a critical issue due to financial constraints and limited technical know-how.

The semi-aerobic landfill developed in the ’80s at Fukuoka University (Japan) may constitute an effective option with a view to sustainability, as it has been designed to reproduce an aerobic environment within the waste mass to accelerate landfill stabilization, thus reducing aftercare. The pivotal function of a semi aerobic

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landfill is represented by the leachate collection system consisting of a main central bottom pipe, with branch pipes terminating in an open leachate retention pond to allow the outflow of leachate and facilitating the ingress of air into the waste layer. The pipes are designed to allow only one-third of the section to fill with leachate, leaving the remaining space for air to flow (Hanashima et al., 1981; Theng et al., 2005; SPREP, 2010).

The advantages of the semi aerobic landfill have been confirmed in several studies. These advantages are: the improvement of carbon degradation rate, one order of magnitude higher than in anaerobic systems (Ahmadifar et al., 2016; Cossu et al., 2003; He et al., 2012); the enhancement of nitrogen removal (Cossu et al., 2003; He et al., 2011, 2012; Shao et al., 2008; Yang et al., 2012; Zeng et al., 2006); the reduction of methane generation (Ahmadifar et al., 2016; Cossu et al., 2003; Huang et al., 2008; IPPC, 2006; Sutthasil et al., 2014; Wu et al., 2017; Yang et al., 2012); the increased carbon gasification (Shimaoka et al., 2000).

The implementation of semi-aerobic landfill in a tropical climate may however affect the waste degradation process due to climatic conditions: lack of moisture during the dry season decreases or even halts biological activity; heavy rainfalls during the wet season result in a high contaminant load in leachate (Rafizul and Alamgir, 2012) and may interfere with oxygen dispersion within the waste (producing a change from semi-aerobic to anaerobic conditions). To overcome the dry season issues, excess leachate, stored during the previous wet season, can be recirculated (Tränkler et al., 2005).

The application of this technology may prove particularly effective in developing countries (DCs) (Theng et al., 2005), the majority of which are located in the tropical climate zone. In DCs open dumps of raw waste are still today the most widely used form of waste disposal since social, economic and technical constraints limit the implementation of an effective and durable SWM system (Brunner and Fellner, 2007). The major culprits include the scarce environmental awareness of the Administrators, lack of infrastructures, lack of available funds and dearth of skilled technicians to sustain the management of the plants. To ensure the sustainability of an engineered landfill, Allen (2002) suggested the following options: low cost solutions in terms of development, operation and maintenance; simple easily implemented technologies and a maximum utilisation of natural resources and properties of in situ materials. Accordingly, the concept of sustainability in DCs is largely represented by the application of any kind of conceivably affordable solution with the aim of meeting at least the minimum required standards.

With regard to waste quality, to decrease potential leachate pollution during the wet period, Tränkler et al. (2005) suggested the design of an open landfill for use in a tropical climate using low organic content waste, similar to that adopted to dispose of residual waste from enhanced MSW collection applied in the majority of industrialised countries (Di Maria et al., 2013). Conversely, wastes with a high percentage of putrescible content continue to represent worldwide the most significant portion of waste composition (The World Bank, 2012). The quantity of organic waste in the municipal solid waste stream is influenced by numerous factors; however, the main driving force that influences waste organic fraction is economic development: according to the World Bank (2012), the percentage of organic matter in the urban waste stream ranges from 54 to 64% in Lower income countries, to 28% of raw waste in High-Income Countries.

The focus of this study was to evaluate a controlled alternate dual-step management of semi-aerobic landfill in the specific Aw tropical climate. According to the Köpper-Geiger climate classification, the tropical Aw climate (Tropical wet and dry Savanna climate) is the second most diffuse climate worldwide, characterized by a dry season lasting 5–6 months with little or no rainfall, and precipitation between 800 and 1600 mm concentrated over the remaining six months during the wet season (Chen and Chen, 2013; Essenwanger, 2001; Kottek et al., 2006; Peel et al., 2007).

The aim was to accelerate landfill stabilization: during the dry season the in situ composting process was simulated by means of leachate recirculation, whilst during the wet season a flushing simulating rainfall was applied. Two different types of waste characterized by different percentages of organic fraction were tested: residual waste from separate collection (“R” waste), and high organic content waste (“O” waste). The performance of the semi-aerobic reactors was compared with that of anaerobic reactors: waste stabilization, leachate and gas quality were studied and discussed in terms of degradation kinetics, ammonia removal, gasification enhancement, methane generation reduction, and Final Storage Quality (FSQ) achievement.

2. Materials and methods

2.1. Waste samples

Residual waste obtained following enhanced separated collection was used for the experiment. Waste was shredded and passed through a 6 cm sieve. The “R” (Residual) waste was raw residual waste yielding a 4% content of kitchen residues of the total wet waste; high organic content “O” (Organic) waste was obtained by increasing the organic content of “R” waste up to 50 wet wt% taking kitchen waste from municipal separate collection. Characterization of the two waste samples is provided in Table 1: “R” waste represents the typical waste composition in industrialized countries after enhanced separate collection; “O” waste reproduces the typical waste composition in low and middle income countries situated in tropical zones (The World Bank, 2012).

2.2. Equipment

The experiment was carried out using eight cylindrical Plexiglass® lysimeters (1 m height, inner diameter of 24 cm). Each column was lined at the bottom with 10 cm thick gravel layer (∅20–30 mm) to facilitate leachate drainage.

To simulate semi-aerobic conditions, a slotted aeration pipe (4 cm diameter) was placed in the gravel at the bottom of four columns, open to the air, and no top cover was provided. A 1 cm diameter plastic pipe was inserted into the waste body of each column to detect gas quality during the experiment.

Conversely, to implement anaerobic conditions, four columns were completely sealed and a top cover added, with Tedlar bags being provided for gas sampling.

Table 1
Waste composition and characterization of “R” (Residual) and “O” (Organic) waste.

		“Residual”	“Organic”
Categories	Kitchen residues (%)	4	50
	Green and wooden materials (%)	6	3
	Paper and paperboard (%)	20	11
	Textiles (%)	6	3
	Plastics (%)	24	13
	Metals (%)	4	2
	Glass (%)	10	5
	Inert (%)	10	5
	Under-sieve (20 mm) (%)	16	8
Characterization	Waste mass (kg)	9.0	9.0
	TS (%)	65.1	35.5
	VS (%TS)	49.7	69.0
	TOC (gC/gTS)	24.0	40.1
	RI_4 (mgO_2/gTS)	55.0	85.3

A holed plate for water irrigation was placed on the top of each column.

Leachate was drained through a collection port located at the bottom of each column.

The eight columns were equipped with Thermo Systems TS100 temperature probes.

Both anaerobic and semi-aerobic columns were thermo insulated for temperature control.

A scheme of the due type of lysimeters is illustrated in Fig. 1.

2.3. Methodology

The experimental study lasted six months, simulating the alternation of two phases: the composting phase during the dry season (0–96th day) and the flushing phase during the wet season (97–192th day). The eight landfill bioreactors were operated in duplicate under two different process conditions (Table 2): four as semi-aerobic bioreactors ("S") with natural heat convection according to semi-aerobic concept; the other four reactors under anaerobic conditions ("An"). Two of each type of process reactors were filled with the same type of waste ("O" or "R") in order to obtain two replicates for each kind of waste and process, according to the scheme in Table 2.

Columns were filled with 9 kg of waste at the beginning of the first phase and an additional 9 kg was added at the beginning of the second phase. Initial density was approximately 0.5 kg/L.

Environmental temperatures were maintained in the range suggested for tropical climate between 18° and 30 °C (Whittaker, 1975; Kottek et al., 2006). Water irrigation in the first phase was initially defined according to the PAF model (Cossu et al., 2003), although some adjustments were required to optimise the composting process: during this phase the rain simulation range was 0.22–0.5 L/d, achieving L/S 1.7 and 3.1 ($L_{water\text{-}in}/kg_{TS}$) in R and O waste columns, respectively. During the second phase columns were irrigated daily with 0.9 L/d to reproduce the wet tropical season with a total precipitation of 1400 ml.

At the beginning and end of both phases waste was sampled from each reactor to evaluate organic stabilization by means of RI (respirometric index), TC, TOC, TS, and VS analysis. TC and TOC on solid samples was measured by means of a TOC–VCSN

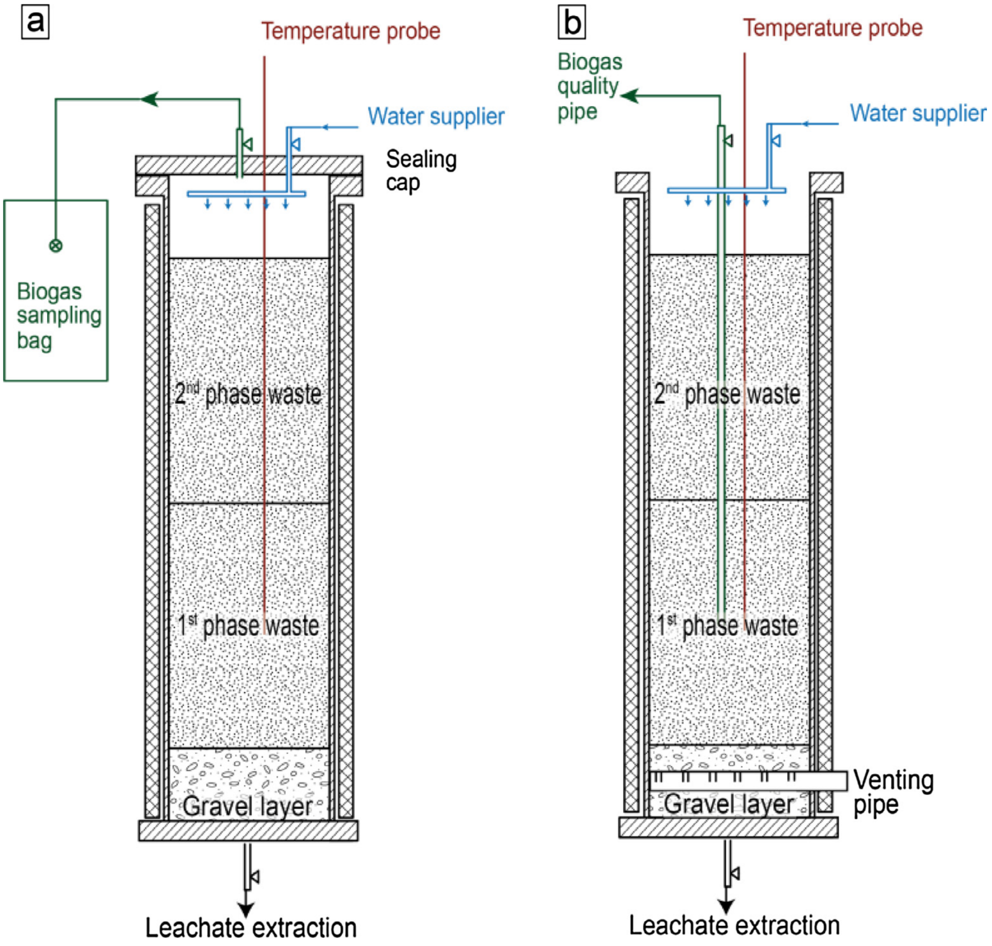


Fig. 1. Anaerobic (a) and semi-aerobic (b) reactor schemes.

Table 2
Experimental reactors and process conditions.

Waste typologies	Anaerobic reactor	Semi aerobic reactor	I phase (96 days)	II phase (96 days)
"O" waste (50% putrescible content)	An-O1 An-O2	S-O1 S-O2	Dry	Wet
"R" waste (4% putrescible content)	An-R1 An-R2	S-R1 S-R2	Dry	Wet

Shimadzu Analyzer. Respiration Index (RI4 and RI7 mgO_2/gTS) was determined by means of Sapromat apparatus (H + P Labortechnik, Germany). Leachate was periodically tested throughout the experiment for pH, alkalinity, TS, VS, organic content (VFA, COD, TOC, BOD_5), nitrogen compounds (TKN, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, $N\text{-}NO_2^-$) and Cl^-.

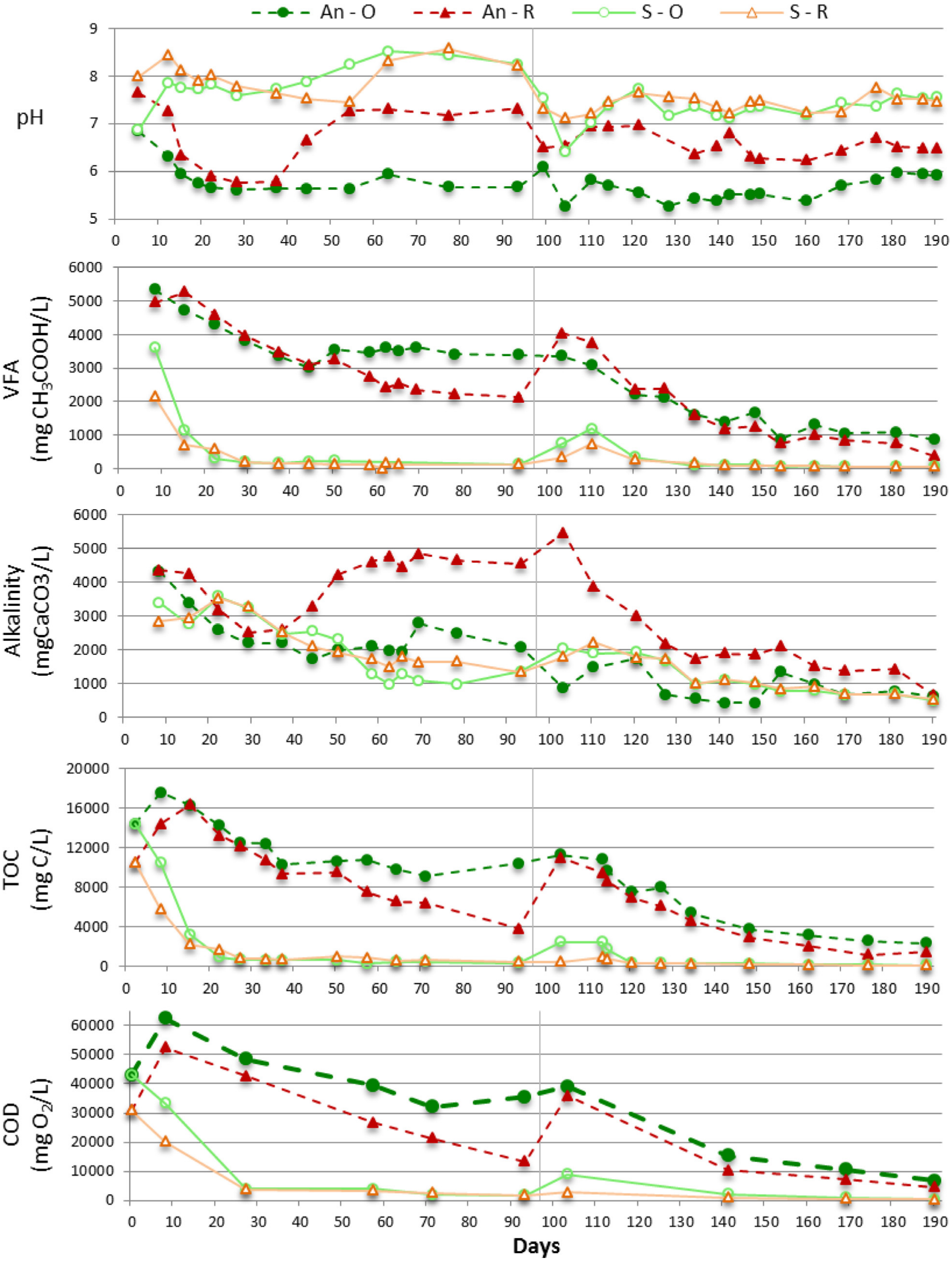


Fig. 2. pH, VFA, alkalinity, TOC and COD variation throughout the entire test (the vertical line indicates the starting point of the second wet phase).

Heavy metals (Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn) were measured on the leachate samples using an ICP-OES Perkin Elmer Optima 4200 DV following the procedure of IRSA/CNR 29/2003 vol. 1 n. 3020. The same heavy metals were monitored in solid samples according to the digestion method EPA n. 3050/96B, and then EPA method n. 6010C/07.

Biogas concentrations in terms of CO_2, CH_4 and O_2, were measured using a portable analyzer (Eco-Control LFG20).

Solid, liquid and gas samples were analysed in line with Standard International Methods.

The results of analyses are given as averages of the two column replicates.

Performance of the semi-aerobic system under the dual-phase management will be discussed with the use of first order kinetics removal and in compliance with the FSQ (D.G.R. 2461/14) requirements.

3. Results and discussion

3.1. Leachate quantity and quality

The leachate collected at the end of both phases revealed higher evaporation in the semi aerobic columns: particularly in the anaerobic columns the extracted leachate quantity was 10% higher during the first phase and 5% higher in second phase.

Fig. 2 illustrates leachate pH, Volatile Fatty Acids (VFA), alkalinity, TOC and COD throughout the entire test.

pH values in the S columns invariably exceeded 7, both in organic and residual waste columns due to aerobic conditions. In An-O, a more evident and longer acidogenic phase occurred due to the higher organic content and anaerobic slower kinetics ($pH < 6$, high VFA concentration, and insufficient alkalinity to buffer), producing a potential inhibition of methanogenesis (Cossu et al., 2016). At variance, in An-R reactors with lower organic content, pH values increased after 40 days ($pH > 6$, sufficient alkalinity) and methanogenesis commenced (see Fig. 6 and further discussion).

During the second phase, after an initial adjustment due to the contribution of the second waste layer, flushing produced a marked decreased in all parameters, with the exception of pH, which maintained remarkably stable values until the end of the experiment.

COD and TOC decreased much more rapidly in S than in An leachates in both phases due to the faster aerobic kinetics (Ritzkowski et al., 2007). Waste typology seems to affect the performance of anaerobic rather than aerobic processes, as attested by the finding of considerably different in the first phase for An-O and An-R, but not in S columns. In the second phase, in which flushing was the main process applied, both An-O and An-R yielded similar performances. Analysis of TOC removal kinetics (the results of which are reported in Table 3), is discussed below and confirmed the previous assumptions.

Fig. 3 illustrates TKN, ammonia, nitrite and nitrate concentrations in leachates during the experiments. TKN and ammonia trends were similar in An-O and An-R, highlighting the scarce influence produced by the organic concentration of wastes. Concentrations in the range of 1000 and 20 mg/N-NH_4^+ were detected at the end of the dry and wet phases, respectively. No nitrification occurred in An columns throughout the experimental period, as expected. On the other hand, nitrification was clearly evident in both semi-aerobic reactors, where the conversion of ammonium into nitrites and nitrates was detected from around the 30th day during the dry phase and around 120th day during the wet phase (25 days after wet phase begun). TKN and ammonia values reached values lower than 40 mg N/L at the end of both phases. In the same way as TOC, a higher removal rate occurred during the wet phase, as discussed in the following paragraph and indicated in Table 3.

Moreover, the low concentrations detected at the end of the second phase appear to confirm the effect of dilution, due to heavy rainfall simulation. This is clearly true for the anaerobic columns since TOC and ammonia output loads (Fig. 4) indicated a higher flushing during the second phase. Particularly, in the second phase, TOC load in leachate was approximately 2-fold higher on average, and NH_4^+ load more than 2.5-fold higher. A different behaviour was registered in the S columns, in particular S-R, in which TOC and NH_4^+ loads were an average of 1.08 and 0.6 times, respectively, those observed in the first phase. This finding highlighted the positive effect of the first composting phase: the higher the degradation rate, the lower the carbon and nitrogen contaminant release in leachate (Cossu et al., 2003).

3.2. Flushing and biodegradation

To better comprehend the processes that occurred during the second phase of the study, NH_4^+/Cl^-, TOC/Cl^- ratios and degradation kinetics were calculated.

Solubilisation, biodegradation and flushing all produce an effect on Ammonia and TOC concentration trends, particularly since Chloride can be only removed by washing out from waste (Fellner et al., 2009); constant NH_4^+/Cl^-, TOC/Cl^- ratios over time indicate the unique effect of flushing, whilst an increase or decrease of these ratios highlight the simultaneous action of the other two processes.

The behaviour of ratios during the wet phase (97–192th day) is illustrated in Fig. 5. In anaerobic columns, although Ammonia and TOC concentrations decreased during the second phase, the Ammonia and TOC over Chloride ratios increased: NH_4^+ and TOC decreased at a much slower rate than Chloride, suggesting that

Table 3
First order removal kinetic rates and % contribute of biodegradation (k^*) to the removal process.

	(day^{-1})	S-O columns		S-R columns		An-O columns		An-R columns	
		k	r p-value	k	r p-value	k	r p-value	k	r p-value
Dry phase	k TOC	0.099	0.9825 0.0001	0.064	0.9571 0.0007	0.010	0.8884 0.0654	0.013	0.9696 0.0171
	k NH_4^+	0.038	0.9512 0.0138	0.040	0.9507 0.0132	0.001	−0.3968 0.2302	0.001	0.4756 0.0201
Wet phase	k TOC	0.285	0.9948 0.0001	0.162	0.9828 0.0023	0.026	0.9762 0.0234	0.027	0.9931 0.0067
	k NH_4^+	0.085	0.9620 0.0768	0.089	0.9100 0.0506	0.029	0.8622 0.0903	0.035	0.9554 0.0271
	k Cl^-	0.047	0.9936 0.0003	0.023	0.9650 0.0216	0.034	0.9346 0.0100	0.036	0.9852 0.0015
	k^* TOC (%)	0.238 (83)		0.139 (86)					
	k^* NH_4^+ (%)	0.038 (45)		0.065 (74)					

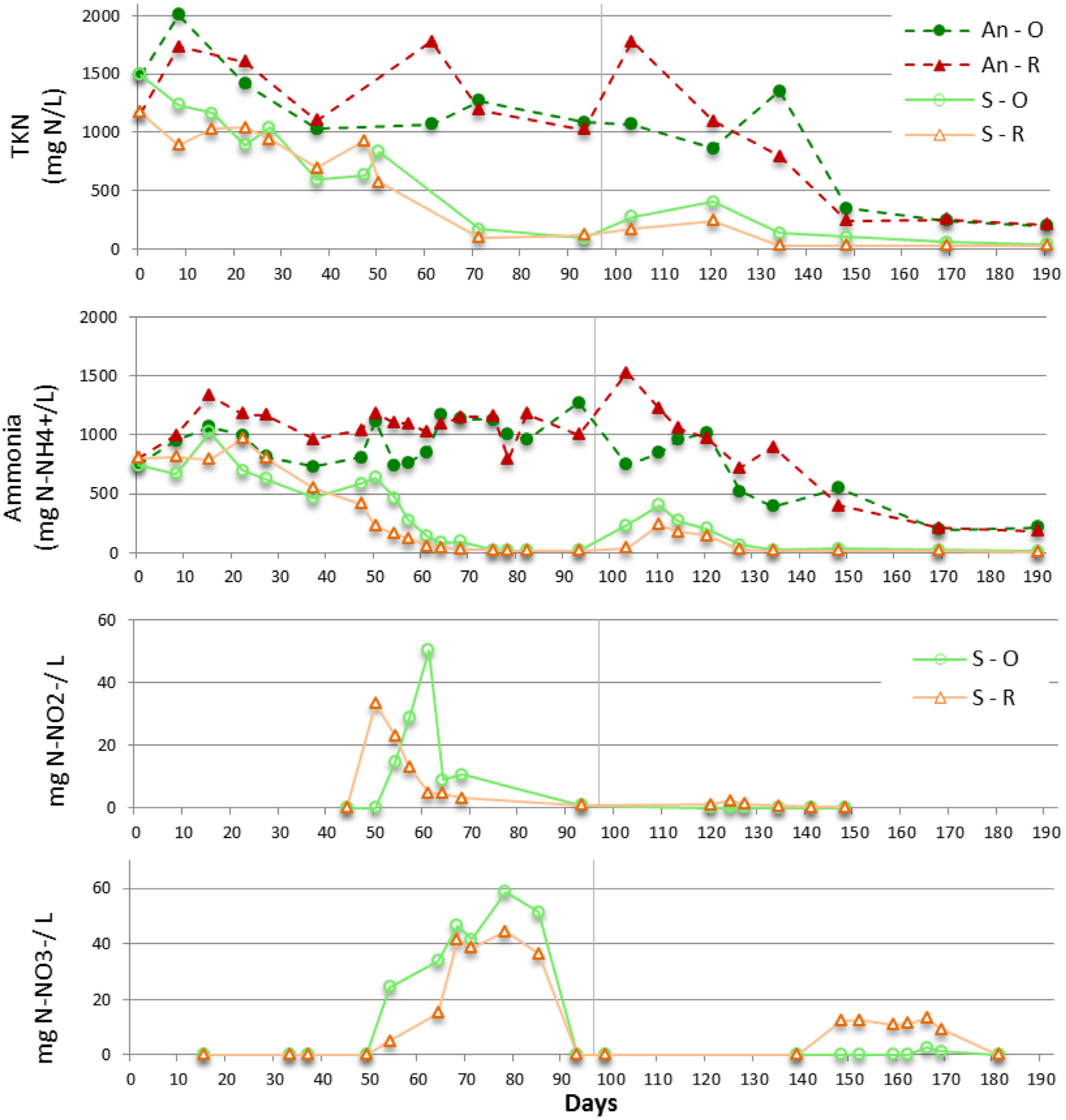


Fig. 3. Behaviour of Nitrogen compounds during the experiment.

ammonification of organic Nitrogen and solubilisation of complex TOC exceeded the flushing effect, while biodegradation was found to be limited.

Divergent behaviours were detected in the semi-aerobic reactors: the initial positive trend was followed by a decrease when biodegradation and flushing occurred simultaneously. Once TOC and Ammonia had reached quite low concentrations, the ratios started to increase due to an ongoing decrease in Chloride concentration.

According to the following equations, first order kinetics (Heimovaara et al., 2014) were calculated for the removal process of Chloride, Ammonia and TOC to better evaluate the contribution of biodegradation and flushing on the overall removal process:

$$\frac{dC}{dt} = -kC$$

$$C_t = C_0 * e^{-kt}$$

where

C = concentration of considered contaminant (mg/L)
C_t = concentration at time t (mg/L)
C_0 = concentration ant the beginning of the removal process (mg/L)
k = removal kinetics (day^{-1})
t = time of removal process (d)

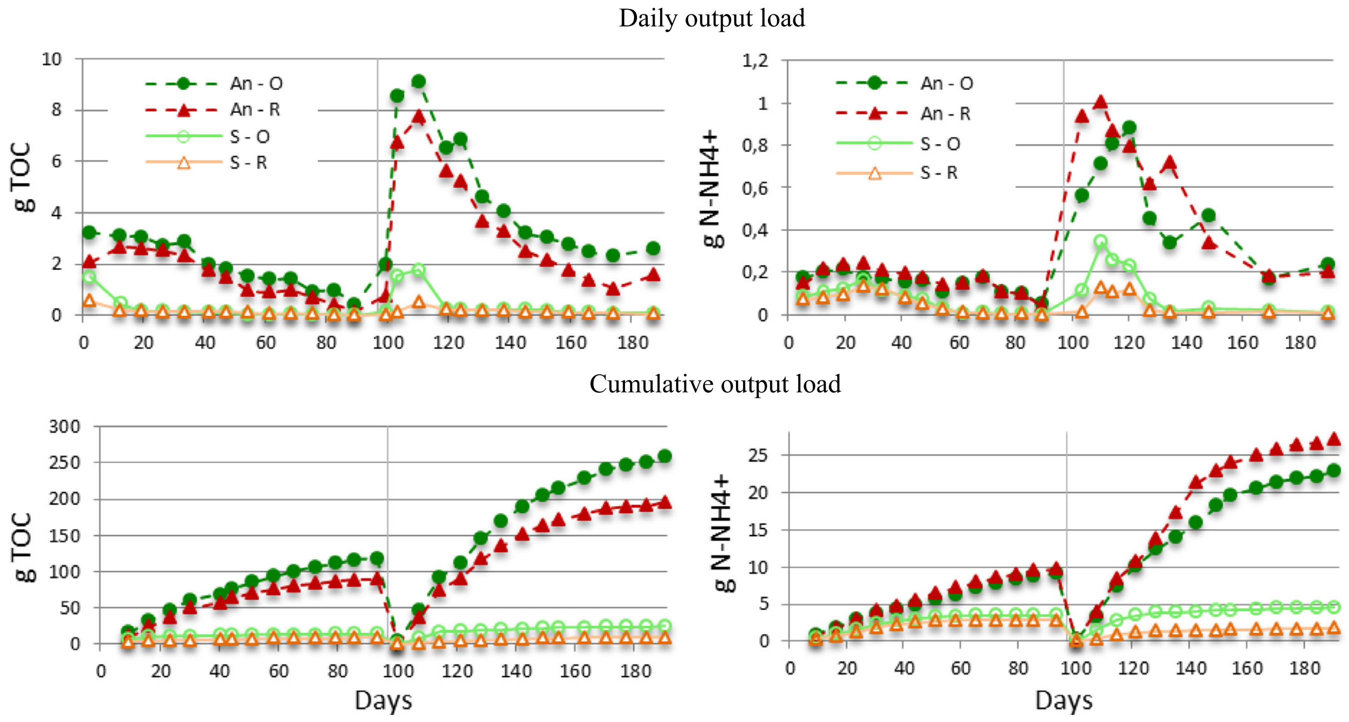


Fig. 4. Variation of the daily ammonia and TOC output loads based on a weekly average and cumulative ammonia and TOC load during the experiment.

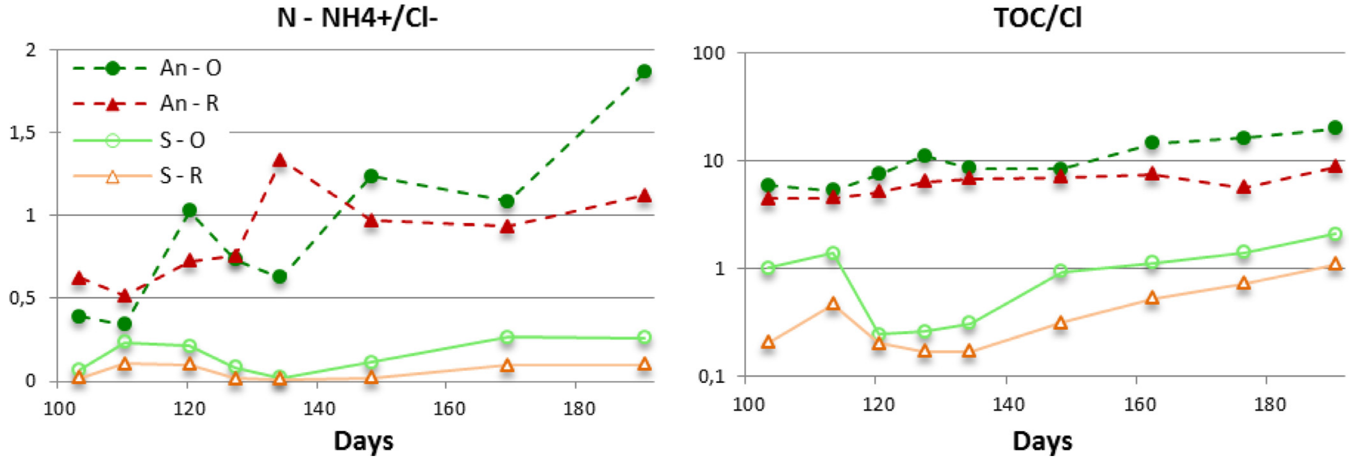


Fig. 5. Variation of Ammonia/Chlorides and TOC/Chlorides (in log scale) ratios during the second phase.

Model performances have been assessed to verify the degree of collinearity between modelled and observed concentration values by means of Pearson's correlation coefficient (r) (Moriasi et al., 2007), and significance level of the correlation provided with p-value, corrected for autocorrelation (Pyper and Peterman, 1998). Correlation coefficient ranged between −1 and 1, and a perfect positive linear relationship was revealed for $r = 1$; the correlation is considered statistically significant for $p < .05$.

First order kinetics calculated during the dry and wet period, and the % contribution of biodegradation estimated during the wet phase, are presented in Table 3, with r and p-values as performance indicators. As expected, during both phases k TOC was much higher (6–10 times) in semi-aerobic than in anaerobic columns. Ammonia removal kinetics were higher in S columns.

During the wet phase, k TOC and k NH_4^+ in An columns were similar to k Cl^-, confirming flushing as the predominant process. In semi-aerobic columns, removal kinetics were a combination of biodegradation and flushing processes. According to Fellner et al. (2009) and assuming that Chloride removal kinetics represented the flushing removal process, the only contribute of biodegradation, k^*, has been estimated by subtracting k Cl^- from k NH_4^+ and k TOC. Biodegradation kinetics of TOC showed a significant increase during the wet phase.

Correlation coefficient and p-values confirmed a good approximation at the first order kinetic model, displaying r values close to 1 and significance level ranging from 0 to 10%. The only exception was observed for k NH_4^+ in An columns during the first phase, due to the low ammonia removal rate.

3.3. Biogas composition

Biogas composition during the study period (Fig. 6) confirmed the poor influence of waste composition on the behaviour of semi-aerobic lysimeters during both phases: CO_2 was detected

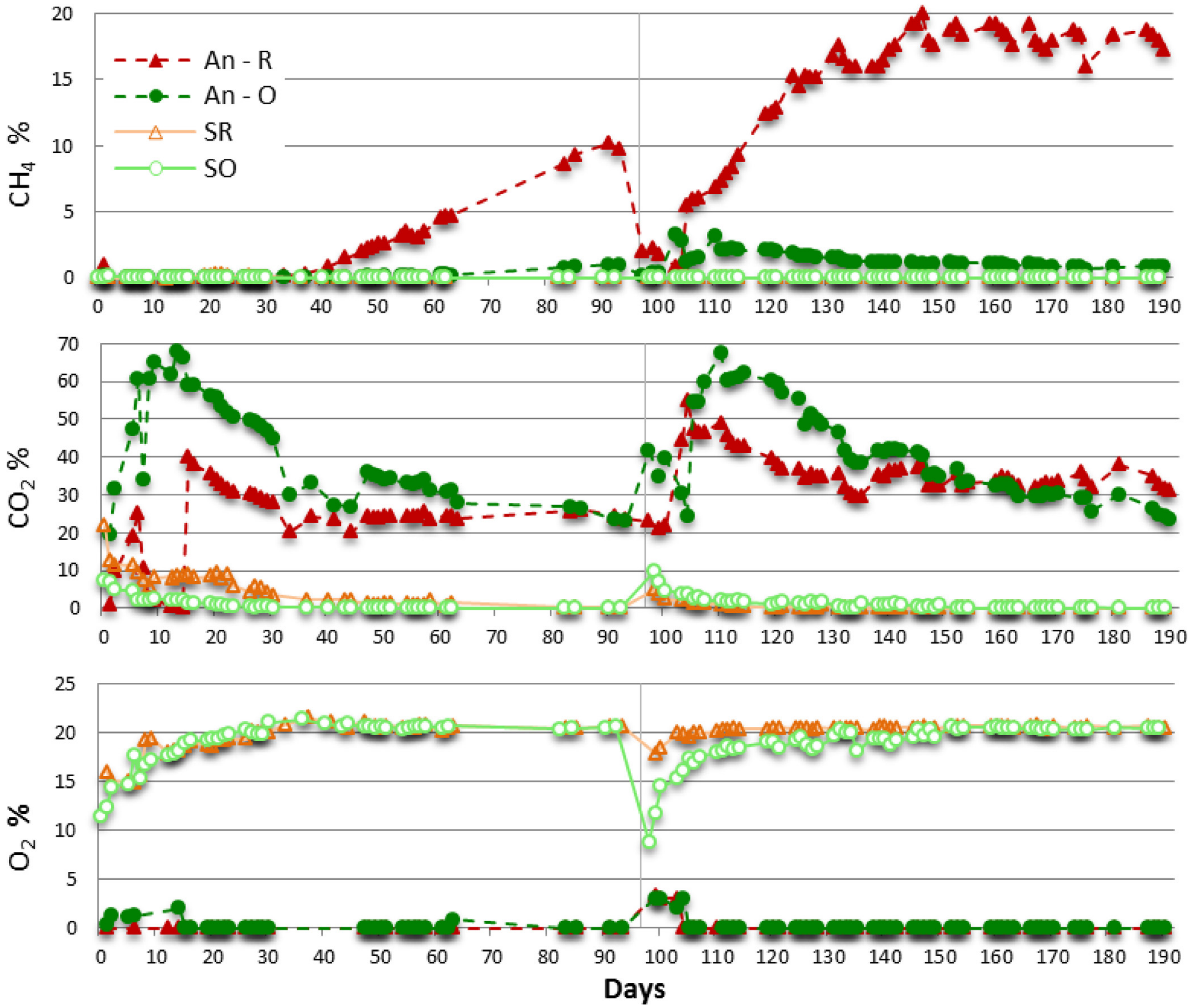


Fig. 6. Gas composition in reactors throughout the entire test.

over the first few days of the two phases as a result of the degradation of readily biodegradable compounds; subsequently, a similar composition to ambient air (20% O_2) was detected, underlining the effectiveness of the semi-aerobic system. In An-O no methanogenesis took place due to the presence of a low pH during both phases, with mainly CO_2 being detected; in An-R lysimeter CH_4 production commenced following an increase of pH.

Table 4
Waste characterization at the start and end of the experiment. Data relating to metals at the end of the second phase refer to waste strata on the bottom of lysimeters.

	Input waste		End second phase (data in brackets are the % removal)			
	O	R	An-O	An-R	S-O	S-R
TS (kg)	6.40	11.73	4.72(26)	7.56(36)	3.78(41)	6.95(41)
VS (kg)	4.41	5.82	3.24(26)	3.91(33)	1.62(63)	2.62(55)
TOC (kg)	2.56	2.82	1.65(36)	2.32(18)	0.96(63)	1.50(47)
IR4 (mgO_2/gTS)	85.3	55	48.1(44)	38.9(30)	8.9(90)	4.8(92)
Cd (mg/kgTS)	1.8	4.5	0.8	0.7	0.7	0.6
Cr (mg/kgTS)	13.2	15	14	12	17	13.4
Cu (mg/kgTS)	343	735	100	113	211	314
Fe (mg/kgTS)	3208	4319	4065	4581	6363	7667
Mn (mg/kgTS)	72.3	98.2	117	210	245	305
Ni (mg/kgTS)	9	9	16	14	13	27
Pb (mg/kgTS)	36	41	40	51	101	141
Zn (mg/kgTS)	220	125	238	209	316	546

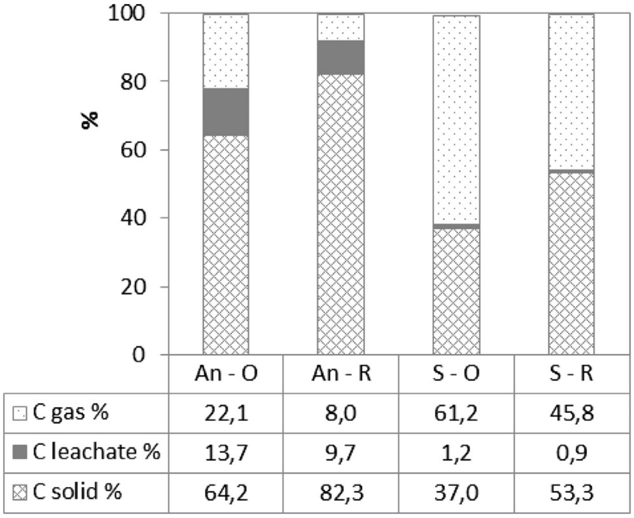
3.4. Waste characterization and carbon mass balance

Waste characterization at the beginning and end of the experiment (see Table 4) was assessed to better evaluate biodegradation of the organic matter under the aerobic and anaerobic conditions applied. As mentioned previously (Table 1), the putrescible content in “O” waste was higher than in “R” (approximately 20% more versus TOC and VS content); however, input TOC was quite similar and “O” matter was characterized by lower amounts of TS and VS due to the high moisture content.

In all semi-aerobic lysimeters much higher TOC and VS reductions were observed than in anaerobic columns, reflecting the final RI_4 values (43.5 mgO/gTS as average value in An and 7.7 mgO/gTS in S), thus confirming how the aerobic process had elicited a much higher stabilization.

Greater percentage decreases in VS (63%) and TOC (63%) parameters were observed in S-O columns. Indeed, the effectiveness of the semi-aerobic process was confirmed by the finding of a 90% RI_4 variation compared to a 29% variation in anaerobic columns.

The fate of carbon under anaerobic and semi-aerobic conditions was evaluated by means of carbon mass balance (Fig. 7): carbon was measured in initial and final waste samples (Csolid) and in the leachate throughout the entire experiment (Cleachate). Carbon gasification was taken as the difference (Cgas) between the total C inputs and total outputs. Confirming Shimaoka et al. (2000) and Cossu et al. (2003), the highest gasification occurred under semi-aerobic conditions, with between 45 and 60% of carbon being transferred to biogas and only 0.9–1.2% released through leachate emissions. Carbon gasification was limited in anaerobic columns and C was mainly accumulated in the final solids (64.2% in An-O, 82.3% in An-R) due to slow biodegradation, or transferred to the liquid phase (13.7% in An-O, 9.7% in An-R) due to lower pH and flushing. As expected, higher gasification was observed in “O” waste, due to the higher putrescible organic content in initial waste.



	An - O	An - R	S - O	S - R
☐ C gas %	22,1	8,0	61,2	45,8
■ C leachate %	13,7	9,7	1,2	0,9
▨ C solid %	64,2	82,3	37,0	53,3

Fig. 7. Percentages of carbon accumulation in solid phase (C solid) and transfer into liquid (C leachate) and gas phase (C gas) during the experiment.

With regard to heavy metals, at the end of the second phase tests were conducted in the bottom layer of the waste to check what degree of accumulation or mobilisation had occurred (Table 4). Higher concentrations were observed in semi-aerobic reactors: anaerobic conditions characterized by lower pH values promoted the mobilisation of heavy metals (Sinan Bilgili et al., 2007), whilst semi-aerobic reactors appeared to act as final sink in view of the presence of more stabilised substances (e.g.: humic substances) and alkaline conditions (Qu et al., 2008). Thus, flushing during the second phase seemed to enhance mobilisation from anaerobic but not from semi-aerobic lysimeters.

3.5. FSQ requirements

Performance of the semi-aerobic system at the end of the innovative dual-step management was assessed in line with Final Storage Quality (FSQ) requirements, according to the reference legislation (D.G.R. 2461/14).

On the basis of the results obtained (see Table 5), all semi-aerobic columns achieved the prescribed requirements for BOD_5, COD, BOD_5/COD and ammonia, displaying values lower than the respective FSQ. Particularly, the best performance was observed for “R” waste, due to the lower organic input.

The highest release of Heavy Metals (HM) occurred in anaerobic columns, exceeding limit values established by law for Iron and Manganese. As mentioned in the previous paragraph and according to Sinan Bilgili et al. (2007), acidic conditions promoted HM release from anaerobic columns, while stabilization of organic matter (probably into humic substances) and alkaline conditions in semi-aerobic reactors increased sorptive capacity of waste mass and reduced HM mobilisation (Qu et al., 2008). Neither anaerobic nor aerobic columns reached RI_4 reference limit, however, under semi-aerobic conditions “R” waste achieved a final value close to the threshold.

4. Conclusions

According to the literature, semi-aerobic conditions promote a better stabilization of organics but particularly the dual-step

Table 5
Final Storage Quality requirements suggested by the Lombardy Region, Italy (D.G.R. 2461/14), and final values achieved in lysimeters at the end of the experiment.

Sample	Parameter	FSQ values	AN-O	AN-R	S-O	SR
Leachate	COD mg/L	1500	6800	4580	370	305
	BOD5/COD	0.1	0.33	0.34	0.06	0.02
	Ammonia (mg/L)	50	216	181	11	6
	Cd (µg/L)	20	<10	<10	<10	<10
	Cr (µg/L)	2000	<10	102	<10	<10
	Cu (µg/L)	1000	212	225	251	234
	Fe (µg/L)	2000	3867	7667	1060	687
	Mn (µg/L)	2000	2013	2287	117	61
	Ni (µg/L)	2000	152	206	72	75
	Pb (µg/L)	200	<10	42.7	38	20
	Zn (µg/L)	3000	1070	737	702	447
Solid	RI_4 (mgO_2/gTS)	2	48	38	10	5

management contributed to the FSQ achievement over oneyear period of simulation, complaining the target values for BOD_5, COD, BOD_5/COD and ammonia in the final leachate, RI_4 in the solid samples.

Semi-aerobic stabilization kinetics were found to be 6–10-fold faster compared to the anaerobic process, promoting higher carbon gasification levels with no methane production, as higher ammonia transformation to nitrates.

Overall performance of the semi-aerobic lysimeters did not seem to be significantly influenced by the different initial organic content. During the first phase (characterized by relatively thin waste layer and controlled rain irrigation carried out by means of leachate recirculation, where possible), composting took place, thus enhancing the stabilization of waste. In the second phase (characterized by flushing simulating the effect of rainfall in tropical areas), both biodegradation and flushing effect occurred in the removal of contaminants, and organic removal kinetics increased.

Conversely, anaerobic columns were affected by the presence of a diverse waste composition; indeed, particularly with the "O" waste, a lower pH caused by a higher degree of acidification, contributed both to carbon accumulation in the solid during the first dry phase, and to its release in leachate during the flushing period.

The innovative dual-step management strategy implies a "horizontal growth" of the landfill, implying a need for high space requirements and resulting in high leachate production, thus linked to higher landfill management costs. However, if space is not a limiting factor, the generation of leachate is fundamental in ensuring irrigation during the dry season and enhancing both leachate evaporation and treatability, thus reducing volumes and mitigating management costs.

Further studies should be carried out to confirm the results obtained in the kinetics analysis, to further investigate the role of the composted layer in enhancing the removal of leachate contaminants and to evaluate the effects of additional waste layers after the first year of management.

References

Ahmadifar, M., Sartaj, M., Abdallah, M., 2016. Investigating the performance of aerobic, semi-aerobic, and anaerobic bioreactor landfills for MSW management in developing countries. J. Mater. Cycles Waste Manage. 18, 703–714. https://doi.org/10.1007/s10163-015-0372-0.

Allen, A.R., 2002. Low cost natural solutions to landfill management for developing nations. In: Kocasoy, G., Atabarut, T., Nuhuoðlu, Ý. (Eds.), Appropriate Environmental and Solid Waste Management and Technologies for Developing Countries.

Brunner, P.H., Fellner, J., 2007. Setting priorities for waste management strategies in developing countries. Waste Manage. Res. 25, 234–240. https://doi.org/10.1177/0734242X07078296.

Chen, D., Chen, H.W., 2013. Using the Koppen classification to quantify climate variation and change: an example for 1901–2010. Environ. Dev. 6, 69–79. https://doi.org/10.1016/j.envdev.2013.03.007.

Cossu, R., 2009. From triangles to cycles. Waste Manage. 29, 2915–2917. https://doi.org/10.1016/j.wasman.2009.09.002.

Cossu, R., Morello, L., Raga, R., Cerminara, G., 2016. Biogas production enhancement using semi-aerobic pre-aeration in a hybrid bioreactor landfill. Waste Manage. 55, 83–92. https://doi.org/10.1016/j.wasman.2015.10.025.

Cossu, R., Raga, R., Rossetti, D., 2003. The PAF model: an integrated approach for landfill sustainability. Waste Manage. 23, 37–44. https://doi.org/10.1016/S0956-053X(02)00147-2.

D.G.R. 2461/14 – Delibera Giunta Regionale n° 2461, 2014. Linee guida per la progettazione e gestione sostenibile delle discariche. Bollettino Ufficiale Regione Lombardia, n.41 (10/10/2014).

Di Maria, F., Micale, C., Sordi, A., Cirulli, G., Marionni, M., 2013. Urban mining: quality and quantity of recyclable and recoverable material mechanically and physically extractable from residual waste. Waste Manage. 33, 2594–2599. https://doi.org/10.1016/j.wasman.2013.08.008.

Ellen MacArthur Foundation, 2013. Towards the circular economy, vol. 1. J. Ind. Ecol. 1, 4–8. https://doi.org/10.1162/108819806775545321.

Essenwanger, O.M., 2001. Classification of Climates, World Survey of Climatology 1C, General Climatology. Elsevier, Amsterdam.

EU, Proposal of a Directive of the European Parliament and of the Council, 2015. <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015PC0595>.

Fellner, J., Döberl, G., Allgaier, G., Brunner, P.H., 2009. Comparing field investigations with laboratory models to predict landfill leachate emissions. Waste Manage. 29, 1844–1851. https://doi.org/10.1016/j.wasman.2008.12.022.

Hanashima, M., Yamasaki, K., Kuroki, T., Onishi, K., 1981. Heat and gas flow analysis in semiaerobic landfill. J. Environ. Eng. Divis., Proc. Am. Soc. Civ. Eng. 107 (EE1), 1–9.

Heimovaara, T.J., Cossu, R., van der Sloot, H.A., 2014. State of the art and perspectives for sustainable landfills. In: Cossu, R., van der Sloot, H.A. (Eds.), Sustainable Landfilling. CISA Publisher, ISBN 978-88-6265-005-2.

He, P., Yang, N., Gu, H., Zhang, H., Shao, L., 2011. N2O and NH3 emissions from a bioreactor landfill operated under limited aerobic degradation conditions. J. Environ. Sci. 23, 1011–1019. https://doi.org/10.1016/S1001-0742(10)60574-8.

He, Y., Guo, L., Gao, J., 2012. The advantages and mechanism of semi-aerobic landfill. Energy Procedia 17, 391–396. https://doi.org/10.1016/j.egypro.2012.02.111.

Huang, Q., Yang, Y., Pang, X., Wang, Q., 2008. Evolution on qualities of leachate and landfill gas in the semi-aerobic landfill. J. Environ. Sci. 20, 499–504. https://doi.org/10.1016/S1001-0742(08)62086-0.

IPPC, 2006. IPPC Guidelines for National Greenhouse Gas Inventories. Volume 5: Waste (Chapter 3: Solid Waste Disposal).

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Köppen-Geiger climate classification updated. Meteorol. Zeitschrift 15, 259–263. https://doi.org/10.1127/0941-2948/2006/0130.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50, 885–900. https://doi.org/10.13031/2013.23153.

Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 11, 1633–1644.

Pyper, B.J., Peterman, R.M., 1998. Comparison of methods to account for autocorrelation in correlation analyses of fish data. Can. J. Fish. Aquat. Sci. 55, 2127–2140. https://doi.org/10.1139/f98-201.

Qu, X., He, P.J., Shao, L.M., Lee, D.J., 2008. Heavy metals mobility in full-scale bioreactor landfill: initial stage. Chemosphere 70, 769–777. https://doi.org/10.1016/j.chemosphere.2007.07.013.

Rafizul, I.M., Alamgir, M., 2012. Characterization and tropical seasonal variation of leachate: results from landfill lysimeter studied. Waste Manage. 32, 2080–2095. https://doi.org/10.1016/j.wasman.2012.01.020.

Ritzkowski, M., Heyer, K.U., Stegmann, R., 2007. Emission behavior of aerated landfill material. In: Ritzkowski, M., Stegmann, R. (Eds.), Landfill Aeration. CISA Publisher, ISBN 978-88-6265-002-1.

Shao, L.M., He, P.J., Li, G.J., 2008. In situ nitrogen removal from leachate by bioreactor landfill with limited aeration. Waste Manage. 28, 1000–1007. https://doi.org/10.1016/j.wasman.2007.02.028.

Shimaoka, T., Matsufuji, Y., Hanashima, M., 2000. Characteristic and mechanism of semi-aerobic landfill on stabilization of solid waste. Intercontinental Landfill Research Symposium.

Sinan Bilgili, M., Demir, A., Ince, M., Özkaya, B., 2007. Metal concentrations of simulated aerobic and anaerobic pilot scale landfill reactors. J. Hazard. Mater. 145, 186–194. https://doi.org/10.1016/j.jhazmat.2006.11.014.

SPREP, 2010. A Practical Guide to Landfill Management in Pacific Island Countries and Territories, vol. 1 – Inland-based Waste Management, second ed. ISBN: 978-982-04-0398-7.

Sutthasil, N., Chiemchaisri, C., Chiemchaisri, W., Wangyao, K., Tawprayoon, S., Endo, K., Yamada, M., 2014. Comparison of solid waste stabilization and methane emission from aerobic and semi-aerobic landfills operated in tropical conditions. Environ. Eng. Res. 19, 261–268.

The World Bank, 2012. What a Waste: A Global Review of Solid Waste Management 98.

Theng, L.C., Matsufuji, Y., Mohd, N.H., 2005. Implementation of the semi-aerobic landfill system (Fukuoka method) in developing countries: a Malaysia cost analysis. Waste Manage. 25, 702–711. https://doi.org/10.1016/j.wasman.2005.01.008.

Tränkler, J., Visvanathan, C., Kuruparan, P., Tubtimthai, O., 2005. Influence of tropical seasonal variations on landfill leachate characteristics – results from lysimeter studies. Waste Manage. 25, 1013–1020. https://doi.org/10.1016/j.wasman.2005.05.004.

Whittaker, R.H., 1975. Communities and Ecosystems. Macmillan, ISBN 9780024273901.

Wu, X., Yue, B., Huang, Q., Wang, Q., Lin, Y., Zhang, W., Yan, Z., 2017. Spatio-temporal variation of landfill gas in pilot-scale semi-aerobic and anaerobic landfills over 5 years. J. Environ. Sci. (China) 54, 288–297. https://doi.org/10.1016/j.jes.2016.09.015.

Yang, Y., Yue, B., Yang, Y., Huang, Q., 2012. Influence of semi-aerobic and anaerobic landfill operation with leachate recirculation on stabilization processes. Waste Manage. Res. 30, 255–265. https://doi.org/10.1177/0734242X11413328.

Zeng, X.L., Ding, W.C., Long, T.R., Zhang, L.L., Lin, C.B., 2006. Influence of landfill structures on stabilization of fully recycled leachate. J. Cent. South Univ. Technol. (English Ed.) 13, 321–324. https://doi.org/10.1007/s11771-006-0133-2.

Paper VII. Optimised management of semi-aerobic landfilling under tropical wet-dry conditions

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Optimised management of semi-aerobic landfilling under tropical wet-dry conditions

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Keywords: developing countries, semi-aerobic landfill, tropical climate, sustainable landfill, landfill bioreactor

ABSTRACT

The processes involved in semi-aerobic landfills are heavily influenced by local climate conditions and waste composition. In particular, when considering rainfall seasonality in a tropical climate, the lack of moisture during the dry season and heavy rainfalls during the wet season may negatively affect biodegradation processes and landfill emissions. The aim of the present study was to investigate the performance of semi-aerobic landfill under tropical dry-wet climate conditions and to assess the potential benefits afforded by appropriate management of water input when operating the landfill by overlaying a new layer of waste in each climate season. Six lab-scale lysimeters were operated in two phases to reproduce, on two subsequent waste layers, a sequence of dry and wet tropical seasons: two with an initial dry phase, two an initial dry phase under controlled watering and two with an initial wet phase, during which leachate was stored to allow recirculation during the subsequent dry phase. In each pair of lysimeters one was filled with low putrescible content waste and the other with high putrescible content waste.

Although appropriate management of water input significantly improved landfill performance under dry climate conditions, the overlaying of a new layer of waste in each climate season played a fundamental role in ensuring good stabilisation over the one year simulation period; following stabilisation, the landfill bottom layer acts as an internal attenuating biological filter. In particular, under initial dry conditions, final BOD COD and ammonia values detected were below 20mgO2/L, 200mgO2/L, and 30mgN/L, respectively.

1. INTRODUCTION

The role of landfilling in modern waste management strategies is based on two concepts: environmental sustainability and sinking of elements (Cossu and Stegmann, 2018). Sustainability can be achieved by means of a combination of different technologies, including semi-aerobic landfilling. This method is based on a specific design which promotes the passive natural aeration of waste mass through a temperature difference present between landfill waste mass and external ambient. The design is aimed at reproducing an aerobic environment within the waste mass accelerating stabilisation, whilst avoiding typical operational costs linked to air injection/biogas management. The achievable benefits of semi-aerobic landfilling have been confirmed by several studies (i.a. Grossule et al., 2018; Ahmadifar et al., 2016; Aziz et al., 2010) and include: improvement of carbon and nitrogen degradation rate due to the aerobic processes, reduction of methane generation and increased carbon gasification rate.

Landfill stabilisation is heavily influenced by specific local climate conditions and composition of landfilled waste. The key factors controlling the stabilisation processes in a semi-aerobic landfill are water availability and putrescible organic content of landfilled waste, which may fluctuate considerably according to geographical position and socio-economic condition (Grossule and Lavagnolo, 2019). Water availability is fundamental for the biodegradation processes to promote the removal of soluble non-degradable contaminants; however, excessive water availability interferes with advective air flow promoting anaerobic processes. The putrescible fraction in waste is responsible for the main environmental impacts deriving from landfilling (methane and CO2 emissions, emissions of carbon and nitrogen contaminants in leachate, odours, risks of fires, etc.). Impacts are mitigated through the promotion of aerobic stabilisation processes in semi-aerobic landfill, although high putrescible waste content may potentially reduce the advective circulation of air, enhancing anaerobic processes and negatively influencing the quality of the gas released into the atmosphere.

A previous study (Grossule and Lavagnolo, 2019) investigated the stabilization performance of semi-aerobic landfill under conditions of different water availability and putrescible waste content.

The results of the study demonstrated that low water availability limits biodegradation processes in the presence of low putrescible content waste, while high water availability and high putrescible content waste results in anaerobic processes affecting the quality of biogas and leachate emissions. Proper management of water input proved to be an effective solution in improving landfill performance.

Tropical climate poses significant challenges for a proper semi-aerobic landfill management, alternating extreme rainfall conditions. In particular, according to the Kopper Geiger climate classification, the specific Savanna tropical climate (Aw), which represents the second most diffuse climate worldwide, is characterized by alternating dry (little or no precipitation) and wet seasons (heavy precipitations) (Chen and Chen, 2013; Kottek et al., 2006).

To overcome the negative impacts of rainfall seasonality on semi-aerobic landfill performance, Lavagnolo et al. (2018) proposed a dual-step management consisting in the storage of excess leachate during the wet season, and subsequent recirculation during the dry season to enhance biodegradation activity and perform an in-situ leachate treatment. Compared with anaerobic conditions, the results obtained were extremely positive leading to a more rapid and intense biological stabilisation of the waste mass.

The goal of this study was to investigate, using lab scale lysimeters, performance of a semi-aerobic landfill under tropical wet and dry climate conditions and to assess the potential benefits afforded by appropriate management of water input when operating the landfill by overlaying a new layer of waste in each climate season. In particular, given the relevance of water availability, the initial phase of the semi-aerobic landfill related to the specific climate season (wet or dry) was specifically considered.

The following three paradigmatic conditions were studied:

- Initial phase during the dry season, without any external water addition;
- Initial phase during the dry season, with controlled water addition;
- Initial phase during the wet season, with storage of leachate for subsequent recirculation during the dry phase.

These initial conditions are identical to those adopted in a previous study by the same Authors (Grossule and Lavagnolo, 2019).

The paper aims to provide an answer to the following question: “How would alternate landfilling phases under different climatic conditions (wet-dry), with and without proper water input control, influence the landfill behaviour in terms of stabilisation, long-term emissions of leachate and biogas, and general operational issues?".

Six lab-scale lysimeters were operated in two phases to reproduce, on two subsequent waste layers, a sequence of dry and wet tropical seasons: two with an initial dry phase, two with an initial dry phase under controlled watering and two with an initial wet phase, during which leachate was stored to allow for subsequent recirculation during the dry phase. In each pair of lysimeters one was filled with low putrescible content waste and the other with high putrescible content waste. Following the initial phase, represented by the results reported previously by the same Authors (Grossule and Lavagnolo, 2019), a second phase was simulated by adding to the previously used lysimeters a second layer of fresh waste under alternating climate conditions.

Solid, leachate and gas quality were monitored and stabilisation performances assessed.

2. MATERIALS AND METHODS

2.1. *Waste samples*

Two different types of waste were tested, reproducing Municipal Solid Waste (MSW) with Low Putrescible (LP) and High Putrescible (HP) content. LP waste, yielding a 9% wet weight of kitchen wastes, consisted in residual waste from MSW source segregation and separate collection. HP waste was obtained by mixing LP waste with source segregated kitchen waste in order to achieve a 50% w/w ratio.

The composition of the waste used in the two different experimental phases and the main analytical parameters are reported in Table 1.

2.2. *Equipment*

The experiment was carried out using six cylindrical Plexiglass lysimeters (1.0 m height, inner diameter of 40 cm). Each column was equipped at the bottom with a slotted pipe (8 cm diameter), open to the air.

Table 1. Composition of the different types of waste (LP, HP) tested during the first and second phases. (LP= Low Putrescible waste, HP=High Putrescible waste).

		First phase		Second phase	
		LP	HP	LP	HP
Categories	Paper and paperboard (%)	19.9	11.0	17.9	9.9
	Plastics (%)	17.5	9.6	17.4	9.6
	Metals (%)	1.9	1.1	1.8	1.0
	Aggregates (%)	9.6	5.3	14.1	7.8
	Textiles (%)	2.1	1.2	1.8	1.0
	Glass and inerts (%)	8.9	4.9	8.1	4.5
	Kitchen residues (%)	9.2	50.0	9.4	50.0
	Green and wooden materials (%)	3.1	1.7	2.4	1.4
	Under-sieve (20 mm) (%)	27.7	15.3	27.0	14.9
Characterization	Waste mass (kg)	27	27	27	27
	TS (%)	56.9	39.5	56.3	37.9
	VS (%TS)	72.7	84.4	70.5	74.5
	TOC (gC/gTS)	34.5	40.3	30.2	35.4
	RI_4 (mgO_2/gTS)	38.4	93.3	26.7	6.4

A 20 cm layer of gravel (size 16-32 mm) was placed at the bottom of lysimeters to allow leachate drainage and facilitate air circulation. Gas sampling valves were fitted laterally, while leachate was collected at the bottom of each column. Columns were thermally insulated by a coating system made of polyethylene. Temperatures in each column were monitored by means of thermocouples (Thermo Systems TS100).

A perforated plate placed at the top of each column allowed uniform water irrigation.

Following operations for the first phase (Grossule and Lavagnolo, 2019), columns were lengthened by flanging an additional cylinder section in order to perform the second phase (Figure 1).

Reactors were operated in a thermally controlled room.

2.3. Methodology

The research programme is graphically illustrated in Figure 2. The experiment lasted approximately 6 months, divided into two subsequent phases (0-108th day and 109-2016th day). Six lysimeters were operated, each reproducing both a dry and a wet tropical season: two with an initial dry phase (D), two with an initial dry phase under controlled watering (D’) and two with an initial a wet phase, with storage of leachate for subsequent recirculation during the dry phase (W). In each pair of lysimeters one was filled with low putrescible content waste (LP) and the other with high putrescible content waste (HP).

The columns were filled with 27 kg waste at the beginning of the first phase, with addition of a further 27 kg at the beginning of the second phase. An approximate initial compaction of 0.5 kg/L was achieved. A 5 cm layer of gravel was placed on top of both waste layers to ensure uniform water irrigation.

Environmental temperature values in the testing room were varied and maintained between 18°C and 30°C to reproduce the night/day cycle, producing a significant influence on the temperature gradient between the waste mass and the external ambient temperature, and thus natural air circulation.

During the wet phase a water input of 3 L/d was adopted in all columns to reproduce water infiltration corresponding to a yearly mean

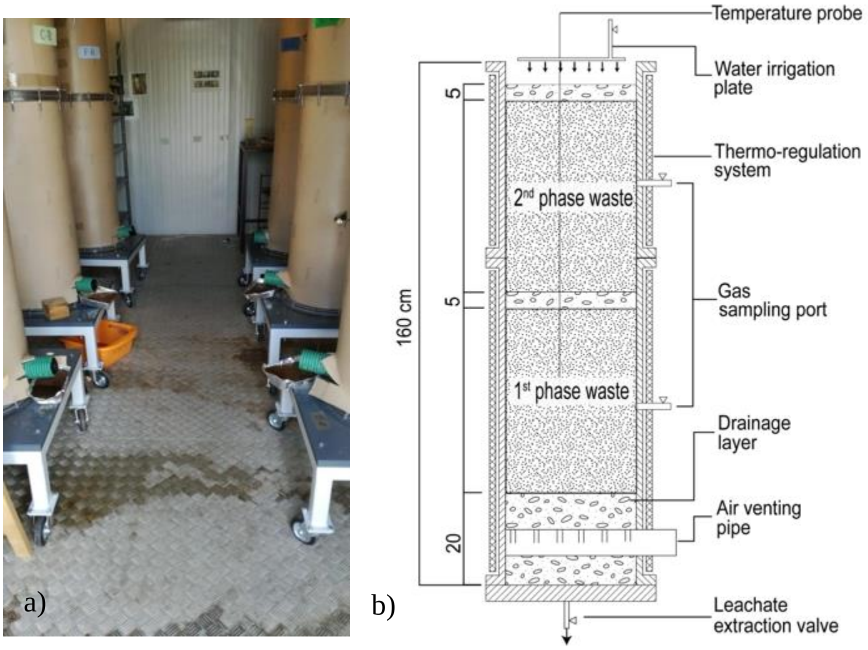

Figure 1. Set up of the semi-aerobic landfilling reactors (a) and constructive details of the individual reactors (b). The lengthening of columns to enable conduction of the second research phase is indicated.

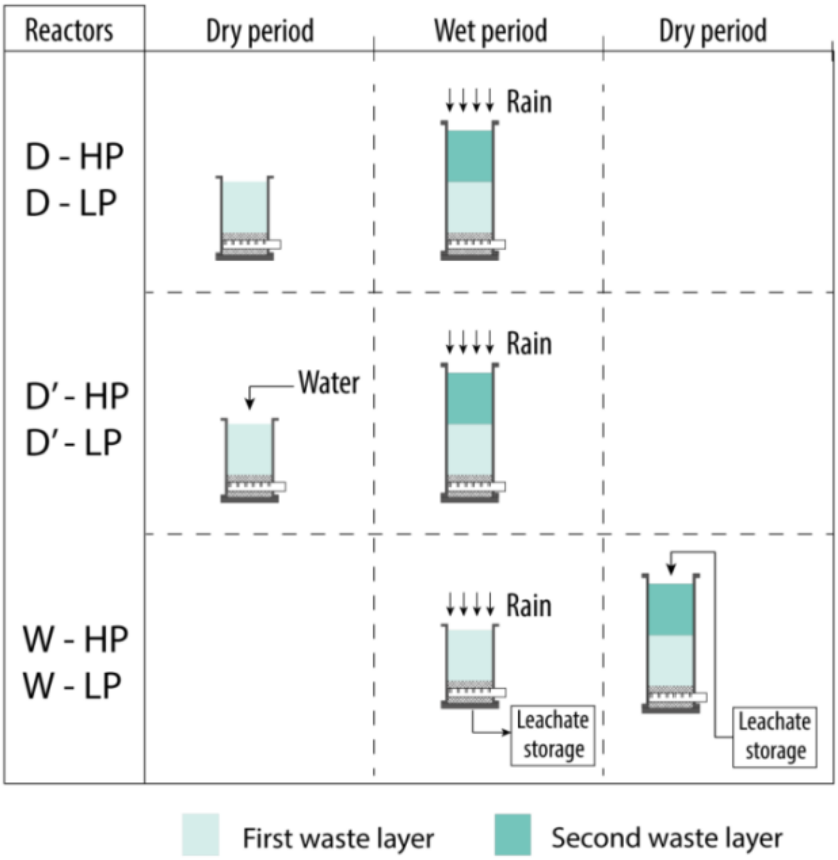

Figure 2. Research programme. (According to the first simulated season: D=Dry conditions, D'=Dry conditions with controlled watering, W=Wet conditions. According to tested waste type: HP= High putrescible content waste; LP=Low putrescible content waste).

precipitation of 1400 mm. This corresponded to a liquid to solids ratio (L/S) of 20.5 and 14.4 L/kgTS in columns with HP waste and LP waste, respectively. During the dry phase, no water was added to D columns, reproducing dry climate conditions. Conversely, in D' and W columns a hydraulic load of 0.25 L/d was added during the dry phase to reproduce optimal water availability for biodegradation, achieving a final L/S ratio of 2.2 and 1.6 L/kgTS in columns with HP waste and LP waste, respectively, as suggested by Lavagnolo et al. (2018). Hydraulic load was achieved by means of water irrigation in D' columns, and by recirculating leachate stored during the wet phase, in W columns.

During the experimental test, solid, liquid, and gas samples were analysed according to International Standard Methods. Biogas concentrations of CO_2, CH_4 and O_2 were monitored using an Eco-Control LFG20 analyser.

At the beginning and end of both phases, waste was sampled from each reactor and the following parameters measured: 4-day Respirometric Index (RI_4), Total Carbon (TC), Total Organic Carbon (TOC), Total Kjeldahl Nitrogen (TKN), TS and VS. TC and TOC on solid samples were determined using a TOC–VCSN Shimadzu Analyzer. RI_4 was measured using a Sapromat respirometer (H+P Labortechnik, Germany).

pH, alkalinity, TS and VS, volatile fatty acids (VFA), chemical oxygen demand (COD), TC and TOC, five-day biochemical oxygen demand (BOD_5), nitrogen compounds (TKN, ammonia, nitrate, nitrite) and chlorides, were regularly analysed in leachates.

3. RESULTS AND DISCUSSION

3.1. Temperatures

Figure 3 illustrates the temperature values and water availability over time for all tested columns, referred to the fresh waste layers in the two experimental phases.

Water availability can be defined as follows (Eq. 1):

$$\mathrm{wa} = \mathrm{ew} + \mathrm{L/S} = \mathrm{u} \cdot \frac{\mathrm{kg\ waste}}{\mathrm{kg\ TS}} + \mathrm{L/S} \quad \mathrm{Eq\ (1)}$$

Where:

wa: water availability (kgH_2O/kg TS)

ew: endogenous water (kgH_2O/kg TS) = $\mathrm{u} \cdot \frac{\mathrm{kg\ waste}}{\mathrm{kg\ TS}}$

L/S: liquid (input water) over solid ratio (kgH_2O/kg TS) in a given time.

u: moisture in waste to be landfilled (kgH_2O/kgwaste).

Generally, in all test columns temperature values were in line with the degradation processes, registering higher values at the start, which gradually decreased over time.

Temperatures were generally higher in columns containing low putrescible waste (LP) under dry climate conditions. The highest values (58°C) were observed in the first phase in the D-LP Column (Low putrescible under dry conditions) and in the second phase in the W-LP column in the new layer added under dry conditions.

The results obtained suggested that the higher the water availability (endogenous waste moisture + water input), the lower the temperatures. In particular, as confirmed by the quality of the biogas (Figure 4), increased water availability due to excess external addition of water negatively influenced natural

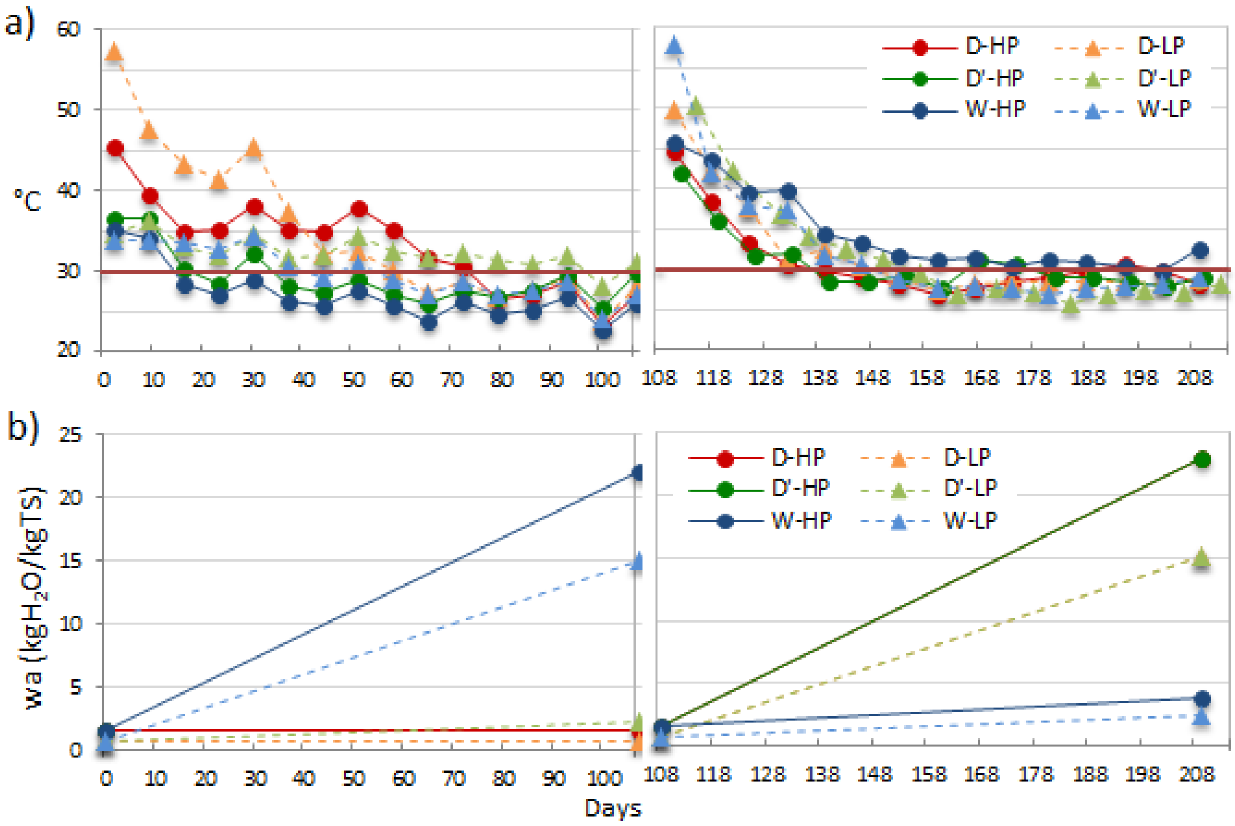

Figure 3. Temperature values (a) and water availability (b) in the layers of fresh waste in the first and second phase for all testing columns.(D=Dry conditions, D'=Dry conditions with controlled watering; W=Wet conditions, HP=Waste with high putrescible content; LP=Waste with low putrescible content).

air advection, resulting in reduced aerobic oxidative processes, and consequently lower temperature values. During the first phase, temperature values remained higher than ambient values over a lengthier period of time compared to the second phase. This should be ascribed to the different putrescible content of the waste (RI_4 values in HP columns were 93 and 63 mgO_2/gTS for the 1st and 2nd phase, respectively, while for LP were 38 and 27 mgO_2/gTS).

3.2. Landfill gas composition

Volumetric percentages of the most significant LFG components (CH_4, CO_2 and O_2) are represented in the stacked area chart in Figure 4, together with stability values measured at the beginning and end of each individual phase.

At the beginning of all individual phases, aerobic conditions elicited rapid degradation of the readily-biodegradable fractions, depletion of oxygen (<5%) and a consequent high production of CO2.

During the first phase gas composition, decrease in CO_2 concentrations and final waste stability (RI_4 values) were driven by waste type and water availability. In particular, the combination of high putrescible waste and high water availability resulted in anaerobic effects and limited waste stabilisation (D'-HP, W-HP), while low putrescible waste and high water availability resulted in flushing effect and promoted high contaminant mobility (D'-LP, W-LP); low water availability halted the biodegradation processes (D-LP).

Proper water availability management and the proportioning of endogenous water (naturally present in putrescible fraction) and water input, significantly improved landfill performance.

During the second phase, water input (rainfall infiltration for D and D' columns; leachate recirculation for W column) moved the soluble putrescibles from the fresh waste layer to the bottom layer, provoking rising concentrations of CO_2 and decreasing RI_4 values in the bottom layer. RI_4 values remained constantly below 12 mgO2/g TS and the lowest values (6-7 mgO2/g TS) were observed for all LP columns and for the column with High Putrescible waste, under dry climatic conditions. This suggested that during the 2nd phase the first layer in all columns completed the stabilisation processes and became a bottom layer, acting as a sort of internal Biological Filter for leachate from the new layer of fresh waste. On the other hand, the second waste layer (fresh waste) achieved good stabilisation values, below 20 mgO_2/g TS, which was particularly low in W columns under controlled water input, with values around 3 mgO_2/g TS compared to D and D' columns under wet conditions.

Methane generation occurred mainly with HP waste, particularly in the presence of high water availability, achieving the highest methane concentrations (up to 10%) in W-HP column during the first wet phase.

3.3. Leachate quality and quantity

In all columns during the 2nd phase leachate generation ranged between 70-80%(wa), with the exception of the column with leachate recirculation and high putrescible waste (W-HP) where over 100%(wa) was reached.

Leachate produced during the 2nd phase was collected from the bottom of the columns and analysed. The results were compared with those obtained in the first phase.

COD and BOD concentrations in leachate during the test period are illustrated in the stacked area chart of Figure 5, jointly with BOD/COD ratio trend, while Total Organic Carbon (TOC), Volatile fatty acids (VFA) are represented in Figure 6.

The above-mentioned Biological Filter effect of the bottom layer during second phase is clearly evident from the behaviour of all parameters. In particular, the concentrations achieved for all parameters during the wet phase were much lower in D and D' columns (during the second phase) compared to those achieved in W columns, in which the wet phase coincided with the first phase. The same considerations are valid for the dry phase, when not considering D columns in which no/limited leachate generation occurred. Final BOD values in leachate were comprised between 5-20 mg/L, while COD values were around 200 mg/l. Only in W columns, BOD and COD values after 200 days, were respectively 20 and 790 mg/L in W-HP and 5 and 510mg/L in W-LP, corresponding to negligible values from an environmental point of view (D.G.R. 2461/14, reference legislation).

Similar behaviour was displayed by TOC, which remained around 50-60 mg/l in all columns ,with the exception of W columns. In particular, 280 and 200 mgC/L were detected in columns with High putrescible and Low putrescible waste, respectively.

The ratio of VFA/TOC in the second phase remained generally low, averaging around 0.1-0.5 mg CH_3COOH/mg C (Figure 7a). This aspect, together with the evident stability of pH over time (pH values around 7.7, see Figure 7b), highlighted the role carried out by stabilised waste in the bottom layer during the second phase.

The Biological Filter effect on the contrary was less evident with regard to nitrogen transformation, particularly during the wet phase. In this case, wet conditions in the second phase reduced air circulation, thus decreasing nitrogen oxidation, while the watering of columns promoted hydrolysis of Organic nitrogen and flushing of Ammonia Nitrogen. Final TKN concentrations ranged between 10 and 30 mg/l, with the exception of W-HP where a concentration of 80 mg/L was found. The behaviour of the different nitrogen compounds throughout the two climate phases tested is represented in Figure 8.

4. CONCLUSIONS

Based on the above -reported results the following conclusive remarks can be drawn:

- Semi-aerobic landfilling is potentially heavily influenced by tropical wet-dry climate, due to the influence produced by water availability and different putrescible content of waste on natural advective air circulation.
- Previous studies (Grossule and Lavagnolo, 2019) have demonstrated that consistently balanced availability of water, both in terms of endogenous water naturally present in the putrescible fraction, and external water input (rainfall, leachate recirculation), promotes good natural air circulation while supporting aerobic degradation processes during the dry phase;
- When implementing semi-aerobic landfill under tropical dry-wet climate conditions, the overlaying of a new layer of waste in each climate season plays a fundamental role in ensuring good stabilisation. In particular, alternation of new waste layers together with rainfall seasonality, maintaining constant operational conditions throughout the entire climate season (wet or dry) for each individual layer will contribute towards enhancing stabilisation of the landfill bottom layer, which behaves as an internal attenuating biological filter for leachate produced during subsequent phases;
- during the wet season flushing effect, in terms of mobility of contaminants, and anaerobic processes prevail over semi-aerobic conditions limiting natural air circulation;
- during the dry season, by ensuring a constantly balanced water availability through proportioning of putrescible waste content and external water addition, the circulation of natural air can be conveniently maintained.

In conclusion, a semi-aerobic landfill operated under wet-dry climate conditions can be managed as a hybrid reactor, aerated throughout the dry season and flushed in anaerobic conditions in the wet season.

However, the positive results obtained in this preliminary investigation should be confirmed by further pilot studies in order to identify and define appropriate design parameters.

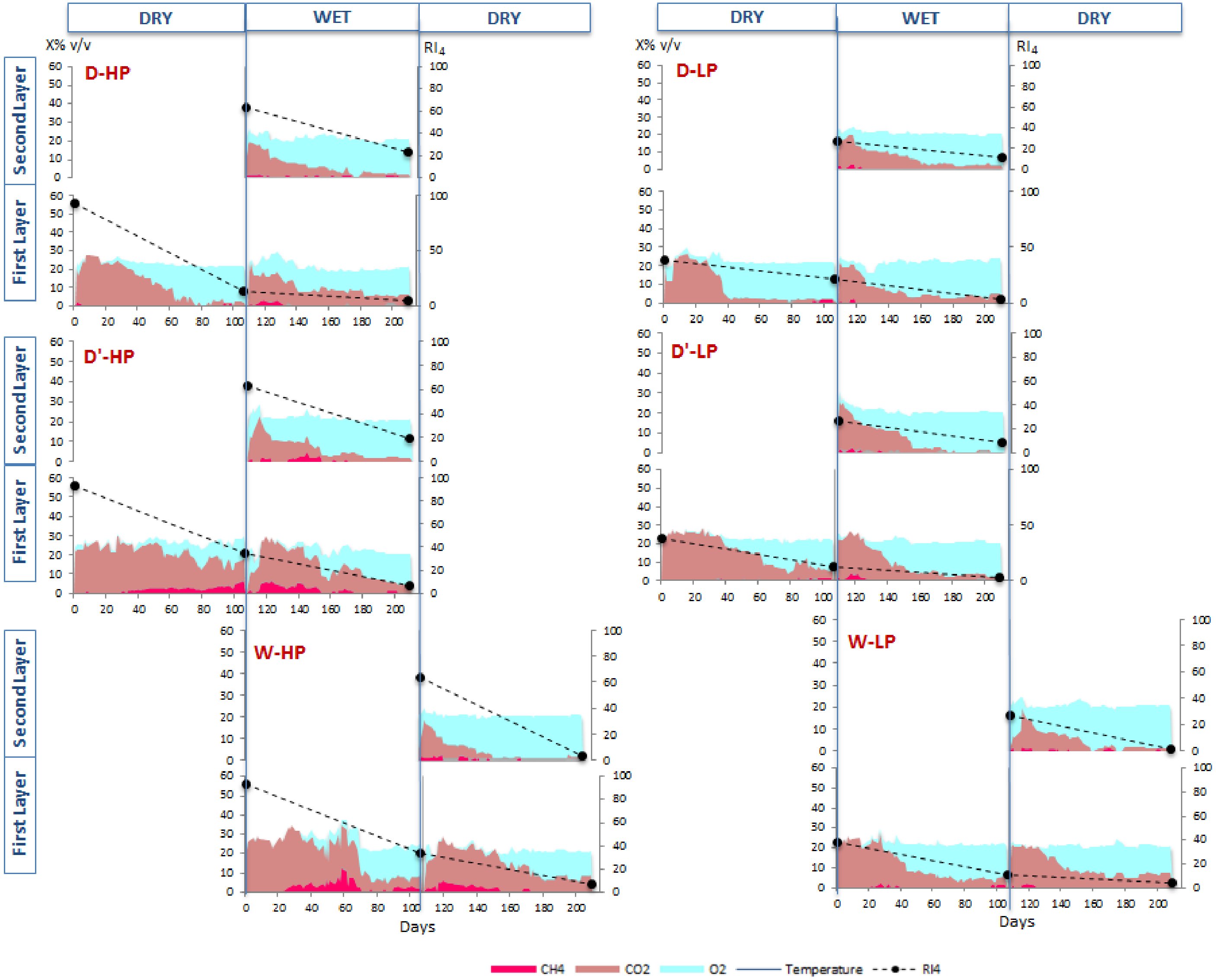

Figure 4. Landfill gas (LFG) composition (Stacked area chart) and waste stabilisation in the lysimeters, over testing time. (X% v/v: volumetric gas fractions,; RI4: 4 days Respirometric Index, mgO2/kgTS). Nitrogen gas is not represented. RI4 values are only referred to the beginning and end of each individual phase; the line connecting these values is only indicative to facilitate reading. (D=Dry conditions, D'=Dry conditions with controlled watering; W=Wet conditions, HP=Waste with high putrescible content; LP=Waste with low putrescible content).

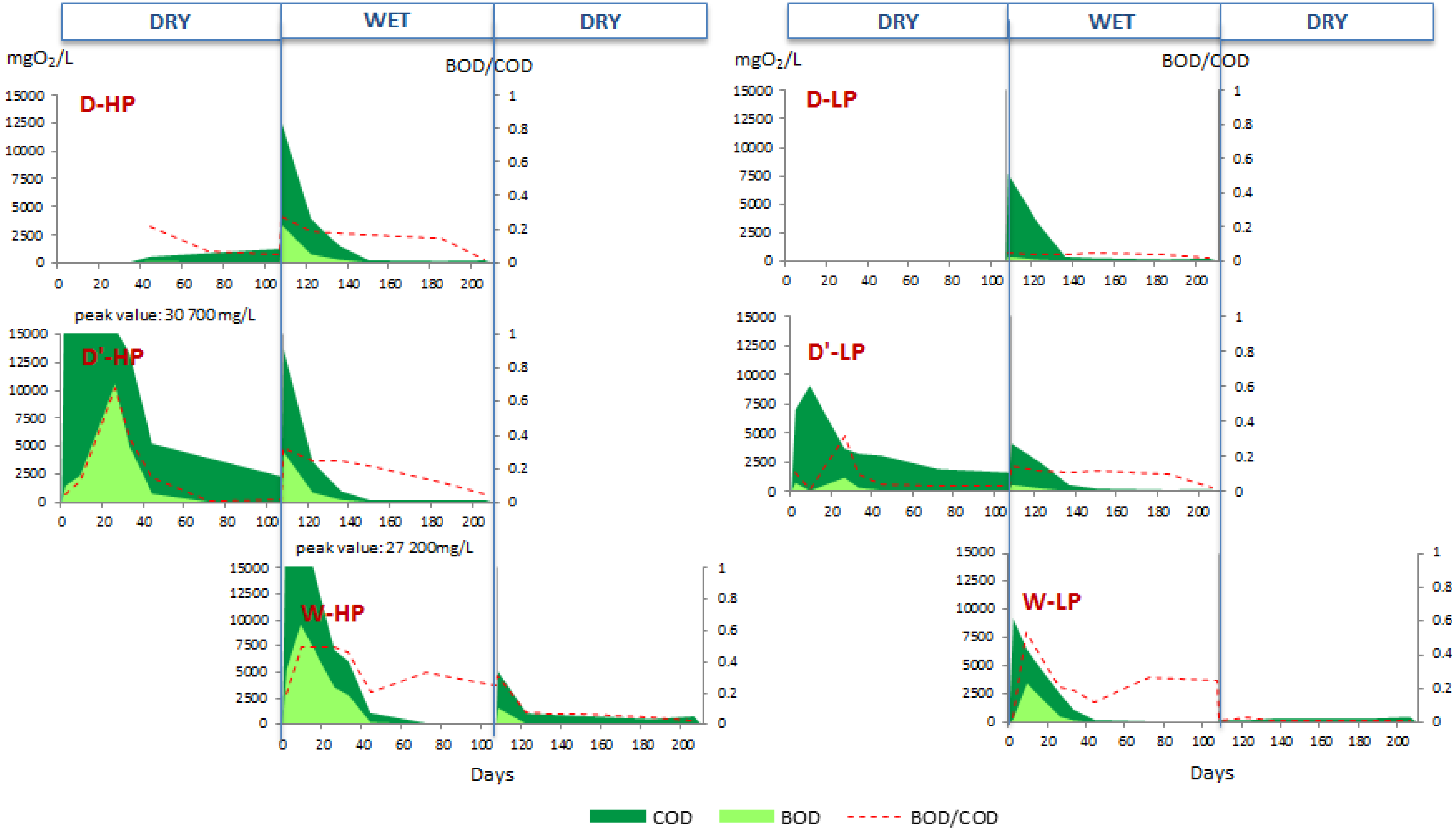

Figure 5. BOD/COD ratio, BOD and COD concentrations in leachate (overlapped area chart) vs. testing time, for the different lysimeters. D=Dry conditions, D'=Dry conditions with controlled watering; W=Wet conditions, HP=Waste with high putrescible content; LP=Waste with low putrescible content.

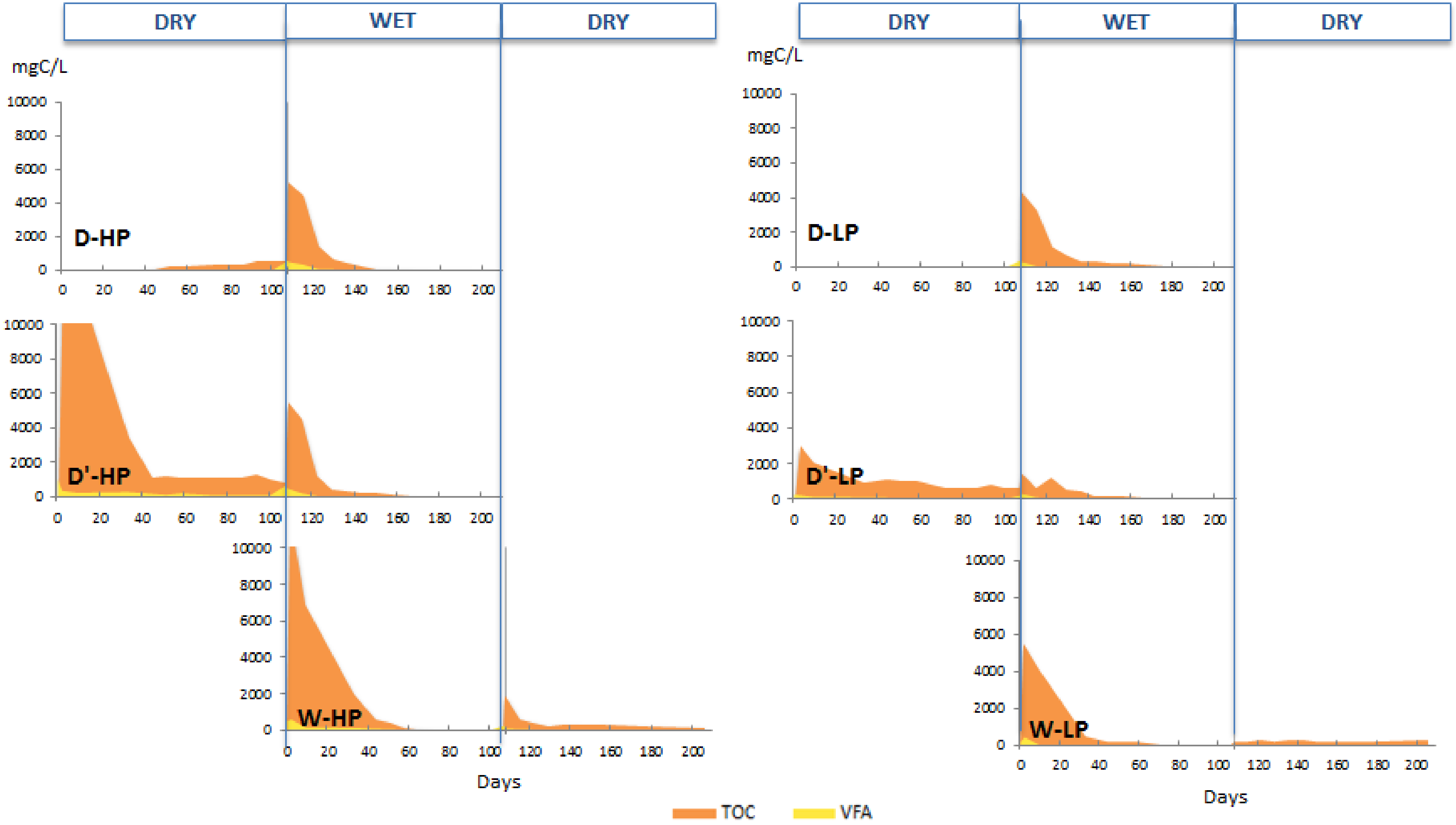

Figure 6. pH, VFA and TOC concentrations in leachate (overlapped area chart) vs. testing time, for the different lysimeters. D=Dry conditions, D'=Dry conditions with controlled watering; W=Wet conditions, HP=Waste with high putrescible content; LP=Waste with low putrescible content.

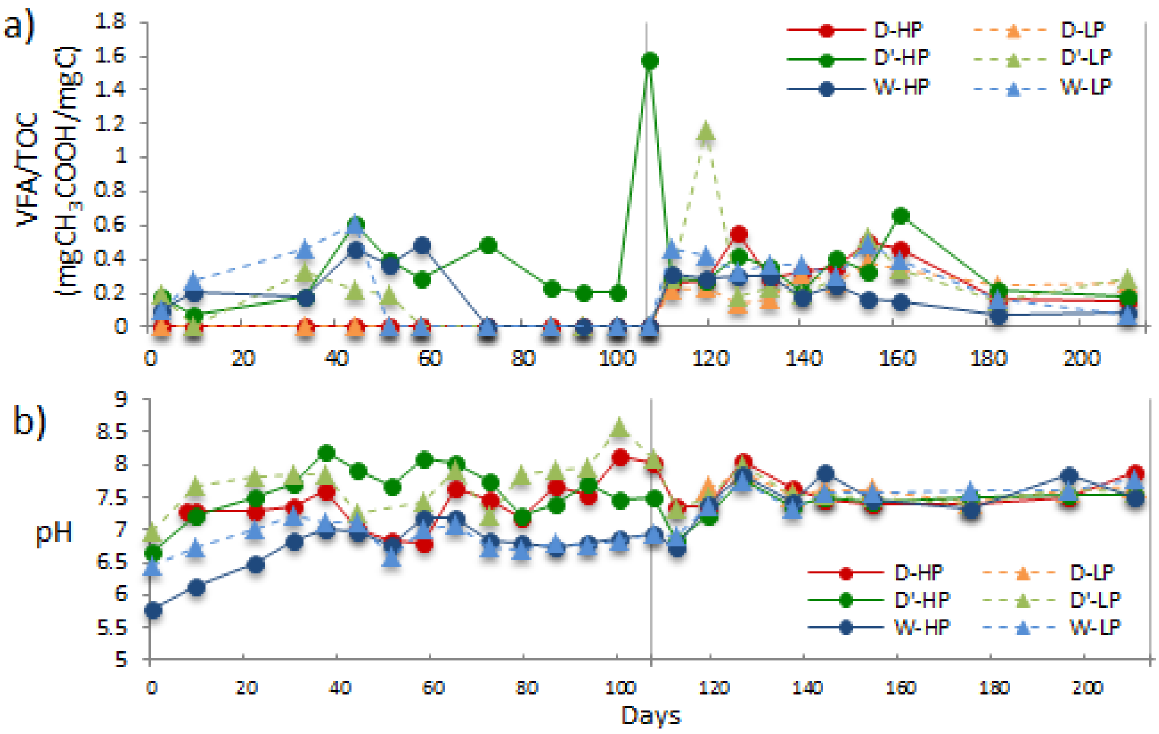

Figure 7. VFA/TOC ratios (a) and pH values (b) measured over time in leachate collected at the bottom of all test columns during the first and second climate phases.

REFERENCES

Ahmadifar, M., Sartaj, M., Abdallah, M., 2016. Investigating the performance of aerobic, semi-aerobic, and anaerobic bioreactor landfills for MSW management in developing countries. J. Mater. Cycles Waste Manag. 18, 703–714. doi:10.1007/s10163-015-0372-0

Aziz, S.Q., Aziz, H.A., Yusoff, M.S., Bashir, M.J.K., Umar, M., 2010. Leachate characterization in semi-aerobic and anaerobic sanitary landfills: A comparative study. J. Environ. Manage. 91, 2608–2614. doi:10.1016/j.jenvman.2010.07.042

Chen D and Chen HW (2013) Using the Köppen classification to quantify climate variation and change: An example for 1901-2010. Environmental Development 6(1): 69–79. DOI: 10.1016/j.envdev.2013.03.007.

Cossu, R., Stegmann, R. Solid Waste Landfilling, Concepts, Processes, Technology. Elsevier, 2018, ISBN: 9780128183366.

D.G.R. 2461/14 – Delibera Giunta Regionale n progettazione e gestione sostenibile delle discariche. Bollettino Ufficiale Regione Lombardia, n.41 (10/10/2014).

Lavagnolo, M.C., Grossule, V., Raga, R., 2018. Innovative dual-step management of semi-aerobic landfill in a tropical climate. Waste Manag. 1–10. doi:10.1016/j.wasman.2018.01.017

Grossule, V., Lavagnolo, M.C., 2019. Lab tests on semi-aerobic landfilling of MSW under varying conditions of water availability and putrescible waste content. Submitted to Journal of Environmental Management. (19/9/19)

Grossule, V., Morello, L., Cossu, R., Lavagnolo, M.C., 2018. Bioreactor landfills : comparison and kinetics of the different systems, Detritus, 03, 100–113.

Kottek M, Grieser J, Beck C, et al. (2006) World map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift 15(3): 259–263. DOI: 10.1127/0941-2948/2006/0130.

Paper VIII. The treatment of leachate using Black Soldier fly (BSF) larvae: adaptability and resource recovery testing

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Research article

The treatment of leachate using Black Soldier Fly (BSF) larvae: Adaptability and resource recovery testing

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ABSTRACT

The benefits of using Black Soldier Fly (BSF) larvae in biowaste treatment include: commercial value of the stabilized residue, production of biomass rich in fats and proteins, suitable both for biodiesel production and animal feeding. The use of BSF for leachate treatment would introduce a blue low cost solution in the landfill technology, particularly appropriate in developing countries, where landfilling is still widely applied. This paper aimed to investigate the adaptability of BSF larvae to leachate environment, by using different leachate concentrations (25%, 50%, 75%, 100%) and two different feeding substrates: liquid (pure leachate) and semi-solid (wheat bran mixed with leachate). In all tests mortality was less than 50% and it was mainly linked to food shortages: the higher the nutrient content in leachate, the higher the larval development. Dry mass characterisation demonstrate that BSF prepupae biomass can be exploited as an alternative energy source in the production of biodiesel.

1. Introduction

In the context of the Circular Economy, the use of Black Soldiers Fly (BSF) for biowaste treatment could be a significant option for either managing the waste and providing resources in term of materials and energy. Indeed, in the larval stage BSF are capable of metabolising and stabilising huge amounts of putrescible waste, transforming it into valuable biomass rich of proteins and fats, suitable to be used respectively for animal feeding and biofuel production.

BSF has been successfully applied to different kinds of biowaste, including food waste, dairy manure, kitchen waste, agricultural residues, etc. (see following section). Leachate from MSW landfilling is traditionally characterised by a high biodegradable organic content, thus representing an unexplored source for BSF application. Indeed, the high degradable organic content in leachate is one of the most challenging issues in MSW landfilling (environmental impacts, complexity and costs of treatment processes, etc.), as confirmed by Cossu and Stegmann (2018).

Although throughout the European Union landfilling is considered an obsolete waste management technology, the system continues to represent the most-widely applied disposal method worldwide, particularly in developing countries (DCs), being an economically and technically affordable means of preserving public health and the environment (Grossule et al., 2018; Lavagnolo et al., 2018). Moreover, landfilling represents an unavoidable and strategical step in any Circular Economy aimed at closing the materials loop by providing a final sink for no longer technically or economically valuable residual fractions (Cossu, 2009).

Leachate treatment may prove to be somewhat problematic in DCs for the following reasons:

- Landfilling in DCs is the most widely-used waste management system;
- Domestic wastes are characterised by a high putrescible content, and consequently leachate is highly concentrated in terms of BOD, COD and TKN (organic and ammoniacal nitrogen);
- Singular climate conditions (tropical weather, monsoon regimes, etc.) may produce a significant influence on the quality and generation of landfill leachate (i.e. huge amounts in wet periods, high organic concentration in dry periods);
- Traditional leachate treatment technologies adopted in industrialised countries may be too complex and inappropriate in terms of equipment supply, operation and maintenance;
- High capital and operational costs in leachate treatment are not compatible with typical DCs economies.

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Based on the above, the use of BSF larvae may constitute a viable process for potential implementation in the context of leachate treatment schemes, both in developing and industrialised countries where MSW landfilling is still applied (Canada, Australia, USA, etc.).

This paper aimed to investigate the adaptability of BSF larvae to leachate environment.

A lab-scale testing programme was established according to the following operational conditions:

- exposure of BSF larvae to different percentages of leachate in the feeding liquid (from 25 to 100%)
- substrate conditions simulating growth of larvae in a liquid media, such as a leachate pond, and semisolid media mixing liquid media to wheat bran bedding often adopted in rearing of BSF larvae (Shakil Rana et al., 2015).

The main objectives of the programme were to investigate the following parameters:

- Wet weight of larvae variation over time
- Larvae mortality
- Time required to achieve the prepupal stage
- Percentage of prepupation (achievement of prepupa stage)
- Protein and lipid contents, including profiling of fatty acids.

Before detailing the testing programme and presenting the relevant results, a literature review on BSF larvae metabolism and application to biowaste is provided in the next section.

2. Use OF BSF IN waste treatment

2.1. Life cycle of BSF

The life cycle of a BSF consists of four stages: egg, larva, pupa and adult (Fig. 1). The larval stage is the longest and sole feeding stage. The adult fly does not feed and survives only on its body fat reserve, limiting the risk of disease transmission (Banks et al., 2014; Diener et al., 2009; Makkar et al., 2014; Sheppard et al., 2002). Development from larvae to prepupa stage takes about 2–4 weeks, but can be prolonged up to several months if conditions are unfavourable (Makkar et al., 2014; Sheppard et al., 2002; Tomberlin et al., 2009; Zürbrugg et al., 2017). Once they become prepupae, the white colour of larvae starts to darken and they self-harvest by leaving the wet feeding for a driest prepupation site (Banks et al., 2014; Tomberlin et al., 2009).

2.2. Ambient and food growing conditions

BSF are characterised by high adaptability to a series of environmental conditions, food shortages or oxygen deficiencies; by resistance to insecticides and pesticides; and by competition with other flies (Diener and Zurbrügg, 2011; Makkar et al., 2014; Turchetto and Vanin, 2004). However, environmental conditions and food quality/quantity may strongly influence the success and time of development of the BSF larvae. In particular, optimal food quantity and quality, temperature, moisture, photoperiod and pH present in literature are summarized in Table 1.

Several authors (including Tomberlin et al., 2002) have advocated optimal moisture conditions ranging between 30 and 80%, stating that by increasing the humidity of the environment, the success of BSF development increases. However, although BSF larvae are capable of developing under pure liquid conditions, they prefer a moist or semi-solid environment (Lohri et al., 2017).

BSF Larvae feed on a wide range of decomposing organic matter such as spoiled feed, kitchen waste, fish offal, rotting fruit and vegetables, coffee bean pulp, animal manure, and human excreta (Banks et al., 2014; Diener and Zurbrügg, 2011; Newton, 2004). The study by Popa

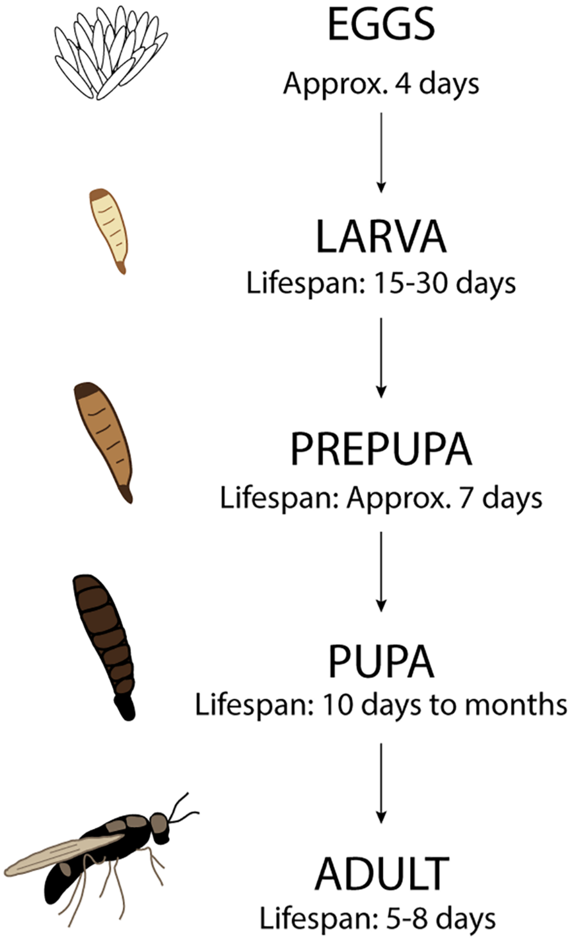

Fig. 1. Life cycle of Black Soldier Fly. Modified from De Smet et al. (2018).

Table 1
Optimal conditions for different parameters driving BSFL development.

Parameter	Optimal conditions	References
Food quantity and quality	125 mg/larva/d of biowaste, 1–2 cm size; 100 mg/larva/d of chicken feed 1 mL organic leachate/larva/week	Zurbrügg et al., 2017; Diener at al., 2009; Popa and Green (2012)
Moisture (%)	65–80% 30–85% 30–90% 60% 70–80%	Lohri et al. (2017); Tomberlin et al. (2002); Sheppard et al. (2002); Myers et al. (2008); Zurbrügg et al. (2017)
Temperature (°C)	27 24.8–38.4 24–40 25–32	Tomberlin et al. (2009); Myers et al. (2008); Tomberlin et al. (2002); Sheppard et al. (2002); Zurbrügg et al., 2017; , Lohri et al. (2017)
Photoperiod (hours)	18 light/6 dark 12 light/12 dark	Zhou et al., 2013; Myers et al. (2008); Diener et al. (2009);
pH	>6	Ma et al., 2017
Initial larvae age for processing biowaste (days)	5 6 7	Tomberlin et al., 2002and Sheppard et al., 2002; Zurbrügg et al., 2017; Diener et al. (2009); Popa and Green (2012);

and Green (2012) is the only one, to our knowledge, to have used BSF larvae for leachate treatment, and which demonstrated the ability of BSF larvae to reduce COD and volatile fatty acids (VFAs), while growing on 1 mL organic leachate/larva/week (recovered from fermenting food scraps and vegetal matter).

2.3. Conversion of biowaste into valuable products

Biowaste conversion occurring during larval development results in biodegradable stabilisation and volume and mass reduction (Lalander et al., 2013; Myers et al., 2008; Newton, 2004). The biowaste mass is reduced by 60–70% w/w while the larval biomass increases up to 20% dry matter. Prepupae of BSF (44% dry matter) contain 36–48% protein and 31–35% fat (Banks et al., 2014; Diener et al., 2009; Sheppard et al., 2002). The protein and fat-rich insect biomass can be exploited either as animal feed (Barroso et al., 2014; Makkar et al., 2014; Surendra et al., 2016) or as an alternative energy source (Li et al., 2011; Surendra et al., 2016; Zheng et al., 2012). Transesterification of the fat extracted from BSF pupae led to the production of biodiesel with good fuel properties (e.g. Viscosity, density, flash point, cetane index) meeting European biodiesel standards (EN14214) (Li et al., 2011).

3. Materials and methods

3.1. Research program

The experiment was performed using six-day-old BSF larvae as suggested in the Literature (Table 1), accommodated in plastic boxes.

Larvae were supported and placed in contact with different substrates:

- L - Liquid;
- W - Mixture of liquid (80%) and wheat bran (20%).

The liquid was a mixture of distilled water and four different percentages of leachate, 25%, 50%, 75%, and 100%.

Each test was conducted in triplicate and each testing box contained 10 larvae.

The testing programme and code of each testing box is detailed in Fig. 2.

3.2. Equipment and growth conditions

Tests were performed in plastic boxes (13.5 cm × 13.5 cm x 5.5 cm, 0.6 L volume). Each box was covered by a perforated plastic lid to allow air circulation. A permeable non-woven fabric was placed between the box and the lid in order to avoid oviposition by other flies. Testing boxes containing liquid substrate were tilted to create a dry zone in the boxes (Fig. 3).

In line with optimal conditions suggested in the literature (Table 1), all tests were carried out in a thermal insulated room under the following controlled environmental conditions:

- temperature range 25–30 °C
- photoperiod Light/Dark of 18/6 h.

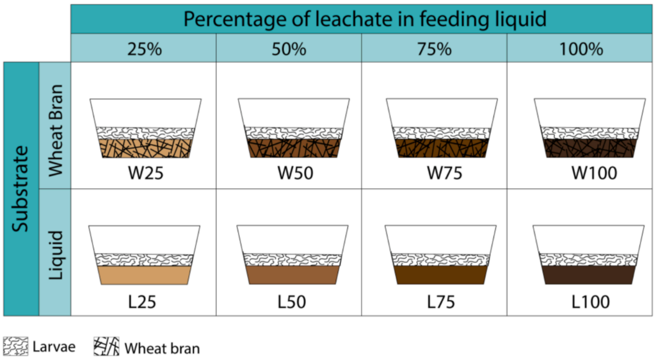

Fig. 2. Graphical description of the testing programme.

3.3. Feeding, operation and monitoring

Feeding comprised 200 mL of liquid placed in all testing boxes. Fifty grams of wheat bran was added to boxes marked “W”. Feed was replaced in each test twice weekly.

The leachate used for the experiment was characterised by analysing the following parameters: pH, Total Organic Carbon (TOC), Chemical Oxygen Demand (COD), 5 days Biological Oxygen Demand (BOD_5), Total Kjeldahl Nitrogen (TKN) and Ammoniacal Nitrogen. The values of the parameters are respectively 8, 3120 mgC/L, 7176 mgO_2/L, 3732 mgO_2/L, 949 mgN/L, 576 mgN/L. The wheat bran was dried at 105 °C before use to remove the original moisture and any microorganisms and insects present.

Boxes were monitored twice weekly at the time of feed replacement. Larvae were collected, washed, individually weighed using an analytical balance and returned to the box on the new substrate.

Larvae were fed until the prepupal stage was reached. Prepupae, easily recognised by the darkening of their colour, were removed, washed, weighed and frozen.

A development time of less than 30 days is expected under optimum feeding conditions. However, if during the experiment prepupae had not developed, feeding of larvae was prolonged up to 60 days and then stopped.

The development of larvae, and consequently the quality and quantity of feeding, was monitored by measuring the following parameters:

- larval wet weight,
- prepupal wet weight
- mortality of larvae
- prepupation (percentage of prepupae formed throughout mean larval development time).

Prepupal composition was evaluated in terms of crude protein and lipid content. Lipids were characterised for fatty acid profile.

In order to elaborate results from the triplicate tests and evaluate the significance of differences, one-way ANOVA with subsequent Tukey HSD tests were performed ($p < 0.05$).

3.4. Analytical procedure

Leachate was analysed according to Standard International Methods. TOC was determined using a TOC–VCSN Shimadzu Analyzer. BOD_5 was evaluated by means of a respirometer (Sapromat E); ammonia was measured with a distillation-titration procedure; TKN was measured through a distillation-titration procedure after an acid digestion phase.

Crude protein content of the prepupae was estimated by measuring TKN. For animal tissue a 16% of Nitrogen over protein content can be assumed (Jones, 1931); TKN results were then multiplied by a conversion factor of 6.25. The results thus obtained would represent an

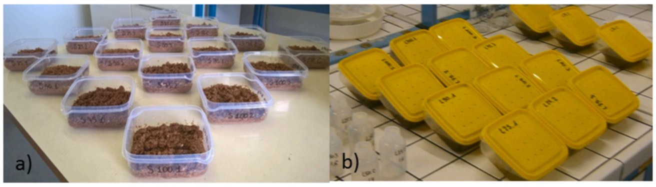

Fig. 3. Testing boxes: a. Uncovered; b. Tilted and covered.

overestimation of the protein content due to the nitrogen content in prepupae chitin, however comparison of results may indicate the effect of different feeding conditions (Diener et al., 2009).

Lipid extraction was performed by means of Accelerated Solvent Extraction (M-ASE), using petroleum ether as solvent for the extraction. Total lipid content was determined gravimetrically after removal of the solvent by evaporation under nitrogen stream at 50 °C. Samples were then transmethylated using a methanolic solution of H_2SO_4 $_($4%) to determine fatty acid methyl esters (FAME). Fatty acid methyl esters (FAME) were quantified by gas chromatography (Shimadzu GC17A).

4. Results and discussions

4.1. Larvae development and mortality

Fig. 4a illustrates the variation of larval wet weight (w/w) vs test duration time. BSF larvae grew under all different feeding configurations, but with different patterns. The larvae supported on wheat bran (W) displayed a faster and higher development when compared with larvae growing on liquid (L) due to the higher food availability provided by bran.

Differences in the bran-supported environment at varying leachate concentrations are not statistically significant ($p < 0.05$), thus confirming the prevailing role of bran as a source of carbon and nutrients. Maximum larvae weight in W tests ranged between 205.0 and 253.7 mg w/w and the all tests ended on the 24th day, when all surviving larvae had matured to the prepupal stage.

On the contrary, in the liquid environment leachate concentration strongly influenced larvae development. Highest wet weight and fastest development to the prepupal stage were observed at a concentration of 100% leachate in the liquid feed (L100). A maximum weight of 119.7 mg w/w (SE 6.93) was registered, with the prepupal stage being reached after 35 days. The difference in weight between L100 and other liquid tests assumes significance ($p < 0.05$) after 17 days (Table 2).

L75, L50 and L25 showed a similar trend throughout the entire test period, achieving a maximum wet weight in the range of 55.5–66.6 mg/larva. After 60 days the tests were stopped and only a few larvae reached the prepupal stage.

The results reveal the absence of any inhibitory effect on larvae development under both substrate conditions to be ascribed to toxicants in leachate. Conversely, higher leachate concentrations provided better feeding condition, when the only available feed was leachate (L tests). These observations are confirmed by Fig. 4b where mortality of larvae is graphically represented under different feeding conditions. Mortality values in the bran-supported boxes varied from 10 to 14%, remaining constantly lower than values observed under liquid conditions. The highest mortality (40%) was observed with the most highly-diluted feeding under liquid substrate conditions (L25), proving that larvae were starving.

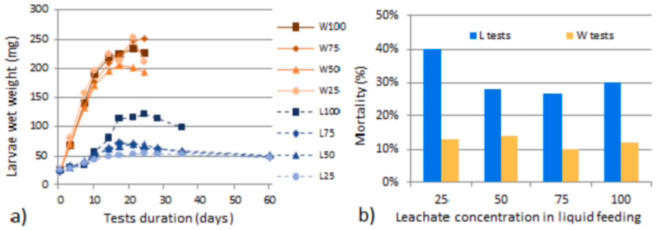

Fig. 4. a) Variation of average larval wet weight under the different feeding conditions adopted (W= Wheat bran substrate, L = Liquid substrate, 25–100 = percentage of leachate in the feeding liquid). b) Larvae mortality (% of dead larvae over the total number of larvae at the start) under the different feeding configurations.

4.2. Prepupae development

Prepupae development results, based on the analysis of a series of parameters, are graphically represented in Fig. 5.

Time required for completion of prepupation (passage from larvae to prepupal stage), as observed earlier, is much shorter for bran-supported tests (around 20 days, irrespective of leachate concentration). Under liquid conditions, prepupation was completed within 35 days only for the highest leachate concentration (L100), while for other concentrations complete prepupation was not reached within the 60-day observation period (Fig. 5a and b). The prepupation percentage (calculated as prepupae formed from living larvae) remained below 20%, and was proportional to leachate concentrations.

Mean prepupae wet weights in wheat bran-supported tests (W) were significantly higher when compared to liquid (L) tests ($p < 0.05$). In W tests prepupal weight ranged from 186.4 to 189.6 mg (w/w) remaining virtually constant. In L tests, prepupal weight decreased proportionally to leachate concentration, with no significant differences (Figs. 5c and 6). Highest weight values were observed in L100, achieving 71.3 mg (SE 4.02). Weight values of prepupae in L75, L50, L25 were 62.4 (SE 3.44), 45.1 (SE 3.97) and 50.2 (SE 0.59) mg w/w, respectively.

The dry mass content of prepupae increased proportionally to leachate concentrations, being significantly low for L50 and L25 tests ($p < 0.05$). The calculated dry weight of prepupae is reported in Table 3.

Once again, prepupal development, as commented above, clearly demonstrated the positive effect produced by leachate with no signs of inhibition effects.

4.3. Prepupae lipids and protein content

The results relating to characterisation of the dry mass accumulated by prepupae during development are reported in Fig. 7 and Table 4. Only situations featuring complete prepupation have been considered. The same figure and table illustrate a comparison of the results obtained during this experiment with data from other literature experiences in which BSF larvae were fed on dairy manure (Li et al., 2011) and food waste (Surendra et al., 2016).

The content of lipids in the dry mass accumulated by prepupae, expressed in terms of percentage of lipids with respect to Total Solids, is represented in Fig. 7a.

The lipid content in prepupae from tests W decreased as leachate concentration increased, ranging between 28.3% and 21.7%, while lipid content in prepupae from tests L100 was 21.2% (Table 4). The obtained values are in line with literature (22% for dairy manure and 31.8% for food waste).

The FAME (Fatty Acids Methyl Esters) profile of extracted lipids is detailed in Table 4.

No significant difference in FAME profiling was observed for the bran-supported tests, with the exception of a lower percentage of linolenic acid (C18:2) with highest leachate dilution (B25). Lauric acid (C12:0) was the most highly prevalent fatty acid, ranging between 58.31 and 59.79%, followed by Palmitic (C16:0), Myristic (C14:0) and Olenic (C18:1) acids (Table 4).

Lower concentrations of Lauric acid (C12:0) and higher concentrations of Palmitic (C16:0) and Olenic (C18:1) acid were reported in literature in studies conducted using dairy manure and food waste. Higher concentrations of Palmitic (C16:0) and lower concentrations of Lauric acid (C12:0) were observed for the L100 test compared to W tests.

The extracted lipids have been also classified into three groups according to saturation: Saturated (SFA), Monounsaturated (MFA) and Polyunsaturated Fatty Acids (PFA). Values are reported in Table 4 and graphically illustrated in Fig. 7. This classification is useful for predicting the quality of the biofuel which could be potentially produced from the prepupae biomass. In fact the degree of saturation of the triglycerides influences some critical parameters of the biofuel, which could be obtained after transesterification (e.g. cetane number, iodine

Table 2
Mean wet weight of larvae and Standard error (SE) at each time step of monitoring until maximum values are reached. Mean values at same time step followed by the same letter do not vary significantly ($P < 0.05$).

Days	0		3		7		10		14		17		21		24	
	Mean (mg)	SE	Mean (mg)	SE	Mean (mg)	SE	Mean (mg)	SE	Mean (mg)	SE	Mean (mg)	SE	Mean (mg)	SE	Mean (mg)	SE
L100	24.1a	1.1	29.2a	1.34	33.8a	2.42	57.4a	8.74	80.5a	15.6	112.9c	4.86	115.2c	5.94	119.7c	6.93
L75	24.5a	1.0	31.6a	1.63	37.2a	2.74	51.2a	4.84	63.1a	6.52	72.0a	6.95	70.9a	7.15	63.5a	8.04
L50	26.3a	0.9	30.3a	1.2	41.8a	2.37	53.2a	3.17	62.3a	3.13	66.6a	3.35	69.6a	3.34	69.5a	3.1
L25	25.4a	1.0	28.2a	1.19	37.6a	2.46	42.4a	2.91	49.4a	2.97	51.5a	3.31	53.4a	3.66	55.5a	3.52
W100	26.1a	0.9	69.2b	3.23	139.2b	5.84	189.8b	6.86	218.1b	10.4	224.6b	7.44	234.7b	3.21	227.6b	4.21
W75	24.1a	1.0	69.7b	4.86	133.9b	7.33	175.8b	6.87	209.9b	9.15	222.8b	2.08	247.9b	4.12	251.1b	3.56
W50	26.8a	1.0	70.8b	4.36	132.9b	8.59	170.1b	8.91	195.6b	12.1	205.0b	3.42	201.3b	2.96	193.8b	2.65
W25	26.4a	0.9	79.6b	3.28	156.7b	6.61	195.7b	8.19	225.2b	7.76	214.1b	2.1	253.7b	5.32	210.9b	5.31

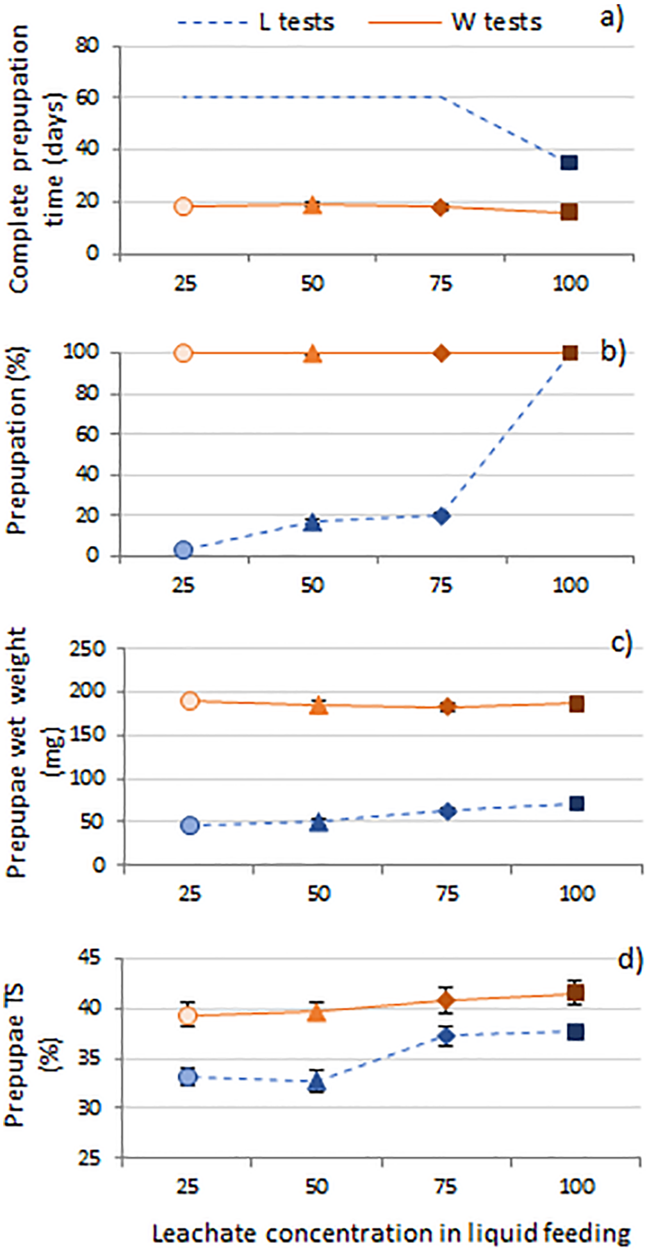

Fig. 5. Prepupae development at different testing conditions: a) complete prepupation time (after 60 days the experiment was stopped irrespective of the percentage of prepupation). b) prepupation percentage. c) prepupal wet weight. d) Total Solids (TS) content in prepupae. * Incomplete.

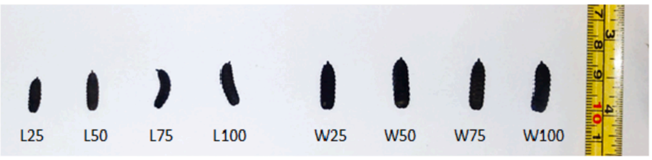

Fig. 6. Prepupae from each test.

Table 3
Mean dry weight of prepupae and development time in all tests. Mean values followed by the same letter do not vary significantly ($P < 0.05$) (* At day 60 the experiment was stopped irrespective of the percentage of pupation).

	Prepupal dry weight (mg)		Development time (d)	
	Mean	SE	Mean	SE
L100	26.9b	1.52	32b	0.86
L75	23.3b	1.28	60*	–
L50	16.5c	1.30	60*	–
L25	15.0c	0.20	60*	–
W100	77.5a	2.34	16a	0.53
W75	75.0a	2.06	17.8a	0.48
W50	73.6a	2.30	18.9a	0.45
W25	74.7a	1.99	18.3a	0.36

value, cold filter plugging point) (Ramos et al., 2009). Ramos et al. (2009) represented in a triangular graph the composition of biodiesel produced by using different vegetable oils in terms of saturated, monounsaturated and polyunsaturated methyl esters (Fig. 8). The compliance with the quality parameters values set by the European standards (UNE-EN 14214) have been described on the same triangular graph by setting three different coloured areas: yellow – limits for cetane number and iodine values are satisfied; blue – limits for cold filter plugging point (CFPP); green – all the limits are respected.

The biodiesel obtainable from BSF biomass falls in the yellow area. Both are not within the green area suggesting that similarly with biodiesel from palm oil a mixture with other biodiesel is required for obtaining the optimal conditions. The predicted biodiesel quality from L100 tests is expected better than predicted biodiesel quality from W tests (Fig. 8).

Protein content in prepupae from tests W decreased as leachate concentration increased, ranging between 50% and 46.4%, while protein content in prepupae from tests L100 was 38.1% (Fig. 7a, Table 4) However, the obtained values are higher compared to those reported in the literature (31.9%–46.3%) (Barroso et al., 2014; Diener et al., 2009; Surendra et al., 2016).

5. Conclusive remarks

From the obtained results the following conclusions can be drawn:

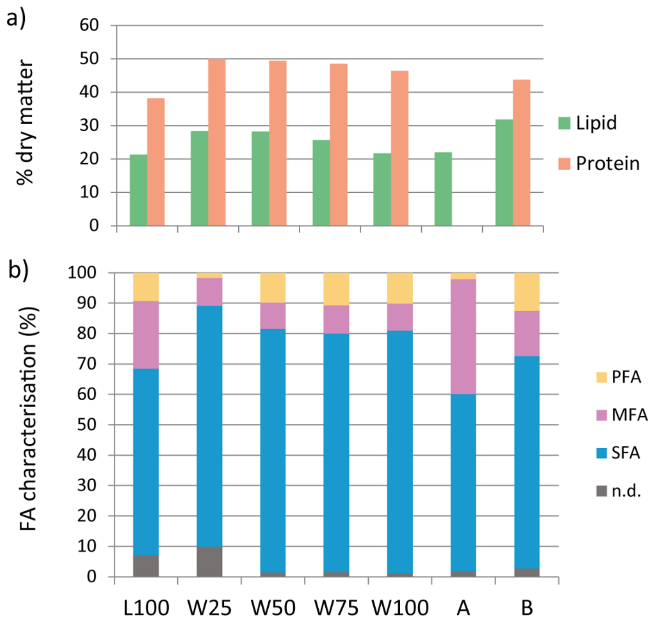

Fig. 7. Crude lipid and protein content (a), fatty acid characterisation (b) of BSF prepupae at different testing conditions, compared to literature data derived from BSF fed on two different substrates. A. dairy manure, (Li et al., 2011). B. food waste, (Surendra et al., 2016). SFA = saturated fatty acids, MFA = monounsaturated fatty acids and PFA = polyunsaturated fatty acids, n. d. = not defined fraction.

- BSF larvae grow and develop while feeding on different substrates containing landfill leachate;
- mortality of larvae was mainly linked to food availability and no significant inhibitory effect can be ascribed to any toxicant in leachate composition;
- larval development under liquid feeding conditions was proportional to the leachate concentration: the higher the nutrient content in leachate, the higher the larval development;
- larvae growth is an indicator of the amount of feed consumed and therefore of substrate treatment capacity;
- lipids and proteins in the prepupae biomass are within the range found in the literature for BSF larvae fed on different biowaste (food waste, dairy manure);
- concentration and profile of lipids and proteins are both influenced by feeding substrate and might be controlled by mixing leachate with different solid substrate;
- BSF prepupae biomass could be exploited as an alternative energy source in the production of biodiesel;
- among the two substrates conditions the semi-solid one proved to better perform than the liquid one.

Further lab studies should be carried out aiming the following:

- investigating treatment efficiencies in terms of contaminants removal and substrate stabilisation;
- testing alternative solid substrates, selecting preferably residues, such as sawdust, spent coffee grounds, spent brewers grounds etc., in order to render the semisolid feeding approach economically advantageous;
- testing leachates with high concentration of degradable organics, typically produced during the dry season in traditional MSW landfills;

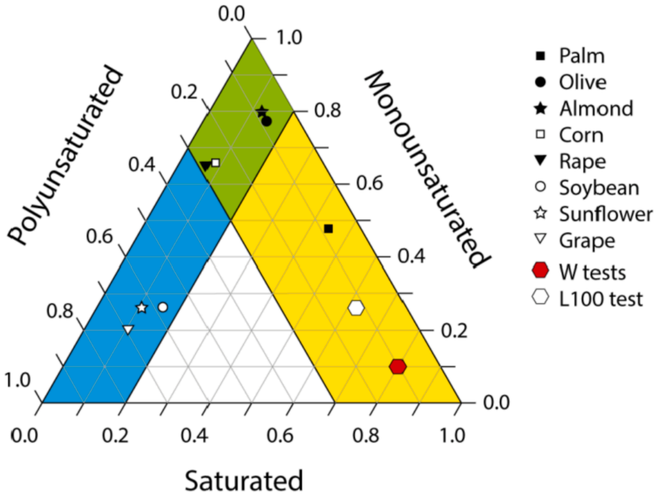

Fig. 8. Composition of biofuels from different vegetable oils and from BSF larvae (W and L100 tests) in terms of saturated, monounsaturated and polyunsaturated FAME. Areas satisfying parameter of the European Standard UNE-EN 14214: yellow, good cetane number and iodine value; blue, good Cold Filter Plugging Point (CFPP); green, biodiesel that fully satisfied UNE-EN 14214 (Modified from Ramos et al., 2009).

Table 4
Protein content, lipid content and fatty acid (FA) profile of BSF prepupae in different tests. The results are compared to literature data derived from BSF fed on dairy manure (A) (Li et al., 2011) and food waste (B) (Surendra et al., 2016). (n.d.: not defined).

	Tested prepupae					Li et al. (2011)	Surendra et al. (2016)
	L100	W25	W50	W75	W100	A	B
Protein content (% dry matter)	38.12	49.96	49.33	48.45	46.40	n.d.	43.70
Lipid content (% dry matter)	21.23	28.29	28.29	28.19	25.58	21.71	31.80
SFA (Saturated FA) (% of total FA)	61.33	79.29	80.20	78.58	79.94	58.20	69.90
MFA (Monounsaturated FA) (% of total FA)	22.20	9.14	8.63	9.28	8.85	37.80	14.90
PFA (Polyunsaturated FA) (% of total FA)	9.33	1.65	9.80	10.68	10.15	2.10	12.50
n.d. (% of total FA)	7.14	9.93	1.37	1.46	1.06	1.90	2.70
Fatty acids (% of total FA) (in brackets the C:D value)[a]							
Capric acid (C10:0)	0.58	1.58	1.62	1.63	1.47	3.10	n.d.
Lauric acid (C12:0)	29.95	58.57	59.60	58.31	59.79	35.60	44.90
Myristic acid (C14:0)	5.49	8.26	8.38	8.07	8.43	7.60	8.30
Palmitic acid (C16:0)	18.84	9.36	9.17	9.11	8.84	14.80	13.50
Palmitoleic acid (C16:1)	10.34	2.40	2.06	2.45	2.24	3.80	2.40
Stearic acid (C18.0)	4.96	1.19	1.14	1.14	1.14	3.60	2.10
Olenic acid (C18:1)	10.51	6.55	6.33	6.50	6.40	23.60	12.00
Linolenic acid (C18:2)	8.04	0.04	8.54	9.31	8.84	2.10	0.10

[a] C:D = total amount of Carbon atoms: number of Double (unsaturated) bonds.

- defining optimal leachate loading rates.

In order to understand and solve engineering issues in view of full scale application a pilot scale investigation would be fundamental with regards to the following aspects:

- feasible and manageable systems for larvae rearing and prepupae harvesting;
- reactors shaping and optimisation of surface need;
- operation (leachate feeding, substrate arrangement and maintenance, etc.);
- economy of the system;
- relevance of any hygienic problems and social acceptance.

Declaration of competing interest

None.

References

Banks, I.J., Gibson, W.T., Cameron, M.M., 2014. Growth rates of black soldier fly larvae fed on fresh human faeces and their implication for improving sanitation. Trop. Med. Int. Health 19, 14–22. https://doi.org/10.1111/tmi.12228.

Barroso, F.G., de Haro, C., Sánchez-Muros, M.J., Venegas, E., Martínez-Sánchez, A., Pérez-Bañón, C., 2014. The potential of various insect species for use as food for fish. Aquaculture 422–423, 193–201. https://doi.org/10.1016/j.aquaculture.2013.12.024.

Cossu, R., 2009. From triangles to cycles. Waste Manag. 29, 2915–2917. https://doi.org/10.1016/j.wasman.2009.09.002.

Cossu, R., Stegmann, R., 2018. Solid Waste Landfilling, Concepts, Processes, Technology. Elsevier, ISBN 9780128183366.

Diener, S., Zurbrügg, C., 2011. Black soldier fly larvae for organic waste treatment—prospects and constraints. SAVE Proc. 52, 978–984.

Diener, S., Zurbrügg, C., Tockner, K., 2009. Conversion of organic material by black soldier fly larvae: establishing optimal feeding rates. Waste Manag. Res. 27, 603–610. https://doi.org/10.1177/0734242X09103838.

De Smet J, Wynants E, Cos P, Van Campenhout L. 2018. Microbial community dynamics during rearing of black soldier fly larvae (Hermetia illucens) and impact on exploitation potential. Appl Environ Microbiol 84:e02722-17. https://doi.org/10.1128/AEM .02722-17.

Grossule, V., Morello, L., Cossu, R., Lavagnolo, M.C., 2018. Bioreactor landfills : comparison and kinetics of the different systems. Detritus J. 03, 100–113.

Jones, D.B., 1931. Factors for Converting Percentages of Nitrogen in Food and Feeds into Percentages of Protein, Circular No. 183. United States Department of Agriculture, Washington, DC.

Lalander, C., Diener, S., Magri, M.E., Zurbrügg, C., Lindström, A., Vinnerås, B., 2013. Faecal sludge management with the larvae of the black soldier fly (Hermetia illucens) - from a hygiene aspect. Sci. Total Environ. 458–460, 312–318. https://doi.org/10.1016/j.scitotenv.2013.04.033.

Lavagnolo, M.C., Grossule, V., Raga, R., 2018. Innovative dual-step management of semi-aerobic landfill in a tropical climate. Waste Manag. 1–10. https://doi.org/10.1016/j.wasman.2018.01.017.

Li, Q., Zheng, L., Cai, H., Garza, E., Yu, Z., Zhou, S., 2011. From organic waste to biodiesel: black soldier fly, Hermetia illucens, makes it feasible. Fuel 90, 1545–1548. https://doi.org/10.1016/j.fuel.2010.11.016.

Lohri, C.R., Diener, S., Zabaleta, I., Mertenat, A., Zurbrügg, C., 2017. Treatment technologies for urban solid biowaste to create value products: a review with focus on low- and middle-income settings. Rev. Environ. Sci. Biotechnol. 16, 81–130. https://doi.org/10.1007/s11157-017-9422-5.

Makkar, H.P.S., Tran, G., Heuzé, V., Ankers, P., 2014. State-of-the-art on use of insects as animal feed. Anim. Feed Sci. Technol. 197, 1–33. https://doi.org/10.1016/j.anifeedsci.2014.07.008.

Myers, H.M., Tomberlin, J.K., Lambert, B.D., Kattes, D., 2008. Development of black soldier fly (Diptera: stratiomyidae) larvae fed dairy manure. Environ. Entomol. 37 (1), 11–15 (February 2008).

Ma, J., Lei, Y., Rehman, K., Yu, Z., Zhang, J., Li, W., Li, Q., Tomberlin, J.K., Zheng, L., 2017. Dynamic Effects of Initial pH of Substrate on Biological Growth and Metamorphosis of Black Soldier Fly (Diptera: Stratiomyidae). Environmental Entomology, (2017) 1-7.

Newton, L., 2004. Using the Black Soldier Fly, as a Value Added Tool for the Management of Swine Manure, vol. 36, pp. 20–22.

Popa, R., Green, T.R., 2012. Using black soldier fly larvae for processing organic leachates. J. Econ. Entomol. 105, 374–378. https://doi.org/10.1603/EC11192.

Ramos, M.J., Fernández, C.M., Casas, A., Rodríguez, L., Pérez, Á., 2009. Influence of fatty acid composition of raw materials on biodiesel properties. Bioresour. Technol. 100, 261–268. https://doi.org/10.1016/j.biortech.2008.06.039.

Shakil Rana, K.M., Salam, M.A., Hashem, S., Ariful Islam, M., 2015. Development of black soldier fly larvae production technique as an alternate fish feed. Int. J. Res. Fish. Aquac. 5, 41–47.

Sheppard, D.C., Tomberlin, J.K., Joyce, J.A., Kiser, B.C., Sumner, S.M., 2002. Rearing methods for the black soldier fly (Diptera: stratiomyidae): table 1. J. Med. Entomol. 39, 695–698. https://doi.org/10.1603/0022-2585-39.4.695.

Surendra, K.C., Olivier, R., Tomberlin, J.K., Jha, R., Khanal, S.K., 2016. Bioconversion of organic wastes into biodiesel and animal feed via insect farming. Renew. Energy 98, 197–202. https://doi.org/10.1016/j.renene.2016.03.022.

Tomberlin, J.K., Adler, P.H., Myers, H.M., 2009. Development of the black soldier fly (Diptera: stratiomyidae) in relation to temperature: table 1. Environ. Entomol. 38, 930–934. https://doi.org/10.1603/022.038.0347.

Tomberlin, J.K., Sheppard, D.C., Joyce, J.A., 2002. Selected life-history traits of black soldier flies (Diptera: stratiomyidae) reared on three artificial diets. Ann. Entomol. Soc. Am. 37 (4).

Turchetto, M., Vanin, S., 2004. Forensic entomology and climatic change. Forensic Sci. Int. 146, 207–209. https://doi.org/10.1016/j.forsciint.2004.09.064.

Zheng, L., Li, Q., Zhang, J., Yu, Z., 2012. Double the biodiesel yield: rearing black soldier fly larvae, Hermetia illucens, on solid residual fraction of restaurant waste after grease extraction for biodiesel production. Renew. Energy 41, 75–79. https://doi.org/10.1016/j.renene.2011.10.004.

Zhou, F., Tomberlin, J.K., Zheng, L., Yu, Z., Zhang, J., 2013. Developmental and Waste Reduction Plasticity of Three Black Soldier Fly Strains (Diptera: Stratiomyidae) Raised on Different Livestock Manures. J. Med. Entomol. 50, 1224–1230. https://doi.org/10.1603/ME13021.

Zurbrügg, C., Dortmans, B., Fadhila, A., Verstappen, B., Diener, S., 2017. From pilot to full scale operation of a waste-to-protein treatment facility. In: Proceedings Sardinia 2017/Sixteenth International Waste Management and Landfill Symposium/2-6 October 2017, S. Margherita di Pula, Cagliari, Italy.

Paper IX. Potential treatment of leachate by *Hermetia Illucens* larvae: performance under different feeding conditions

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Potential treatment of leachate by Hermetia Illucens (diptera, stratyomyidae) larvae: performance under different feeding conditions

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Keywords: Hermetia illucens, blue technology, circular economy, low cost, developing countries, organic waste

ABSTRACT

Hermetia illucens (Diptera, Stratyomyidae) larvae, commonly known as Black Soldier Fly (BSF), were used, due to their versatility and voracity, to treat different semisolid biowastes (e.g. kitchen waste, fish offal, coffee bean pulp, animal manure and human excreta) (i.a. Banks et al., 2014; Diener and Zurbrügg, 2011; Newton, 2004). It has so been observed that biowaste is converted by the larvae into a stable residue and into a protein and fat-rich prepupal biomass, suitable for use as an animal feed and/or in biofuel extraction.

In this study, the potential ability of H. illucens larvae to treat landfill leachate was investigated by mixing leachate with three different solid materials: wheat bran, a biodegradable nutrient substrate traditionally used to feed this species, brewers' spent grain, a biodegradable nutrient residue from the brewery industry, and sawdust, a low biodegradable residue from the wood industry. Larvae growth rate was monitored in terms of weight variation, mortality, time required by larvae to reach the prepupal stage (prepupation time). Prepupal biomass composition was analysed in terms of crude protein, lipids and fatty acids. Substrates were monitored at the beginning and the end of tests for Total Solids, Total Organic Carbon, Total Kjeldhal Nitrogen, Ammonia and (whenever significant) RI7. The best performance was observed with wheat bran and brewers' spent grain, achieving an average larval weight ranging from 155.1-226.1 mg (w/w) with prepupation of more than 80% over a 21-day period. The initial TS, TOC and nitrogen content in feeding substrates had been metabolised (gasified and accumulated in prepupal biomass) by approx. 55%, 60% and 48% respectively. Dry mass characterisation demonstrated the suitability of BSF prepupal biomass for use as an alternative energy source in the production of biodiesel.

1. INTRODUCTION

Leachate treatment continues to represent a critical issue in municipal solid waste (MSW) landfilling, both from a technical and economical point of view (Stegmann, 2018). This aspect is particularly relevant in developing countries where landfilling is the most widely applied solid waste management option (Cossu et al., 2019). Consequently, low cost leachate treatment alternatives are of considerable interest.

One alternative could be afforded by technologies based on the use of the larvae of the black soldier fly *Hermetia illucens* (Diptera, Stratyomyidae), exploiting their high versatility and voracity (Tomberlin et al., 2002). The life cycle of *H. illucens* consists of four stages: egg, larva, pupa and adult. The larval stage is the longest and the sole feeding stage whereas adults of this species do not feed lacking of the oral apparatus. The high content of biodegradable organic material present in the young leachate (Ehrig and Stegmann, 2018) could be converted into a stable residue and into protein- and fat-rich biomass - the *H. illucens* prepupal stage - which can be used to feed animals, mainly vertebrates, and/or for biofuel extraction.

The above-mentioned properties of BSF larvae have been successfully applied in the treatment of a range of semisolid biowastes, including food and animal waste and human excreta (i.a. Banks et al., 2014; Diener and Zurbrügg, 2011; Newton, 2004), however, to date the suitability of this species in the treatment of landfill leachate has not been investigated, with the exception of a preliminary study conducted by Grossule and Lavagnolo (2019). These authors conducted a detailed literature overview of the optimal conditions required for the larval development (food quantity and quality, temperature, moisture, photoperiod and pH) and they investigated the adaptability of *H. illucens* larvae to landfill leachate by varying leachate percentages in the feed and substrates for larvae growth (liquid and semisolid). The best results were achieved using a semisolid substrate (a mixture of leachate and wheat bran). Using a liquid substrate the most positive results were achieved when larvae were exposed to pure leachate. In all tests mortality was less than 50% and was mainly linked to food shortages: the higher the nutrient availability, the higher the larval development. Dry mass characterisation demonstrated that BSF prepupal biomass is suitable for use as an alternative energy source in the production of biodiesel.

The aim of the present study was to investigate the treatment capacity of BSF larvae when leachate was mixed with different kinds of solid materials including residues (brewers' spent grain and sawdust). Larval growth was monitored in terms of wet weight variation, mortality and prepupation percentage. The prepupal biomass composition was analysed in terms of crude protein, lipids and fatty acid profile. Treatment performance was evaluated by measuring the variation of Total Solids (TS), Total Organic Carbon (TOC) and nitrogen compounds in each semisolid substrate. Overall stabilisation was evaluated by measuring 7-days Respirometric index (RI_7).

2. MATERIALS AND METHODS

2.1. Experimental design

The experimental design adopted in this study is summarized in Figure 1.

Six-day old larvae were placed in plastic boxes and fed with leachate using three different semisolid substrates obtained by mixing leachate with three different solid materials (wheat bran-W tests, brewers' spent grain-B tests and sawdust-S tests) until 80% moisture content was achieved. Each test was performed in triplicate. In view of the possibility that larvae, microorganisms and natural phenomena may all contribute to the process of contaminant attenuation, a series of control tests without larvae were performed to evaluate the individual contribution of larvae in the leachate transformation.

2.2. Equipment and breeding conditions

Tests were performed using 12 plastic boxes (18 cm x 12 cm x 8 cm) covered by a system (perforated plastic lid and non-woven fabrics) which allowed air circulation, but prevented the access to any other insect (Figure 1). 300 larvae were placed in each box.

All tests were carried out in a temperature-controlled room with a temperature ranging from 25-30 °C and a photoperiod Light/Dark of 18/6 h.

Figure 1. Experimental set up of the tests and research program. Materials and substrate typologies are graphically indicated.

The solid materials in semisolid tests were selected based on the following observations:

- Wheat bran represents a good quality food, traditionally used for larval breeding (Shakil Rana et al., 2015; Tomberlin et al., 2009).
- Brewers' spent grain is a residue from the beer-brewing process, often used in animal feed due to its high protein content (Lynch et al., 2016).
- Sawdust is a residue from wood transformation work, made up of scarcely degradable compounds (eg: lignin and cellulose); consequently in semisolid testing nutrient availability for larvae was provided mainly by the leachate.

Wheat bran, brewers' spent grain and sawdust were dried at 105° C prior to be used to remove endogenous moisture and undesired organisms. The total amount of semisolid substrate added in each box was 600 g (120 g solid material + 480 g leachate). This dose was calculated on the basis of 2 g of substrate/larva. Taking into account a larval feeding period of 20 days, this corresponded to 100 mg substrate/larvae/day, as suggested by Diener et al. (2009).

Characterisation of leachate and solid materials are illustrated in Table 1.

Leachate quality is typical for young landfills (BOD/COD=0.47) with significant rainfall infiltration.

At the end of the test, residual substrate was weighed, sampled and chemically characterized. Ten randomly selected larvae from each box were also collected, washed, and individually weighed on a weekly basis before being reintroduced into the same box.

Tests continued until the prepupal stage was reached, for a maximum observation time of 60 days, even in the presence of an incomplete prepupation. Prepupae, distinguishable by their darker colour, were removed, washed, weighed and frozen until their analytical characterization.

Larvae growth was assessed in terms of weight variation, mean prepupal dry weight, prepupation time, mortality and percentage of prepupation at the end of the test. The definition of mortality and percentage of prepupation adopted herein is given in Figure 2a.

Prepupal biomass composition was analysed in terms of crude protein, lipids and fatty acids. Substrates were monitored at the beginning and end of tests for TS, TOC, Total Kjeldahl Nitrogen (TKN), Ammonia (NH_4^+), Nitrate (NO_3^-), Nitrite (NO_2^-) and (whenever significant) Respiration index after 7 days (RI_7).

Table 1. Characterisation of leachate and solid materials (wheat bran, brewers' spent grain and sawdust) used for the experiment.

Leachate		Solid materials			
Parameters	Values	Parameters (%d.m.)	Wheat bran (Onipe et al., 2015; Hussien et al., 2019)	Brewers' spent grain (Lynch et al., 2016)	Sawdust (Aigbomian and Fan, 2013)
pH	7.9	Hemicellulose	20.8	19.2-41.9	24.5
TS (mg/L)	7156	Cellulose	16.2	12-33	44
TOC (mgC/L)	467	Lignin	8.5	11.9-27.8	22.4
COD (mgO$_2$/L)	1029	Starch	9.10-38.9	2.7-12	-
BOD$_5$ (mgO$_2$/L)	492	Protein	9.6-18.6	14.2-31	-
TKN (mgN/L)	832	Lipids	2.8	10.6-13	-
NH$_4^+$ (mgN/L)	592				

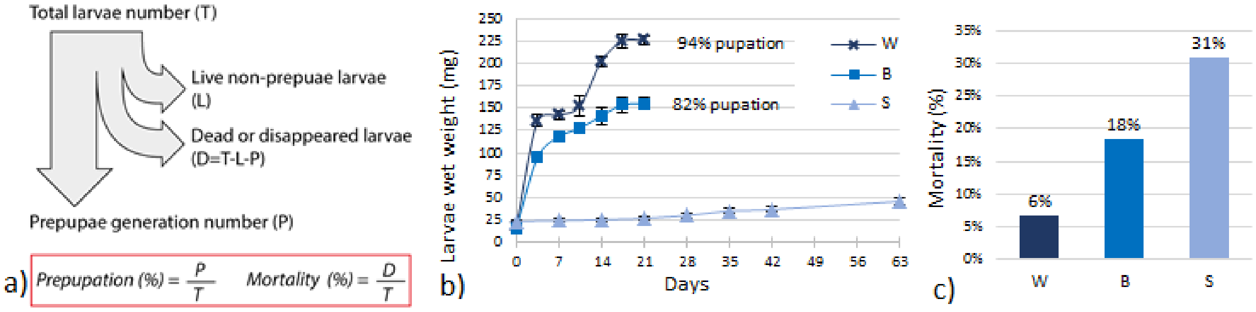


Figure 2. Definition of larvae prepupation and mortality a) and larvae development under different feeding substrates: Average wet weight over the testing period and percentage of pupation(when exiting) at the end of the tests b); mortality c). (W: wheat bran, B: brewers' spent grain, S: sawdust)

The results are reported as the average of data generated by the three replicates.

2.3. **Analytical procedure**

Leachate was analysed according to Standard International Methods. TOC was determined using a TOC–VCSN Shimadzu Analyzer. BOD$_5$ was evaluated by means of a respirometer (Sapromat E); ammonia was measured with a distillation-titration procedure; TKN was measured through a distillation-titration procedure after an acid digestion phase, nitrate and nitrates were measured through a colorimetric method.

Crude protein content of the prepupae was estimated by measuring TKN. For animal tissue a 16% of Nitrogen over protein content can be assumed (Jones, 1931); TKN results were then multiplied by a conversion factor of 6.25. So doing, the obtained results represent an overestimation of the protein content due to the nitrogen content in prepupae chitin, however if used for comparison they are useful to describe the effect of different feeding conditions (Diener et al., 2009).

Lipid extraction was performed by means of Accelerated Solvent Extraction (M-ASE), using petroleum ether as solvent for the extraction. Total lipid content was measured gravimetrically after removal of the solvent by evaporation under nitrogen stream at 50°C. Samples were then transmethylated using a methanolic solution of H$_2$SO$_4$ (4%) to isolate the fatty acid methyl esters (FAMEs). FAMEs were quantified by gas chromatography (Shimadzu GC17A).

Respiration Index (RI$_7$ mgO$_2$/gTS) on solid samples was measured by means of Sapromat apparatus (H+P Labortechnik, Germany).

3. RESULTS AND DISCUSSIONS

3.1 Larvae development

Figure 2 illustrates the development of larvae breed on different substrates. Average larval wet weight (w/w) over the testing period and indication of percentage of pupation is provided in graph (b) while mortality is represented in graph (c). The most satisfactory results were achieved with wheat bran (W test) and brewers' spent grain (B test). After only 21 days the average larvae weight for wheat bran was 226.1 ± 5 mg (w/w) with a prepupation of 94%, while the same parameters for brewers' spent grain were 155. 1 ± 6.8 mg (w/w) and 82%. On the contrary, with sawdust (S test) the average larvae weight was only 46.0 ± 2.9 mg w/w and prepupation had not been achieved even after 63 days of test duration. Mortality values are consistent with the above observations (6%, 18% and 31% in W, B, S tests respectively).

These results reflect the different availability of degradable carbon and nutrients in the tested feeding substrates (Table 1). In particular, wheat bran and brewers' spent grain are characterised by high content of short chain carbohydrates (e.g. starch) and proteins, providing carbon and nutrients further to leachate.

3.2 Treatment capacity

Figure 3 illustrates the average values of TS, TOC and Total nitrogen (TN) loads and respiration index RI_7 of the substrates, at the beginning of the test (Input) and at the end, with (Output larvae) and without larvae (Output control). The only forms of TN detected were organic nitrogen (Norg) and ammonia nitrogen ($N\text{-}NH_4^+$), grouped as TKN.

The amount of TS at the beginning of the tests was set at the same value for all substrates and resulted in 123.4 g (solid material + TS content in leachate). TOC load was roughly similar between wheat bran (63.7g), brewers' spent grain (69.3) and sawdust (60.0g). TKN load values differed significantly among the tested substrates: 4.2, 5.8, 0.4 gN in W, B and S tests respectively. Organic nitrogen (Norg) was the prevailing form of nitrogen for W and B substrates (3.9 and 5.5gN-Norg/larva, respectively). Specific input loads for same parameters expressed in terms of mass per larva are provided in Table 2.

These results reflect the general composition of solids in the individual substrates as described in the literature (Table 1). In fact the most representative organic fractions were short chain carbohydrates (e.g. starch) in wheat bran, proteins in brewers' spent grain and lignin-hemicellulose-cellulose in sawdust.

Removal efficiencies (η) for both "larvae boxes" and "control boxes" are reported in Table 2 and Figure 4 represents graphically the calculated contribution of larvae ($\Delta\eta_{larvae}$) to the removal process according to the following formula:

$$\Delta\eta_{larvae}(\%) = \eta_{larvae} - \eta_{control} = \frac{Output\ control - Output\ larvae}{Input} \cdot 100$$

While the removal efficiencies detected for each individual reactor are dependent on carbon and nutrient availability, $\Delta\eta_{larvae}$ provides the most significant information with regards to role of larvae in leachate treatment.

Larval activity yielded a greater reduction in TS and TOC in "larvae boxes" compared to "control boxes". TOC removal efficiencies were around 60% for W and B tests, while in S tests efficiencies remained below 25% due to the lower biodegradability of sawdust. Larval contribution to the overall removal processes ranged from 12% (W and S tests) to 15% (B tests).

Similarly, for TKN a higher reduction was detected in the "larvae box" compared to controls, although the highest efficiencies were observed in S tests (84.2%), with efficiencies remaining around 48% in W and B tests; this result was_due to the lower load of TKN in S tests. On the other hand, the individual contribution of larval metabolism ($\Delta\eta_{larvae}$) in the different substrates was strictly related to the prevailing form of nitrogen in TKN loads (Figure 3). In S substrates the prevailing component of TKN was Ammonia(Table 1), as

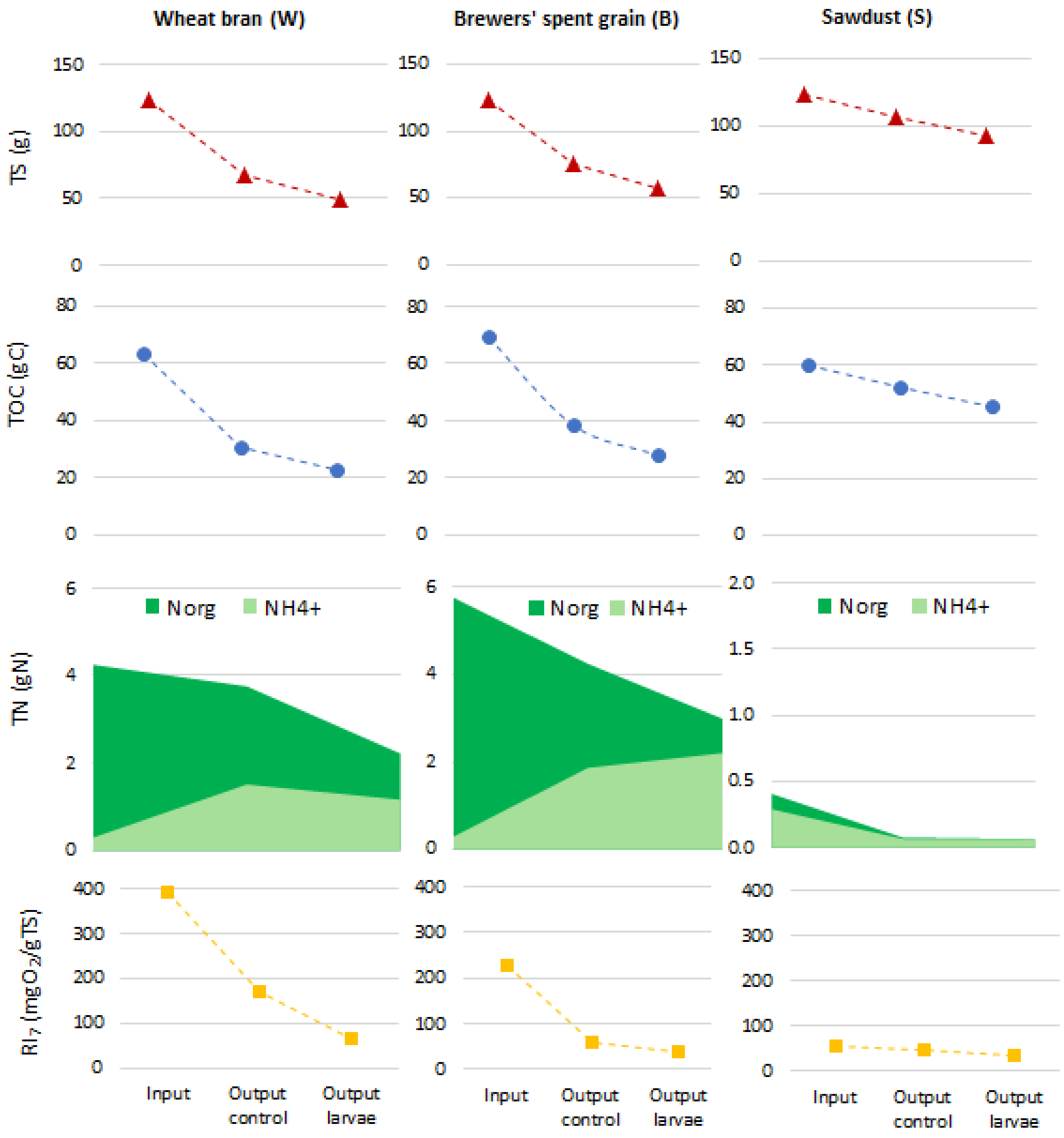


Figure 3. TS, TOC, TN loads (expressed in terms of mass per larva) and respiration indices at 7 days (RI7) in the different semisolid substrates, at the beginning of tests (Input) and at the end, with (Output larvae) and without larvae (Output control).

the main nutrient source was represented by leachate. On the contrary, in W and B substrates, the prevailing form of nitrogen was Norg due to the higher concentration of proteins in wheat bran, and particularly in brewers' spent grain. Differential removal by larvae demonstrated how in the presence of ammonia as the prevailing form of nitrogen, removal of this compound by larvae is negligible ($\Delta\eta_{larvae}$ =2.6% in S tests), whilst when Norg is the prevailing form (W and B tests) the larval metabolism is able to remove it in a very efficient way. Likewise, differences between W and B tests are related to the initial load of nitrogen: Δηlarvae =36.1% in W tests and Δηlarvae =21.8% in B tests are inversely proportional to Norg loads (Figure 3).

These results are in accordance with Popa and Green (2012), who observed that *H. illucens* larvae are not able to metabolise nitrogen in ammonia form. At the same time ammonia nitrogen does not appear to have any toxic

Table 2. TS, TOC, TN, Norg and RI7 reduction efficiency in "larvae box" and in "control box". Input loads of the same parameters (excluding RI7) are provided in terms of mass per larva. (W: wheat bran, B: brewers' spent grain, S: sawdust).

Tests	Para-meters	Input loads (mg/larva)	Removal efficiencies Larvae box (%)	Removal efficiencies Control box (%)
W	TS	411.3	60.1	45.7
	TOC	212.3	63.8	51.4
	TN	14.2	47.8	11.7
	Norg	13.2	73.2	43.3
	RI_7	-	83.5	56.4
B	TS	411.3	53.0	38.2
	TOC	231.1	59.8	44.6
	TN	19.2	48.1	26.3
	Norg	18.3	85.6	56.5
	RI_7	-	83.6	73.7
S	TS	411.3	26.3	14.5
	TOC	200.0	24.4	12.9
	TN	1.4	84.2	81.6
	Norg	0.4	98.6	91.5
	RI_7	-	36.5	13.5

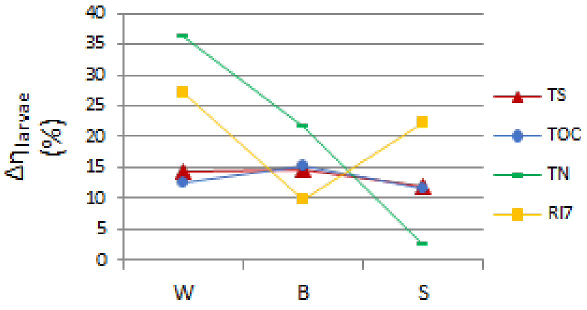


Figure 4. Contribution of larvae metabolism to the removal efficiency of contaminants (TS, TOC, TN) and to stabilisation rate (RI_7). $\left(\Delta\eta_{larvae}(\%) = \frac{Output\ control - Output\ larvae}{Input}\cdot 100\right)$ *(W: wheat bran, B: brewers' spent grain, S: sawdust)*

relevance for larvae development (Grossule and Lavagnolo, 2019).

The biochemical stability of substrates was evaluated by measuring the Respirometric Index at 7 days (RI_7), as reported in Table 2 and Figure 3.

RI_7 varied from 392.2 to 64.9 mgO_2/gTS in the experiment carried out on W substrate, from 228.4 to 37.4 mgO_2/gTS on B substrate and from 52.1 to 33.4 mgO_2/gTS on S substrate.

In all tests larval activity contributed significantly to stabilisation of the substrates, particularly in the W test in which the stability achieved in the "larvae box" was 2.6 fold higher than what observed in the "control box".

3.3 Substrate-to-prepupal biomass conversion and prepupal lipid-protein content

Prepupal wet weight was measured and lipid-protein content analysed in all "Larvae boxes", with the exception of sawdust where no prepupation had taken place. In W and B tests larval wet weight was 0.1761 mg/prepupa (36.7% TS) and 0.1704 mg/prepupa (35.0% TS), respectively. A mass balance of TS, TOC and TN was calculated for each "larvae box". The initial load of the individual substances (TS, TOC, TN) was spread into a final semisolid residue, prepupal biomass (anabolism) and gas emissions, as reported in Figure 5a. Gas emissions were evaluated as difference between initial load and the loads associated to prepupae and residue.

The fraction of TS converted into prepupal biomass was similar in both W and B tests (13.3 and 12.0%) while the gasified fraction of TS was higher for larvae fed on wheat bran (46.8%) compared to those fed on brewer's spent grain (41.0%). Consequently, the amount of residues was inversely proportional (39.9% in W tests and 47.0% in B tests). These results are consistent with those reported by Diener et al. (2009), although our results demonstrated a higher degree of anabolism (higher prepupal biomass).

TOC displayed a similar trend to TS, although with a higher total metabolised fraction (larval biomass + gas emissions) of approximately 60%.

With regards to nitrogen, approx. 52% of the initial TN remained as residue in both W and B

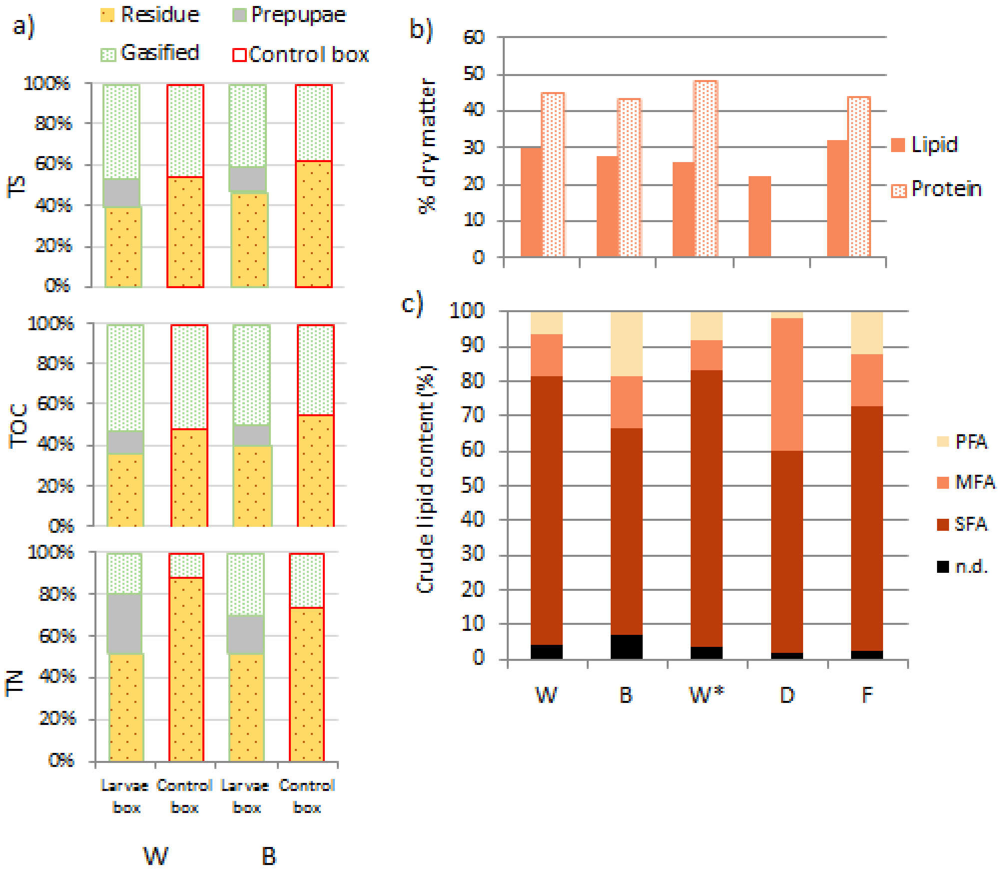


Figure 5. a) Mass balance of the main parameters (TS, TC, TN) characterising the feeding input. The different elements (X) in the input are gasified, accumulated in the prepupal biomass or concentrated in solid residue (Xinput=Xgasified + Xprepupae + Xresidue). The balance is reported for both "larvae boxes" (green framed) and "control boxes" (red framed).
Prepuae biomass characterisation in terms of: b) crude lipid and protein content and c) fatty acid categorisation at different testing conditions (W: Wheat bran, B: Brewer's spent grain), compared to literature data derived from BSF fed on three different substrates: W= mixing of leachate and wheat bran (Grossule and Lavagnolo, 2019), D= dairy manure (Li et al., 2011), F= Food waste, (Surendra et al., 2016).*
SFA=saturated fatty acids, MFA=monounsaturated fatty acids and PFA=polyunsaturated fatty acids, n.d.= fraction not defined.

tests, while a significant fraction was accumulated into the prepupal biomass (28% and 17.9% in W and B tests respectively), containing a higher protein component (Table 3).

Figure 5b-c and Table 3 display data related to the characterisation of prepupal dry mass in terms of lipids and protein in W and B tests, compared to data from the literature obtained in similar studies, in which *H. illucens* larvae were fed on different substrates (mixtures of wheat bran and leachate, dairy manure, food waste).

The protein content ranged between 43 and 45% of dry mass (TS), according with the values reported in the literature (Grossule and Lavagnolo, 2019; Li et al., 2011; Surendra et al., 2016).Lipid content accumulated in the dry mass by prepupae was 29.8% TS and 27.9% TS (Figure 5b), higher than the values reported for a similar substrate (Wheat bran/leachate mixture) and mid-way between the values found for dairy manure (22.0%) and food waste (31.8%) (Grossule and Lavagnolo, 2019; Li et al., 2011; Surendra et al., 2016).

FAMEs profile is consistent with the literature data (i.a. Surendra et al., 2016). Lauric acid (C12:0) was the most dominant fatty acid in both W and B tests, ranging from 32% (B test) to 55% (W test). However, lower concentrations of Lauric acid (C12:0) and higher concentrations of Linolenic acid (C18:2) and Palmitic acid (C16:0) were detected in prepupae fed on Brewer's spent grain compared to W and previous research (Grossule and Lavagnolo, 2019). Classification of the extracted lipids into Saturated (SFA), Monounsaturated (MFA) and Polyunsaturated Fatty Acids is reported in Table 3 and Figure 5c. This classification represents a useful tool for predicting the quality of potential producible biofuel from BSF prepupae. In fact, high concentrations of polyunsaturated fatty acids (PFA) in oil typically reduce oxidative stability in biofuel, while high concentrations of long chain saturated fatty acids (SFA) produce biodiesel with a poor cold flow property. The generally high concentrations of medium chain SFAs (around 70%) and low concentrations of PFAs (6.8-18.9%) indicate the suitability of *H. illucens* prepupae from W and B tests as a potentially good precursor for biodiesel. The results obtained in the present study are mostly consistent with the quality requirements established by the European standards for biofuels (UNE-EN 14214) as reported by Ramos et al. (2009).

Table 3. Protein content, lipid content and fatty acid (FA) profile of BSF prepupae in different tests. The results are compared to literature data derived from BSF fed on a mixture of leachate and wheat bran (W) (Grossule and Lavagnolo, 2019), on dairy manure (D) (Li et al., 2011) and on food waste (F) (Surendra et al., 2016). (n.d.: not defined).*

	Tested prepupae (this study)		(Grossule and Lavagnolo, 2019)	(Li et al., 2011)	(Surendra et al., 2016)
	W	B	W*	D	F
Protein content (% dry matter)	45.2	43.5	48.5	n.d.	43.7
Lipid content (% dry matter)	29.8	27.9	25.9	22.0	31.8
SFA (Saturated FA) (% of total FA)	77.0	59.5	79.5	58.2	69.9
MFA (Monounsaturated FA) (% of total FA)	12.1	14.6	9.0	37.8	14.9
PFA (Polyunsaturated FA) (% of total FA)	6.8	18.9	8.0	2.1	12.5
n.d. (% of total FA)	4.1	7.0	3.5	1.9	2.7
Fatty acids (% of total FA) (in brackets the C:D value)**					
Capric acid (C10:0)	1.5	0.9	1.6	3.1	n.d.
Lauric acid (C12:0)	54.5	31.6	59.0	35.6	44.9
Myristic acid (C14:0)	8.3	5.0	8.3	7.6	8.3
Palmitic acid (C16:0)	11.0	19.6	9.1	14.8	13.5
Palmitoleic acid (C16:1)	3.5	5.4	2.3	3.8	2.4
Stearic acid (C18.0)	1.0	1.3	1.2	3.6	2.1
Olenic acid (C18:1)	7.9	8.2	6.4	23.6	12.0
Linolenic acid (C18:2)	5.2	14.3	6.7	2.1	0.1

**C:D=total amount of Carbon atoms : number of Double (unsaturated) bonds

* Mean values obtained from larvae fed with mixed leachate and wheat bran

CONCLUSIONS

The development and performance of larvae in removing contaminants differed significantly on the tested substrates. In particular, the solid materials which provide nutrients other than leachate displayed the best performance. Larvae supported by substrates containing wheat bran and brewers' spent grain displayed faster growth and lower mortality compared to those fed on sawdust, where leachate represented the main source of nutrients. Consequently, the insufficient nutrient load in the sawdust substrate precluded larval pupation.

The contribution of larvae to the overall removal of contaminants under the best operational conditions ranged between 10 and 15% for TOC, and 21 and 36% for nitrogen, with a specific load of 210-230 mg TOC/larva and 14-19 mg N/larva. No significant removal of ammonia nitrogen by larvae metabolism was observed, although no evident toxic effects on larvae development were detected, at least at the concentrations used.

The initial amount of TS, TOC and TN was spread into a final semisolid residue, prepupal biomass and gaseous emissions. The fraction remaining in the final semi solid residue varied between 40 and 50%, depending on the parameter considered (TS, TOC, TN) and typology of substrate. The fraction uptaken by larvae ranged around 10% for TOC and from 18 to 28% for TN. Lipids and protein concentrations present in the prepupal biomass were 28-30% TS and 43-45% respectively.

On the basis of experimental results, the following conclusions were drawn:

- The load of TOC and TN in the sawdust substrate was insufficient to support larval development. In further studies the concentration and amount of leachate should be increased when using solid materials with low nutrient content.
- Further research should be conducted to define the role and fate of the different forms of nitrogen involved in the removal process.
- The relationship between the specific contaminant load (e.g. mg TOC/larva or mg TOC/g substrate) and removal efficiencies should be investigated in order to identify the optimal load.
- BSF larvae applied to leachate treatment, although providing a limited contribution to the removal of contaminants, might provide a significant source of proteins and lipids suitable for use in animal feed and biodiesel production, respectively.
- When setting up a full-scale application, in addition to first resolving at pilot-scale a series of engineering problems, a BSF larvae unit should be combined with other treatment units in order to reach the required efficiencies to comply with discharge limits established by law.
- Finally, future studies should focus on investigating how the eventual presence in leachate of heavy metals and emerging contaminants may influence larvae metabolism in terms of larval development, treatment efficiencies and quality of the final material resources.

REFERENCES

Aigbomian, E.P., Fan, M., 2013. Development of Wood-Crete from Hardwood and Softwood Sawdust 108–117.

Banks, I.J., Gibson, W.T., Cameron, M.M., 2014. Growth rates of black soldier fly larvae fed on fresh human faeces and their implication for improving sanitation. Trop. Med. Int. Heal. 19, 14–22. doi:10.1111/tmi.12228

Diener, S., Zurbrügg, C., 2011. Black soldier fly larvae for organic waste treatment—prospects and constraints. Proc. … 52, 978–984.

Diener, S., Zurbrügg, C., Tockner, K., 2009. Conversion of organic material by black soldier fly larvae: Establishing optimal feeding rates. Waste Manag. Res. 27, 603–610. doi:10.1177/0734242X09103838

Cossu, R., Grossule, V., Lavagnolo, M.C., 2019. Sustainable low-cost waste management: learning from airlines. Detritus, Volume 06, 1–3. doi: 10.31025/2611-4135/2019.13818

Ehrig, H., Stegmann, R., 2018. Leachate

quality. In Cossu R., Stegmann R., Solid Waste Landfilling, Concepts, Processes, Technology. Elsevier, 2018, ISBN: 9780128183366.

Grossule, V., Lavagnolo, M.C., 2019. The treatment of leachate using Black Soldier Fly (BSF) larvae: adaptability and resource recovery testing. Submitted to Journal of Environmental Management and under review.

Hussien, A.M.S., Badr, A.N., Naeem, M.A., 2019. Innovative Nutritious Biscuits Limit Aflatoxin Contamination. Pak. J. Biol. Sci., 22: 133-142 doi:10.3923/pjbs.2019.133.142

Li, Q., Zheng, L., Qiu, N., Cai, H., Tomberlin, J.K., Yu, Z., 2011. Bioconversion of dairy manure by black soldier fly (Diptera: Stratiomyidae) for biodiesel and sugar production. Waste Manag. 31, 1316–1320. doi:10.1016/j.wasman.2011.01.005

Lynch, K.M., Steffen, E.J., Arendt, E.K., 2016. Brewers ’ spent grain : a review with an emphasis on food and health 553–568. doi:10.1002/jib.363

Newton, L., 2004. Using the black soldier fly, as a value added tool for the management of swine manure 36, 20–22.

Onipe, O.O., Jideani, A.I.O., Beswa, D., 2015. Review Composition and functionality of wheat bran and its application in some cereal food products. Int. J. Food Sci. Technol. 2509–2518. doi:10.1111/ijfs.12935

Popa, R., Green, T.R., 2012. Using Black Soldier Fly Larvae for Processing Organic Leachates. J. Econ. Entomol. 105, 374–378. doi:10.1603/EC11192

Ramos, M.J., Fernández, C.M., Casas, A., Rodríguez, L., Pérez, Á., 2009. Influence of fatty acid composition of raw materials on biodiesel properties. Bioresour. Technol. 100, 261–268. doi:10.1016/j.biortech.2008.06.039Shakil Rana, K.M., Salam, M.A., Hashem, S., Ariful Islam, M., 2015. Development of Black Soldier Fly Larvae Production Technique as an Alternate Fish Feed. Int. J. Res. Fish. Aquac. 5, 41–47.

Stegmann, R., 2018. Strategic issues in leachate management. In Cossu, R.; Stegmann, R. Solid Waste Landfilling, Concepts, Processes, Technology. Elsevier, 2018, ISBN: 9780128183366.

Surendra, K.C., Olivier, R., Tomberlin, J.K., Jha, R., Khanal, S.K., 2016. Bioconversion of organic wastes into biodiesel and animal feed via insect farming. Renew. Energy 98, 197–202. doi:10.1016/j.renene.2016.03.022

Tomberlin, J.K., Adler, P.H., Myers, H.M., 2009. Development of the Black Soldier Fly (Diptera: Stratiomyidae) in Relation to Temperature: Table 1. Environ. Entomol. 38, 930–934. doi:10.1603/022.038.0347

Tomberlin, J.K., Sheppard, D.C., Joyce, J.A., 2002. Selected life-history traits of black soldier flies (Diptera: Stratiomyidae) reared on three artificial diets. Annals of the Entomological Society of America.

THIRD PART

Photo gallery

A. Stages abroad

CÔTE D’IVOIRE

At Coopayea Cooperative

Meeting with the Queen

KUET UNIVERSITY
BANGLADESH

Activities with students

Civil Engineering Department

Need for Italian food: finally a proper Italian lunch!

Coconut addiction

Before tasting Paan....

...tasting Paan....

...after tasting Paan.

Perfect moments at Sunderban mangrove forest…

...and meeting new interesting friends.

B. Conferences

WasteSafe17

Sardinia17

30 YEARS ANNIVERSARY

WasteSafe 2019

BEST PAPER CERTIFICATE

to

Valentina Grossule

of

University of Padova, Italy

has successfully participated and presented a paper Titled "*Performance Analysis Of Semi-Aerobic Landfill Under Different Water Availability Conditions and Putrescible Waste Content*" and selected as "**Dr. Md. Harunur Rashid Best Paper Award**" positioned as 2nd (Second) in the **WasteSafe 2019** - the 6th **International Conference on Integrated Solid Waste and Faecal Sludge Management in South Asian Countries** held on 23-24 February 2019 at Khulna, Bangladesh. This conference is jointly organized by Khulna University of Engineering & Technology (KUET), Bangladesh, Bauhaus University Weimar, Germany, University of Padova, Italy and IWWG.

24.02.2019

Prof. Dr. MuhammedAlamgir
Chairman, WasteSafe 2019 International Conference
Department of Civil Engineering, KUET, Bangladesh

C. Semi-aerobic landfill

FIRST EXPERIMENTAL EXPERIENCE

SECOND EXPERIMENTAL EXPERIENCE

Columns set up: Part 1

Columns set up: Part 2

Waste collection at local Landfill, characterisation and columns filling.

Tropical climate simulation

Outside the snow is falling, but inside the cocoa plants are growing!!

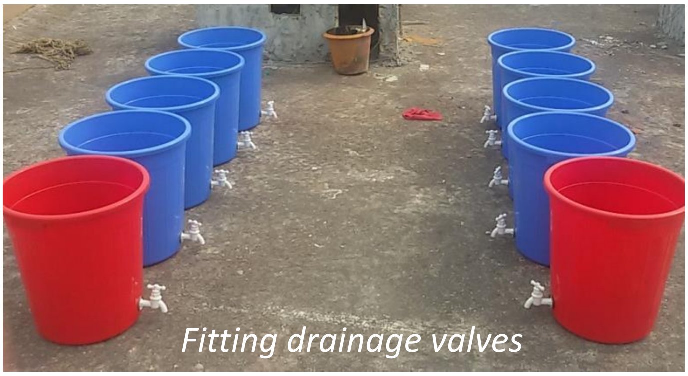
D. Leachate treatment

BLACK SOLDIER FLY LARVAE

SECOND EXPERIMENTAL ACTIVITY

Reactors set up

Monitoring the weight of larvae and football World Cup results!



Fitting drainage valves

Filling reactors with gravel

Soil preparation

Leachate collection at local open dump

..with master students.

Final arrangement
of the reactors under roof

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Research Interests

Low tech cost effective solutions in Environmental Engineering, Sustainable landfilling, role of landfilling inn Circular Economy.

Education

2011 Business Administrationn High School

2014 BSc Environmental Engineering with evaluation 110/110, University of Padova

2016 MSc (Hons) Environmental Engineering, with evaluation 110/100 cum laude, University of Padova

2016-2019 PhD student at Padova University, Department of Civil, Architectural and Environmental Engineering.

Scientific Societies membership

2019 Member of IWWG (International Waste Working Group); Co-chairperson of the IWWG-Young Task Group

2019 Member of GITISA (Italian Group of Environmental Sanitary Engineering)

Research Experiences Abroad

2015 Erasmus student at Middle East Technical University (METU), Ankara, Turkey

2016 On site collection of data for developing modern solid waste management strategies at Agnibilèkrou, Côte d'Ivorie.

2019 Guest researcher for the investigation of the potential of mangroves for the phytotreatment of landfill leachate, at KUET-Khulna University of Engineering & Technology, University, Bangladesh.

Attended conferences

2017 Wastesafe 2017, 5th International Conference on Solid Waste Management in South Asian Countries, 25-27 February, Khulna, Bangladesh.

2017 Sardinia 2017, 16th International Waste Management and Landfill Symposium, 30 Sept – 4 Oct 2019, Cagliari, Italy.

SUM 2018, 4th International Symposium on Urban Mining and Circular Economy, 21-23 May 2018, Bergamo, Italy.

2019 Crete 2018, 6th International Conference on Industrial and Hazardous Waste Management, 4-7 September, Chania, Crete, Greece.

2020 Waste Safe 2019, 6th International Conference on Integrated Solid Waste and Faecal Sludge Management in South Asian Countries, 23-24 February 2019, Khulna Bangladesh.

2020 SUM East 2019, International Symposium on Urban Mining and Waste Management, 20 – 22 May 2019, Suzhou, China.

Publications

International journals

Cossu, R., Grossule, V., Lavagnolo, M.C., 2019. Sustainable low-cost waste management: learning from airlines. Detritus, Volume 06, 1–3. doi: 10.31025/2611-4135/2019.13818

Grossule, V., Morello, L., Cossu, R., Lavagnolo, M.C., 2018. Bioreactor landfills: comparison and kinetics of the different systems. Detritus, Volume 03, 100–113. doi: 10.31025/2611-4135/2018.13703.

Grossule, V., Lavagnolo, M.C., 2019. Lab tests on semi-aerobic landfilling of MSW under varying conditions of water availability and putrescible waste content. Submitted to Journal of Environmental Management (19/9/2019)

Grossule, V., Lavagnolo, M.C., 2019. Optimised management of semi-aerobic landfilling under tropical wet-dry conditions. Submitted to Detritus Journal (19/9/2019)

Grossule, V., Lavagnolo, M.C., 2020. The treatment of leachate using Black Soldier Fly (BSF) larvae: adaptability and resource recovery testing. Submitted to Journal of Environmental management, 253 (2020) 10970, https://doi.org/10.1016/j.jenvman.2019.109707. In press.

Grossule, V., Vanin, S., Lavagnolo, M.C., 2019. Potential treatment of leachate by Hermetia Illucens (diptera, stratyomyidae) larvae: performance under different feeding conditions. Submitted to Waste Management and Research. Accepted.

Lavagnolo, M.C., Grossule, V., 2018. From 3R to 3S: An appropriate strategy for Developing Countries. Detritus, Volume 04, 1-3. doi:10.31025/2611-4135/2018.13749

Lavagnolo, M.C., Grossule, V., Raga, R., 2018. Innovative dual-step management of semi-aerobic landfill in a tropical climate. Waste Manag. 1–10. doi:10.1016/j.wasman.2018.01.017

Lavagnolo, M.C., Grossule, V., 2019. The burden of waste in 21st-century Africa. From the European south, 4, 61-73. ISSN 2531-4130

Conferences proceeding

Grossule, V., Lavagnolo, M.C., 2017. Innovative management of semi aerobic landfill in tropical climates. In proceedings: Wastesafe 2017, 5th International Conference on Solid Waste Management in South Asian Countries, 25-27 February 2017, Khulna, Bangladesh.

Grossule, V., Lavagnolo, M.C., 2017. Innovative semi-aerobic landfill management in tropical countries. In proceedings: Sardinia 2017, 16th International Waste Management and Landfill Symposium, 30 Sept – 4 Oct 2019, Cagliari, Italy.

Grossule, V., Lavagnolo, M.C., 2019. Performance analysis of semi-aerobic landfill under different water availability conditions and putrescible waste content. In Proceedings: WasteSafe 2019, 6th International Conference on Integrated Solid Waste and Faecal Sludge Management in South Asian Countries, 23-24 February 2019, Khulna Bangladesh.

Grossule, V., Cossu, R., Lavagnolo, M.C., 2019. Use of BSF larvae for leachate treatment: adaptability testing. In Proceedings: SUM East 2019, International Symposium on Urban Mining and Waste Management, 20 – 22 May 2019, Suzhou, China.

Book chapter

Cossu, R., Grossule, V., 2018. Landfill bioreactors. In Cossu, R.; Stegmann, R. Solid Waste Landfilling, Concepts, Processes, Technology. Elsevier, 2018, ISBN: 9780128183366.