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OPTIMISED MANAGEMENT OF SEMI-AEROBIC LANDFILLING UNDER TROPICAL WET-DRY CONDITIONS

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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 with 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 20mgO_2/L, 200mgO_2/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. Semi-aerobic landfill is considered a cost-effective technology with huge application potential in Developing Countries (DCs), where the technical and economic resources are limited. 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. Several full-scale semi-aerobic landfills are operating throughout the world, both in industrialised (e.g. Japan, Italy) and developing countries (China, Iran, Malaysia, Pakistan, Samoa, Vietnam) (Matsufuji et al., 2018), however controversial issues relating to leachate generation and management have been raised when operating under tropical climate conditions (Kortegast et al., 2007; Malek and Shaaban, 2008).

Landfill stabilisation in fact 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

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from landfilling (methane and CO_2 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 negatively 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, which affects the majority of DCs, 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?".

2. MATERIALS AND METHODS

2.1 Research program

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 (D), two with an initial dry phase under controlled watering (D') and two with an initial wet phase, during which leachate was stored to allow 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). 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.

The research programme is graphically illustrated in Figure 1.

2.2 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, and it was sampled at the gate of the Legnago (Verona, North Italy) waste treatment facilities. HP waste was obtained by mixing LP waste with source segregated kitchen waste in order to achieve a 50% w/w ratio. Kitchen waste was sampled at the gate of Sesa (Padova, Noth Italy) composting plant.

The composition of the waste used in the two different experimental phases and the main analytical parameters are reported in Table 1.

2.3 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.

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 2).

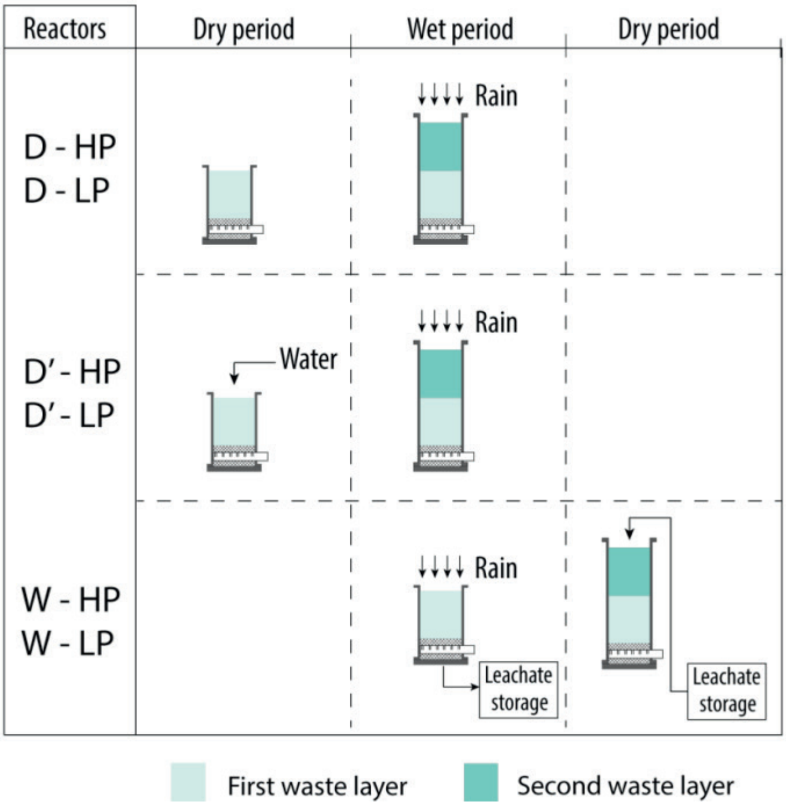

FIGURE 1: Research programme. (According to the first simulated season: D=Dry conditions, D'=Dry conditions with controlled watering, W=Wet conditions. According to tested waste type: HP= High putrescible content waste; LP=Low putrescible content waste).

Reactors were operated in a thermally controlled room.

2.4 Methodology

The experiment lasted approximately 6 months, divided into two subsequent phases (0-108th day and 109-216th day), to reproduce, by controlling the Liquid/Solid ratio, one year landfill operation in around six months. The lab scale operative conditions (temperature, waste granulometry, density, height of the waste layer, etc.) assure accelerated processes compared to the full scale.

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

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 (%TS)	34.5	40.3	30.2	35.4
	RI_4 (mgO_2/gTS)	38.4	93.3	26.7	6.4

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 distilled water input of 3 L/d was adopted in all columns to simulate rainfall and reproduce water infiltration corresponding to a yearly mean 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 daily using an Eco-Control LFG20 analyser.

At the beginning and end of both phases, waste was sampled from each reactor (approx. 100g, from the top at the end of first phase and by emptying the lysimeters at the end of the second phase).The following parameters were measured: 4-day Respirometric Index (RI4), 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. RI4 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 (BOD5), nitrogen compounds (TKN, ammonia, nitrate, nitrite) and chlorides, were regularly analysed in leachates (once/twice weekly).

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 (1):

$$wa = ew + L/S = u \cdot (kg\ waste)/(kg\ TS) + L/S \qquad (1)$$

Where:

wa: water availability (kgH_2O/kg TS)

ew: endogenous water (kgH_2O/kg TS) = u.(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).

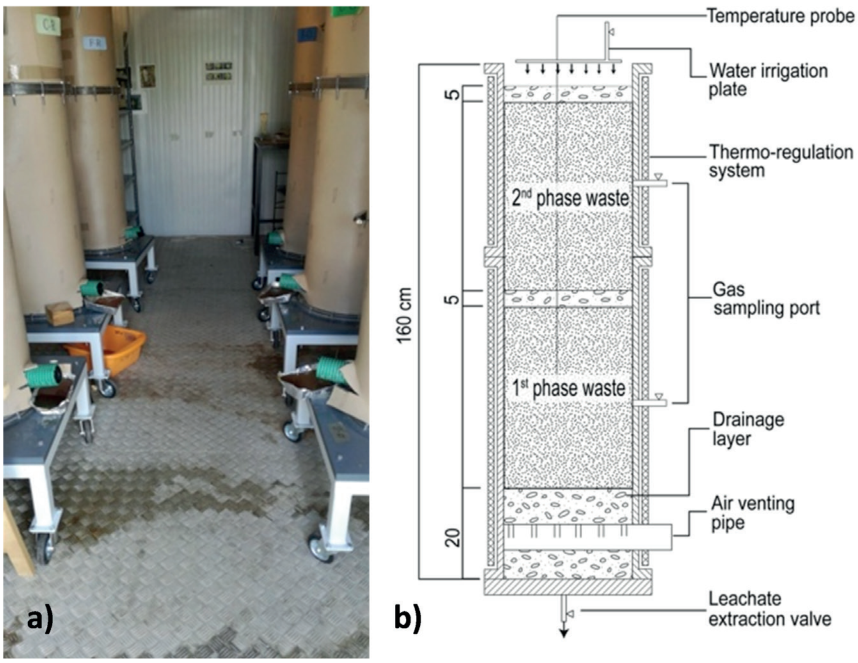

FIGURE 2: Set up of the semi-aerobic landfilling reactors (a) and constructive details of the individual reactors (b). The lengthening of columns to enable conduction of the second research phase is indicated.

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, high water availability results in heat loss in water evaporation and in prevailing of anaerobic processes, with slower exothermic reactions compared to the aerobic processes. It is confirmed by the quality of the biogas (Figure 4): increased water availability due to excess external addition of water negatively influenced natural 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 (RI4 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 (LFG) 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 CO_2.

During the first phase gas composition, decrease in CO_2 concentrations and final waste stability (RI4 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 (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 (D'-LP, D-HP).

During the second phase, water input (simulated 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 RI4 values in the bottom layer. RI4 values remained constantly below 12 mgO_2/g TS and the lowest values (6-7 mgO_2/g TS) were observed for all LP columns and for the column with High Putrescible waste under dry climatic conditions (D-LP). This suggested that during the 2nd phase the first layer in all columns com-

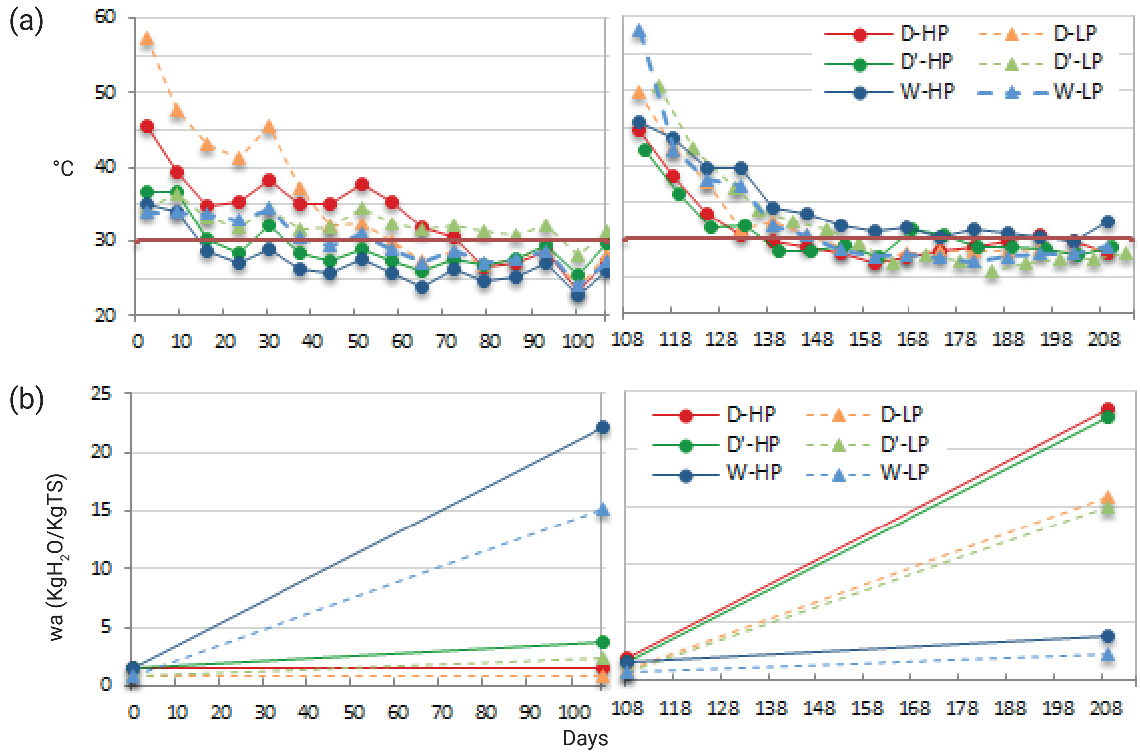

FIGURE 3: Temperature values (a) and water availability (b) in the layers of fresh waste in the first and second phase for all testing columns. The highest environmental temperature is illustrated in the temperature chart with a red line (30°C) (D=Dry conditions, D'=Dry conditions with controlled watering; W=Wet conditions, HP=Waste with high putrescible content; LP=Waste with low putrescible content).

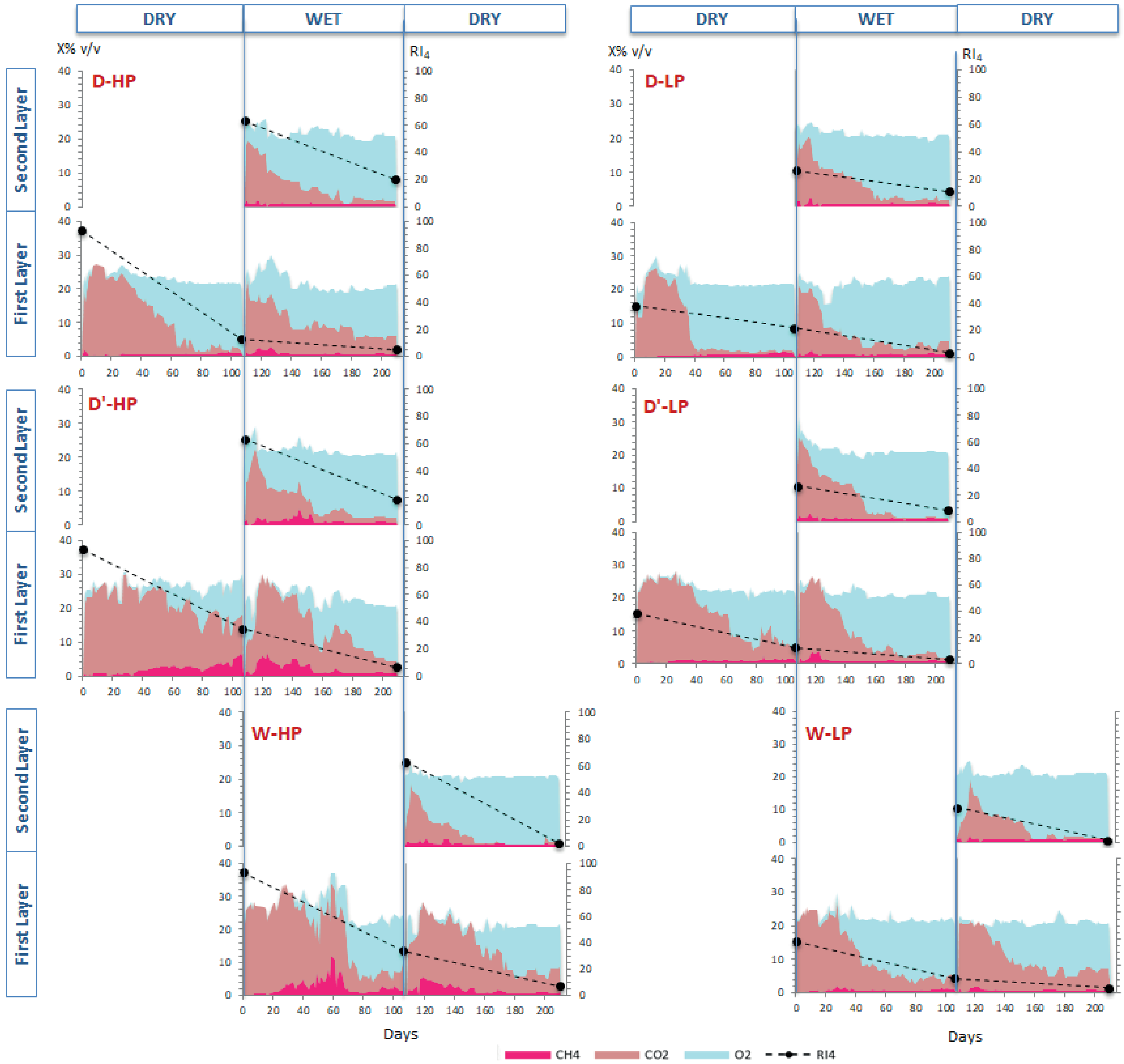

FIGURE 4: Landfill gas (LFG) composition (Stacked area chart) and waste stabilisation in the lysimeters, over testing time. (X% v/v: volumetric gas fractions; RI4: 4 days Respirometric Index, $mgO_2/kgTS$). Nitrogen gas is not represented. RI4 values are only referred to the beginning and end of each 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).

pleted 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.

In general, input of excess water results in initial saturated condition which limits air circulation and promotes anaerobic processes witnessed by an increase in CH_4 concentration (particularly in case of high putrescible waste); later on the flushing effect reduces the presence of putrescible in the waste mass, allowing consequently an increase in the oxygen concentration.

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 might be 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. A consistently balanced availability of water, both in terms of endogenous water naturally present in the putrescible fraction, and external water input (rainfall, leachate recirculation), is foundamental in promoting good natu-

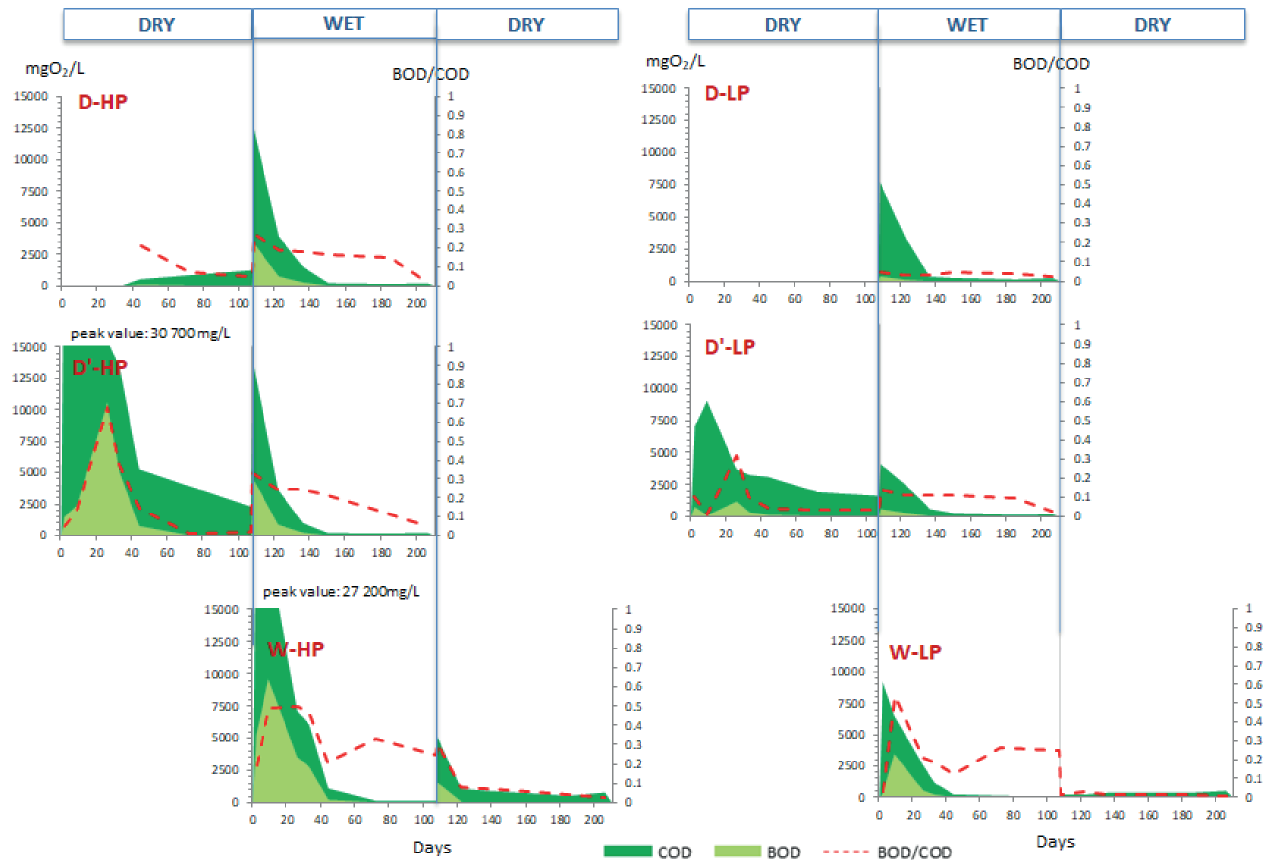

FIGURE 5: BOD/COD ratio, BOD and COD concentrations in leachate (overlapped area chart) vs. testing time, for the different lysimeters. D=Dry conditions, D'=Dry conditions with controlled watering; W=Wet conditions, HP=Waste with high putrescible content; LP=Waste with low putrescible content.

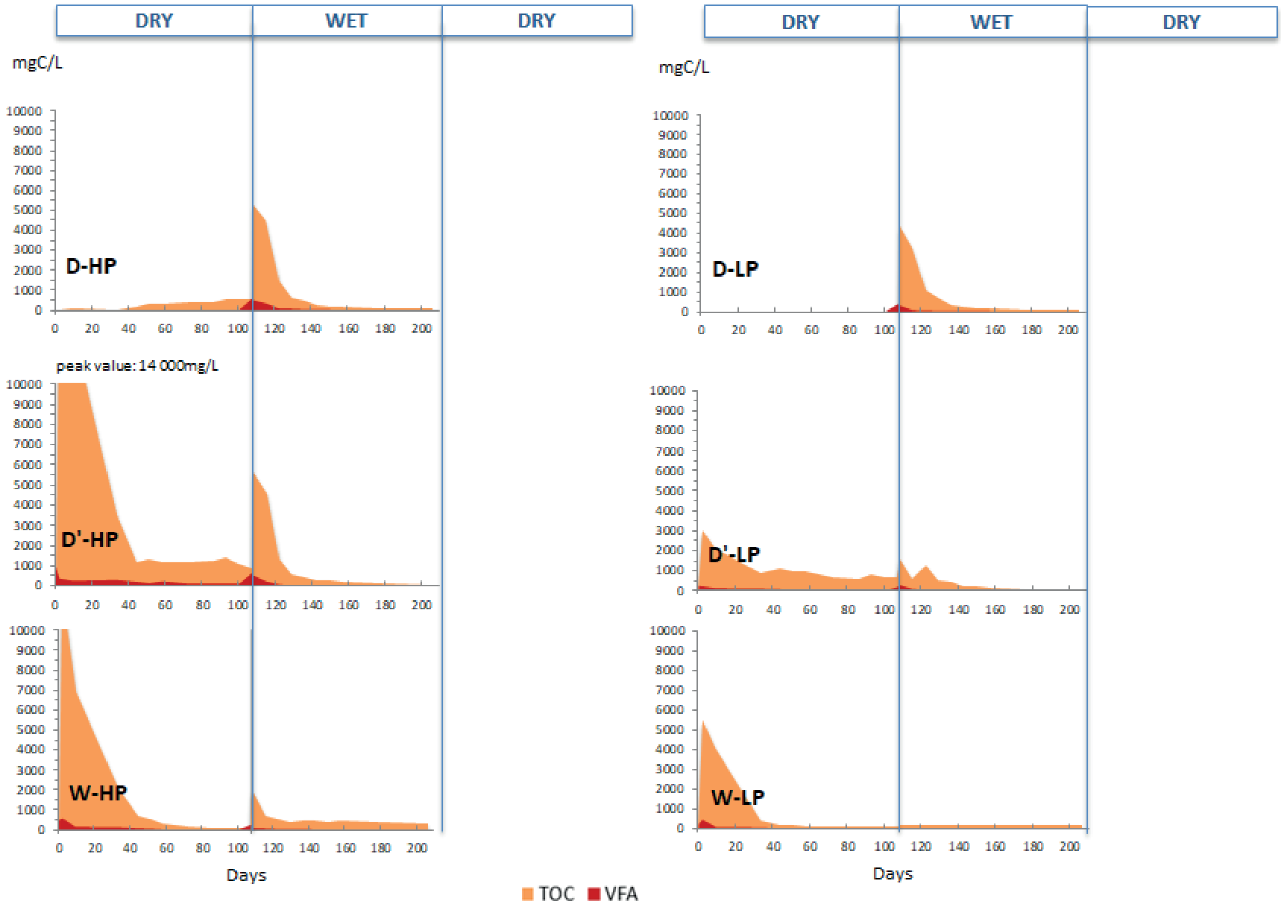

FIGURE 6: pH, VFA and TOC concentrations in leachate (overlapped area chart) vs. testing time, for the different lysimeters. D=Dry conditions, D'=Dry conditions with controlled watering; W=Wet conditions, HP=Waste with high putrescible content; LP=Waste with low putrescible content.

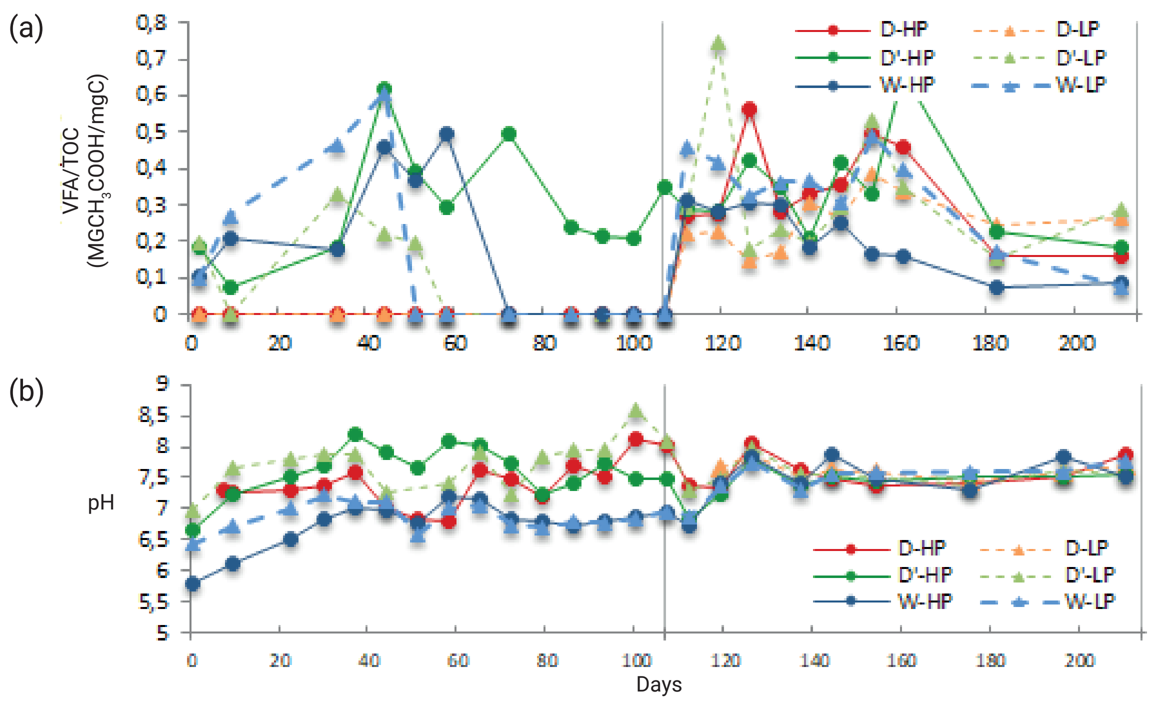

FIGURE 7: VFA/TOC ratios (a) and pH values (b) measured over time in leachate collected at the bottom of all test columns during the first and second climate phases.

ral 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, particularly in case of high putrescible waste;
- 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 in tropical areas 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.

Finally an important full-scale operative issue should be carefully considered and controlled. Under tropical climate conditions a huge amount of leachate might be generated as a consequence of excessive rain infiltration in the wet season. The accumulation of large amount of leachate might negatively affect the convective circulation of air, so reducing the efficiency of semi-aerobic landfilling. Problems like this have been already reported in literature (Cossu, 2019; Kortegas et al., 2007; Malek and Shaaban, 2008). This problem can be controlled by assuring well drained conditions of the waste mass (no use of low permeable material as daily top cover, drainage systems at the different waste layers, regular collection of leachate) and by adopting landfill top covers which reduce the rain infiltration.

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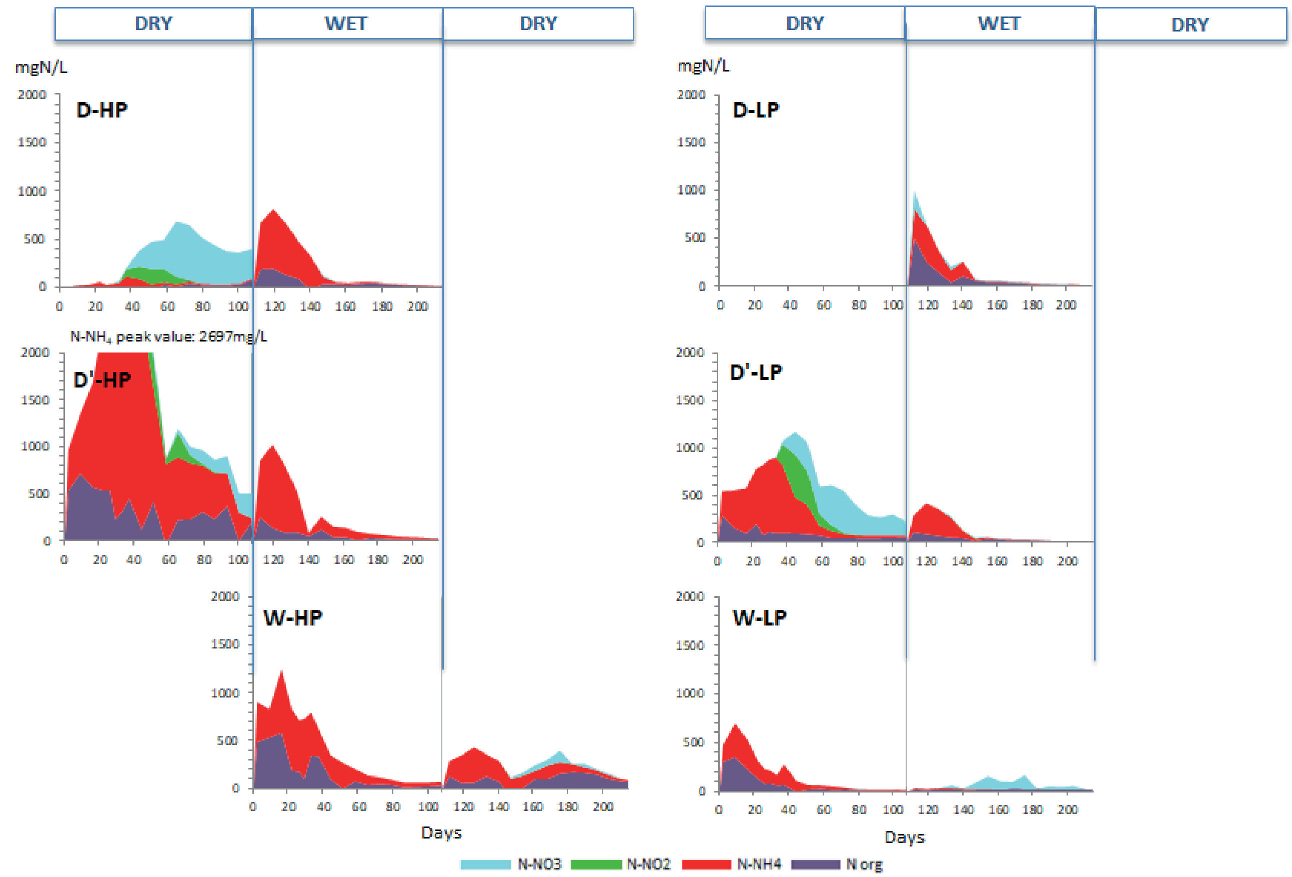

FIGURE 8: $N\text{-}NH^{4+}$, N organic, NO_{2-}, NO_{3-} concentrations in leachate (Stacked area chart) vs. testing time measured for each individual lysimeter, for the two (1st and 2nd) different climate phases. (D=Dry conditions, D'=Dry conditions with controlled watering; W=Wet conditions, HP=Waste with high putrescible content; LP=Waste with low putrescible content).

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