EXPERIMENTAL REDUCTION OF LANDFILL EMISSIONS BASED ON DIFFERENT CONCEPTS. THE PAF MODEL

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SUMMARY: Lab-scale tests and a large lysimeter column were set up to investigate the behaviour of different options for achieving sustainability by reducing long term landfill emissions. The options which have been studied and compared with the traditional anaerobic landfill for unprocessed refuse were: mechanical-biological pretreatment, landfill aeration with forced and with natural advective air flow (semi-aerobic), flushing. Combination of different options have been experimented. The combination of mechanical-biological pretreatment, Aeration by the semi-aerobic method and Flushing (PAF model) seems to synergize the advantages of the individual options. The research is on going and further studies are necessary in order to assess the full-scale applicability of the model.

1. INTRODUCTION

The long-term environmental impact caused by Municipal Solid Waste (MSW) landfills may last for centuries (Kruempelbeck and Ehrig, 1999).

The current technology of landfilling based on anaerobic degradation of waste, gas extraction and leachate containment is inadequate to face the long-term impact of emissions.

Sooner or later liners will leak and drainage systems clog (Rollin et al., 1991; Farquhar, 1989; Brune et al., 1993) and this in addition to the traditional impacts, such as the occurrence of odours, which invariably render landfill siting and public acceptance a problem. Accordingly, the sustainability of a landfill, whereby no environmental problems should be left to future generations, represents the main goal to be achieved by modern landfill strategies.

To date, the main options proposed for the reduction of landfill emissions in order to meet sustainability requirements are:

a) Pre-treatment of waste, either by mechanical-biological processes or by thermal treatment (among others Leikam and Stegmann, 1997; Scheelhase and Bidlingmaier, 1997);
b) In situ aeration of the waste mass by means of natural air inflow (semiaerobic landfill) or by forced aeration (Matsuto et al., 1991; Matsufuji et al., 2000; Hanashima, 1999; M. Hudgins, S. Harper, 1999);
c) Flushing of the waste mass in situ (flushing bioreactor) (Blakey et al., 1997; Karnik and Parry, 1997; Novella et al.,1997; Purcell et al., 1997; Walker et al., 1997; Wingfield-Hayes et al., 1997; Robinson 1998) and even off site (Higuchi and Hanashima, 1999).

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The application of the above mentioned options has proved to be successful in reducing emissions, but several problems may still need to be solved:

- Residual emissions may remain high in some cases (pre-treatment)
- Clogging of drainage may still occur (aerobic landfill)
- Difficult hydraulic circulation and other operative aspects may arise (flushing bioreactor)

The main purpose of our research study was to investigate the behaviour of the different options available for sustainable landfill, using the same type of waste, and to evaluate possible combinations of the latter, including all three options: the PAF (Preatreated Aerobic flushing) model. The study programme performs by the following means:

- Six refuse leaching columns were set up and emissions were observed
- A large lysimeter was set up to test the PAF (Pretreated Aerobic Flushing) model.
- Emission behaviour, hydraulic and mechanical properties, as well as behaviour of waste under the different operational conditions will be evaluated.
- Findings will be applied to full-scale strategies for landfill sustainability

The research study is currently in progress; the present paper refers to the results obtained respect to quality of emissions as observed after 70 days for lab column and 100 days for the lysimeter experiment.

2. MATERIALS AND METHODS

The study was based on the carrying out of two different kinds of tests:
a - lab tests
b - large lysimeter test

2.1 Laboratory tests

Laboratory tests were carried out using six plexiglas columns (height 100 cm, diameter 18 cm), installed in a thermo-insulated room, at a temperature of 35°C.

Each column was used to simulate a different landfill concept; the latter were filled with unprocessed MSW or mechanical biological pre-treated (MBP) refuse and different operational conditions were established, as summarised in Table 1.

The refuse was obtained through sampling at the Legnago (Verona, Italy) composting plant, subsequent to separation of bulky waste, milling and sieving on a 6 cm screen. MBP waste was sampled at the same plant, providing for an additional 3 weeks of forced aeration and 4 weeks of curing phase in windrows.

Prior to filling of columns, the waste material was analyzed as reported in Table 2. Potential Fermentable Solids (PFS) were analyzed by ethanol extraction in Soxhlet apparatus and subsequent acid digestion with HCl (Adani, 1998). TOC was tested by chemical oxidation with potassium dichromate. The respiration index for seven days (IRF) was measured using the Sapromat respirometer (Voith Gmbh).

Heavy metal concentrations were measured, after extraction, by ICP analyzer (Varian mod. Perkin Elmer 4200 DV). The other parameters were measured according to Standard Methods.

Using the same material, leaching tests were carried out at a solid/liquid ratio of 1/20, with distilled water and a solution of 1N of acetic acid as elution liquids, mixed in a Jar Test apparatus for 24 hours.

The analytical results of the leaching tests are reported in Table 3. From the analytical characterization the lower putrescible content and biological activity of the MBP waste, as well as the higher concentration of total nitrogen and heavy metals following the gasification of the organic carbon which occurs during the stabilization process, may be ascertained.

Table 1 - Refuse filling and operational conditions adopted in the test columns in order to simulate different landfill concepts (MSW = unprocessed, MBP = Mechanical Biological Pre-treated Waste, PAF = Pretreated Aerobic Flushing))

Column	Material	Operative Conditions	Landfill Concept
A	MSW	Anaerobic	Traditional landfill
B	MBP	Anaerobic	Pre-treated landfill
C	MBP	Anaerobic with high water input	Flushing bioreactor
D	MBP	Aerobic with high air inflow	Aerated landfill
E	MBP	Aerobic with low air inflow	Semiaerobic landfill
F	MBP	Aerobic with low air inflow and high water input	PAF model

Table 2 - Characteristics of the residues.

Determinand	MSW	MBP
pH	7.2	8
Moisture content (% wet weight)	55	33
TVS (% wet weight)	50	44
PFS (% dry weight)	46	24
TOC (gC/kg TS)	293	208
Ntot (gN/kg TS)	8,82	11,26
C/N	33,3	18,5
IR7 [gO_2/g TS]	213,1	11,6
Cd (mg/kg TS)	0,7	2,9
Zn (mg/kg TS)	162,2	451,2
Ni (mg/kg TS)	15,8	39,2
Pb (mg/kg TS)	83,1	437,4
Cu (mg/kg TS)	49,8	254
Fe (mg/kg TS)	6809	7550
Cr (mg/kg TS)	37,8	25,5

Table 3 - Results of elution tests with distilled water and a solution with 1N acetic acid on MSW waste and MBP waste.

Determinand	*MSW*	*MBP*
	Distilled water	
pH	5,7	7,1
BOD_5 (mg/l)	1850	290
COD (mg/l)	2283	1085
BOD_5/COD	0,81	0,27
TKN (mgN/l)	45	48
NH_3 (mgN/l)	14,8	13,2
	Acetic acid	
Cd (mg/l)	< 0,01	0,01
Zn (mg/l)	1,9	2,19
Ni (mg/l)	0,15	0,18
Pb (mg/l)	0,32	0,53
Cu (mg/l)	0,21	0,66
Fe (mg/l)	5,8	1,09
Cr (mg/l)	0,1	0,27

Rainfall was simulated by feeding the columns with distilled water. The amount of water has been calculated in such a way to simulate long term landfill operation on the basis of the liquid/solid (L/S) ratio.

Columns A, B and C were capped and sealed in order to avoid any air infiltration. Each column was equipped with a flow meter for the air inlet.

The weight of the material deposited in each column and regimes applied for water and air influx are indicated in Table 4. Column C (Flushing Bioreactor) was fed with a flow 3 times higher than the other column, until a liquid/solid ratio = 5 was reached after a 70 day period. Column D (Aerated landfill) was aerated continuously.

In columns E (Semiaerobic Landfill) and F (PAF model), "Semiaerobic like" conditions were achieved by means of intermittent air inflation, as the thermoinsulation at a temperature of 35°C colud not to provide the natural convective flow of air at the basis of the system.

Leachate collected at the bottom of the columns was sampled weekly and the following parameters analyzed: pH, COD, BOD_5, TKN, $N\text{-}NH_4^+$, $N\text{-}NO_x$, metals (Cd, Zn, Pb, Ni, Cu, Fe, Cr).

Biogas from columns A, B and C was collected in gas-tight aluminium bags and the collected volume measured weekly. Levels of CH_4, CO_2 and O_2 (% Vol) present in the biogas from all the columns was measured using an Infrared analyzer (mod. LFG 20).

In columns D, E and F, Oxygen was measured in two fronts along the column height in order to check the oxygen distribution.

Table 4 - Weight of refuse, water and air inflow regime adopted in the column testing programme

Column	*Refuse (kg)*	*Water inflow (l/week)*	*Air inflow*
A	9,32	1,5	-
B	7,93	1,5	-
C	8,12	4,13	-
D	8,14	1,5	100 Nl/h, continuously
E	8,81	1,5	50 Nl/h, 4h/d, 5d/week
F	8,29	4,13	50 Nl/h, 4h/d, 5d/week

2.2 The lysimeter test

Approximately 750 kg of mechanical-biological pre-treated refuse (MBP) was placed in a column with internal square section 0,8 x 0,8 m and a vertical height of 3 m (Figure 1). The column was constructed using steel and thick plexiglass for the walls. The column was equipped with 4 sampling points to allow for temperature measurements and gas sampling points. Gas was analysed using an IR analyser. The walls of the column were insulated with 100 mm of polistyrene panels. Leachate was collected from a 70 mm deep gravel drainage layer situated at the base of the column.

A perforated HDPE pipe, diameter 300 mm, was inserted in the bottom in order to allow for onset of semi-aerobic conditions provided by a convective air flow due to the temperature gradient between ambient and waste mass.

The column was maintained under semi-aerobic conditions without water inflow for 30 days. Subsequently flushing was applied with an inflow of 31 l/week simulating three-fold the infiltrating rainfall with a L/S of 0,41. Leachate was collected weekly and analysed for pH, BOD_5 ,COD, TKN, $N\text{-}NH_4^+$, $N\text{-}NO_x$ and heavy metals.

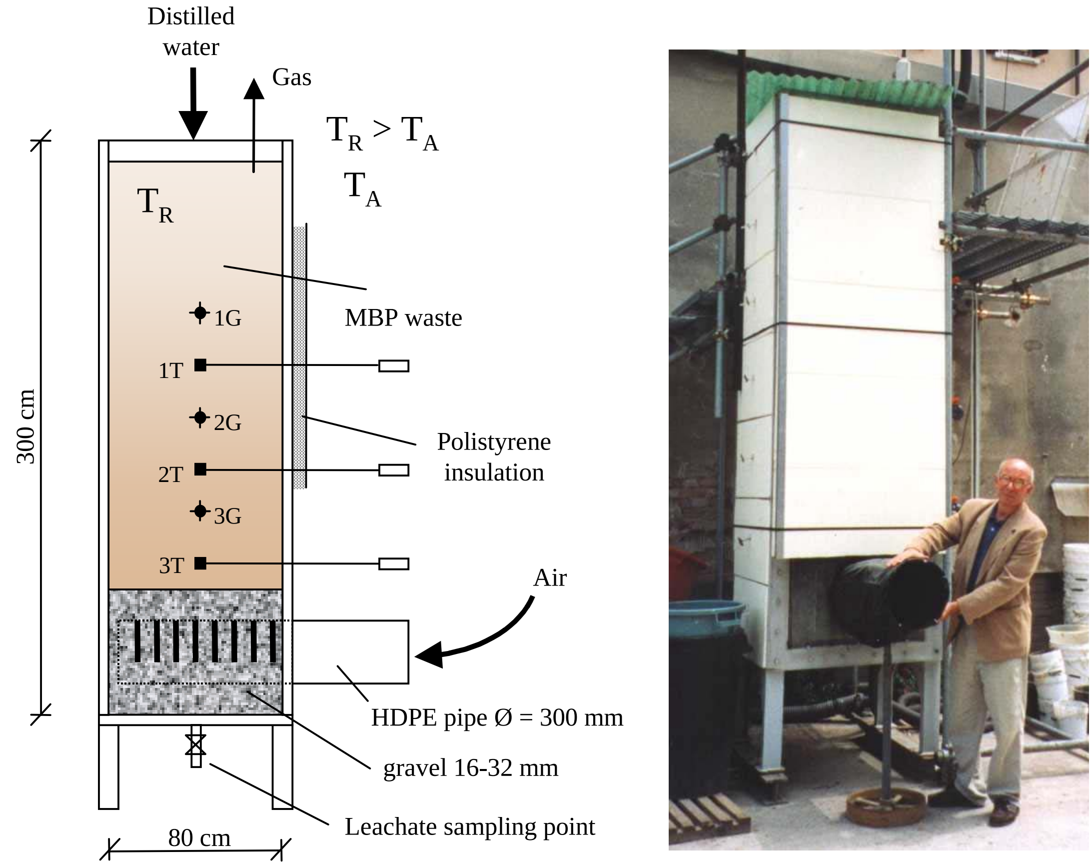

Figure 1. Scheme and picture of the lysimeter column (TR = temperature in the waste mass (35 – 65°C), TA = ambient temperature; 1÷3T, 1÷3G = sampling points for temperature (T) and gas (G).

3. RESULTS AND DISCUSSION

Although the research study is still on-going, the results of the first 70 days of testing are fully significant. At the conclusion of test the residual waste in the columns will be analysed for mass balance calculations. The results obtained are presented herein and discussed on the basis of the most significant parameters. Heavy metals analysed will be not discussed at this stage.

3.1. Leachate composition

3.1.1 pH

The pH curves (Figure 2) tend to vary at an inverse trend respect to that observed for COD. As expected, the lowest values (pH 5.5) were observed in column A, reflecting the evidence of a strong acid phase in the anaerobic degradation of the raw MSW, characterized by a higher content of putrescible organics.

The MBP waste under anaerobic conditions presents higher values (pH 6.5÷6.8) which are however generally lower than under aerobic conditions (pH 7.2÷7.5).

Leachate in column D (aerated landfill) was characterized by the most regular trend, maintaining values around pH 7. The flushed columns (A and F) present a lower pH than the corresponding columns (B and E) without flushing, evidencing a wash-out of buffers from the waste mass.

The pH values observed for the PAF lysimeter show the same trend as the corresponding lab column, with levels remaining invariably above neutral (Figure 2b).

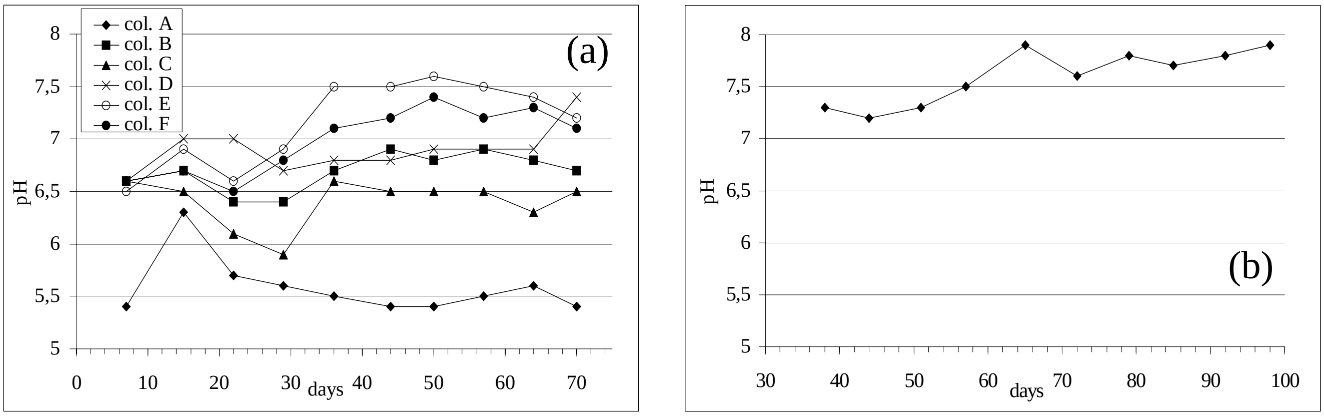

Figure 2. Evolution of pH in the leachate from the different columns (a), and the lysimeter (b).

3.1.2 COD and BOD_5

The concentrations of COD and BOD_5 measured weekly in the different leachates from the lab columns and the corresponding cumulative release are given in Figure 3 and 4. Similar graphs for the lysimeter are given in Figure 5. At the beginning of the test BOD_5 and COD concentrations were, of course, very high in column A, but values around 30000 mg/l of COD and 2500-7000 for BOD_5 were also observed for MBP waste.

The higher degradation rate obtainable in aerobic conditions by forced aeration kept leachate in column D at the lowest initial concentration of BOD_5 and COD.

Flushing of the MBP refuse led to the production of leachate having the lowest values of BOD and COD concentrations. The lowest BOD_5 has been observed in column D (70 mg/l).

Concentration values and cumulative release curves clearly evidentiate the presence of the two mechanisms of organics removal: biological degradation and washing out.

The higher the degradation rate (as in the aerated and semiaerobic landfill) the lower the cumulative organics release. Flushing reduces the availability of organics for degradation and increases the cumulative release. To this regard the anaerobic columns displayed both the highest release and highest concentration values.

A combination of aerobic conditions and flushing (column F, PAF model) produces the best results.

Similar results are observed also in the PAF lysimeter (Figure 5), with clear evidence of a reduction effect following application of flushing, started after 30 days.

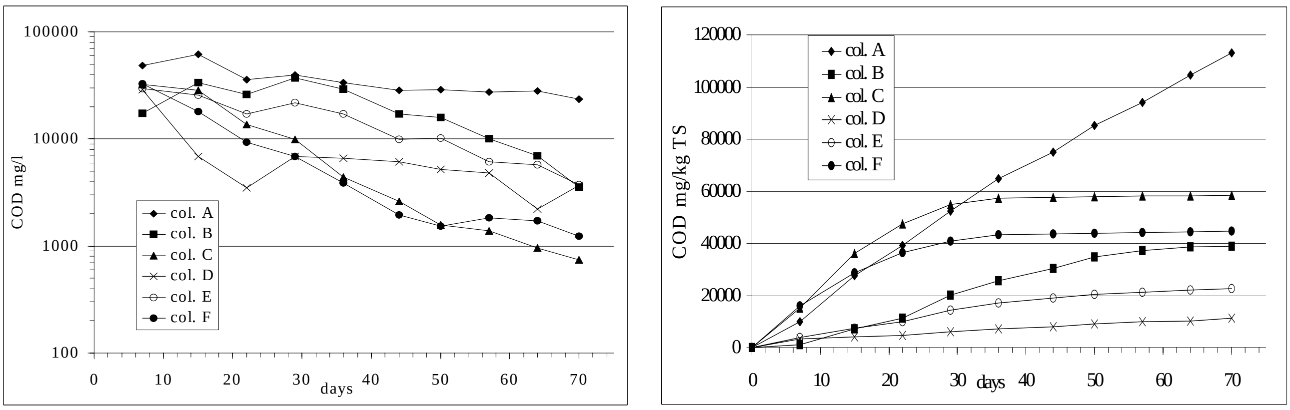

Figure 3. Evolution of COD and the cumulative release in the leachate from the different lab columns.

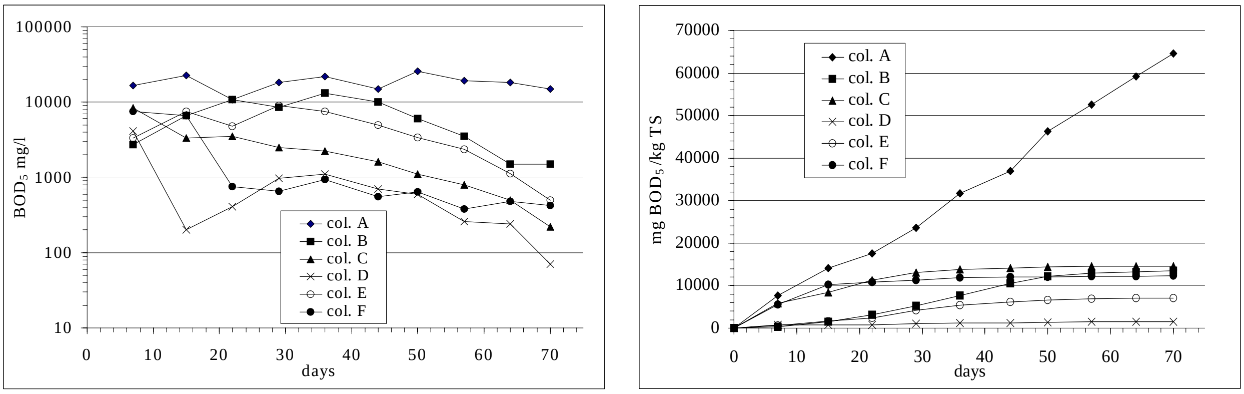

Figure 4. Evolution of BOD_5 and the cumulative release in the leachate from the different lab columns.

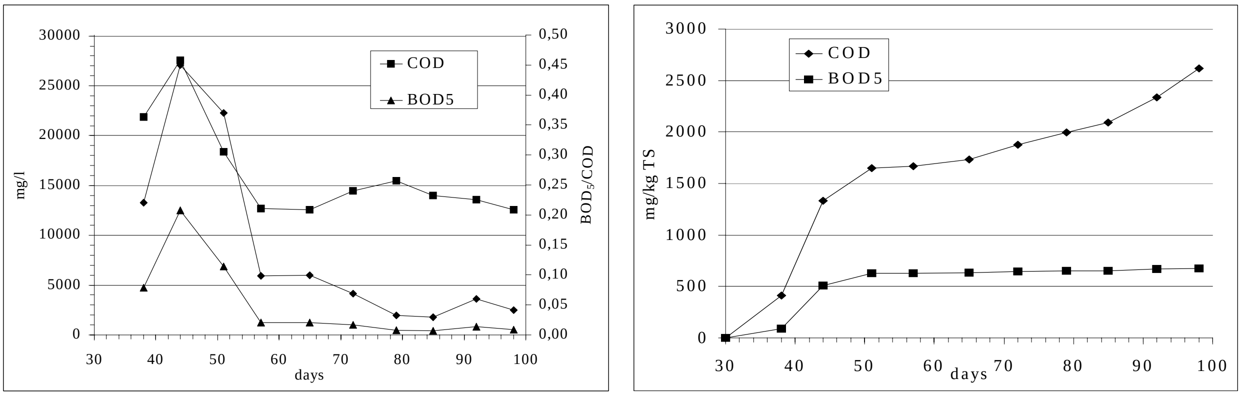

Figure 5. Evolution of COD,BOD_5 and the cumulative release in the leachate from the lysimeter (leachate was collected after 30 days of semierobic conditions without water input, when flushing started to be applied).

3.1.3 Ammonia and TKN

The evolution of Ammonia and TKN concentrations in the six lab columns and the corresponding cumulative release is given in Figure 6 and 7. Some parameters for the lysimeter column are shown in figure 8.

Even with higher initial TKN and $N\text{-}NH_4^+$ concentration for MBP refuse (see also Table 1), the peak concentration of these parameters were observed for the MBP anaerobic reactor (column B). The lowest values are achieved in the flushed columns (F and C), with lower peak $N\text{-}NH_3$ concentrations after 70 days of 38-58 mg $N\text{-}NH_4^+$/l.

As already observed for BOD_5 and COD, the curves of the cumulative release for ammonia evidentiate the extend of the two attenuation mechanism: nitrification and wash-out. Differences between semiaerobic columns with (F) and without (E) flushing show the wash-out effect, higher for the PAF model. Differences between anaerobic (B) and aerobic (D,E) columns show the nitrification effect, while differences between aerated (D) and semiaerobic (E) display the higher nitrification following higher oxygen availability.The lower release is then observed with aerated column where maximum nitrification was achieved.

These considerations are confirmed by the observed $N\text{-}NO_3$ concentrations in the different leachates.

In the lysimeter column the lower peak of ammonia, after 100 days of experiment, was 126 mg $N\text{-}NH_4^+$/l.

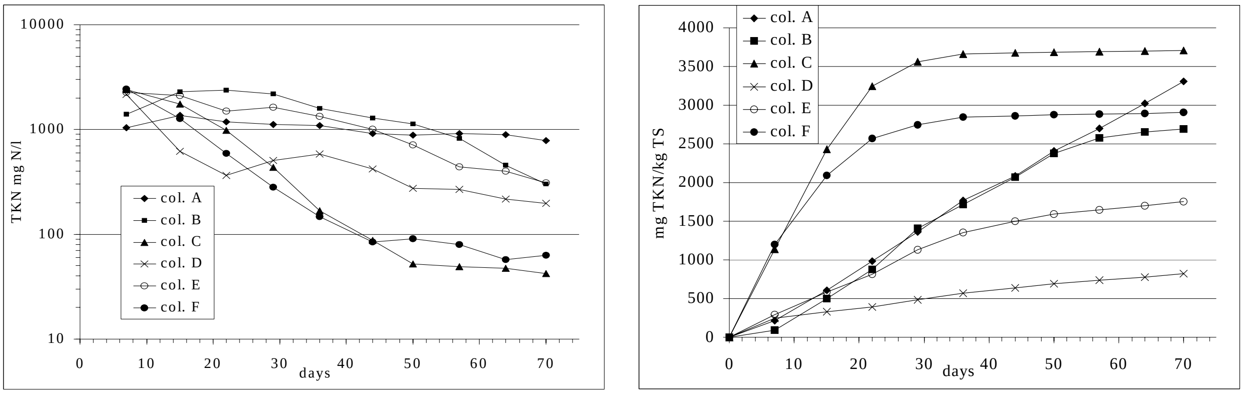

Figure 6. Evolution of TKN and the cumulative release in the leachate from the different columns.

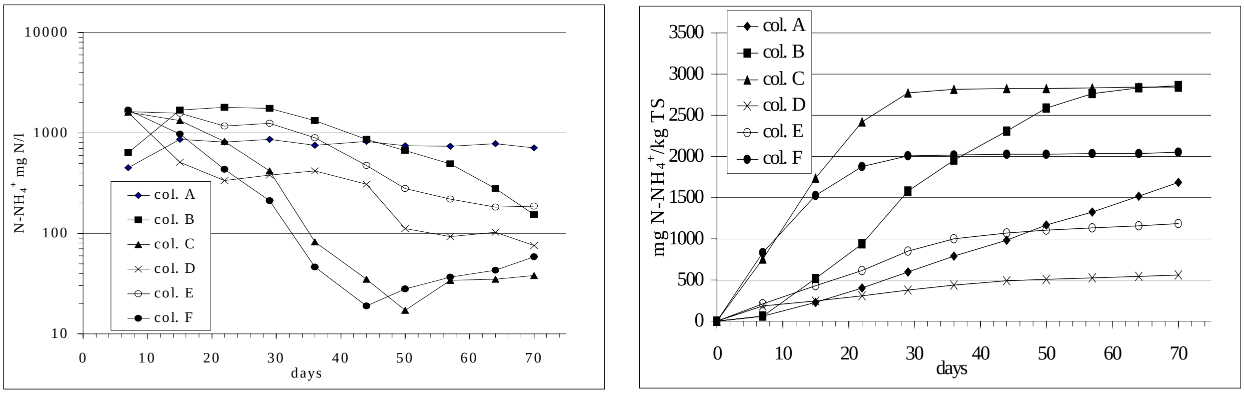

Figure 7. Evolution of NH_3 and the cumulative release in the leachate from the different columns.

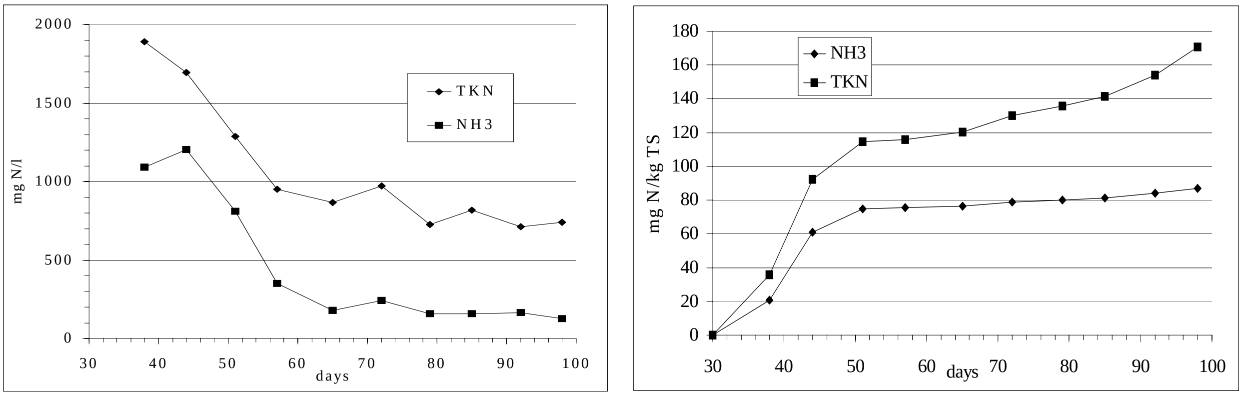

Figure 8. Evolution of TKN, NH_3 and the cumulative release in the leachate from the lysimeter.

3.2. Biogas

Figure 9 shows the evolution over time of the gas composition collected at the head of the three anaerobic columns and the cumulative gas production in the same columns.

Concentrations of methane in the anaerobic column with unprocessed refuse did not appear until 65 days from start of the experiment, being the result of the prolonged acid phase which has already been commented. Both anaerobic columns with MBP waste (B and C) peaked at a methane concentration of 50-60% with a similar evolution over observation time. The total gas production of the column A was very low, again reflecting the prolonged acid phase.

With regard to columns B and C, the one without flushing (B) showed the highest production as result of the higher concentration of carbon, which on the contrary was depleted by flushing (column C). The gas composition measured at two different points along the aerobic columns is given in Figure 10.

The aerated column presented O_2 concentrations close to 20% throughout the entire observation period. Only at the beginning of the experiment low concentrations of CO_2 disappeared later as a result of the reduction of carbon in the waste mass.

In the semiaerobic columns an increase in CO_2 concentration along the height of the column is evident, with similar peak concentrations.

The distribution of O_2 is influenced by flushing, with higher values in the non flushed column. This is an aspect which should be carefully considered when operating a full scale landfill. Indeed, flushing, by invading the pore volume with water could adversely affect the advective flux of air. High O_2 concentrations measured close to the top of the columns are

linked to the compaction of the waste, resulting the sampling point closer to the surface with higher influence of the air infiltration.

Figure 11 show the evolution gas composition and temperature in the PAF lysimeter. In the PAF lysimeter the gas composition, as measured at three sampling points (Figure 1), reflects the operation in two stages. During the semi-aerobic phase without water inflow, methane concentration was invariably low, ranging between 0 and 2% vol, even at those sampling points at a greater distance from the air influx. After flushing, methane concentrations increase, peaking in the 10-15 % vol range. Oxygen was characterized by zero levels, as is typical for the semi-aerobic concept, whilst CO_2 ranged from 15 % up to a peak of 25 %; the remaining gas being N_2. The temperature curve also shows that high flushing reduce the availability of oxygen, as well the carbon concentration in the waste mass. As a result the esothermic energy production and temperature decrease. Gas quality and temperature data provide confirmation that in aeration of a PAF landfill the semi-aerobic and flushing phase should be carefully balanced.

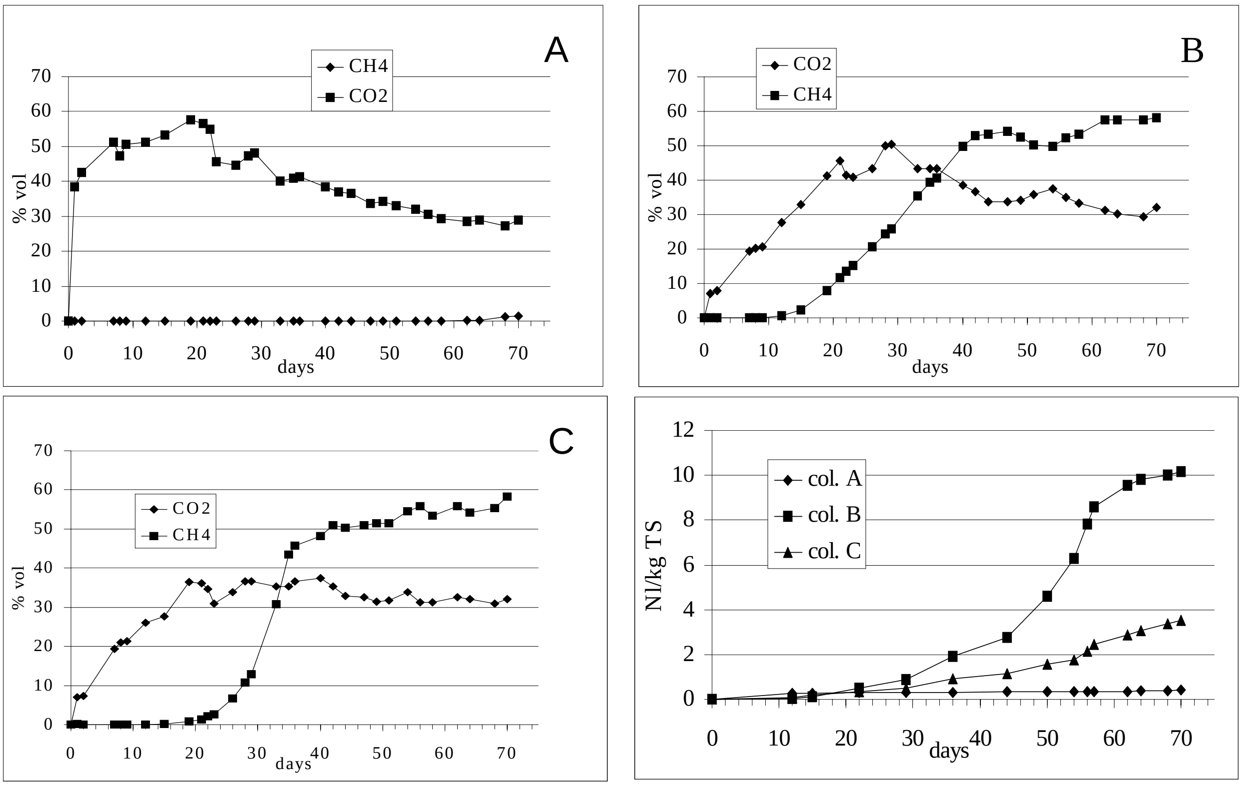

Figure 9. Evolution of gas composition in the three anaerobic columns (A,B,C) and cumulative gas production in the same columns

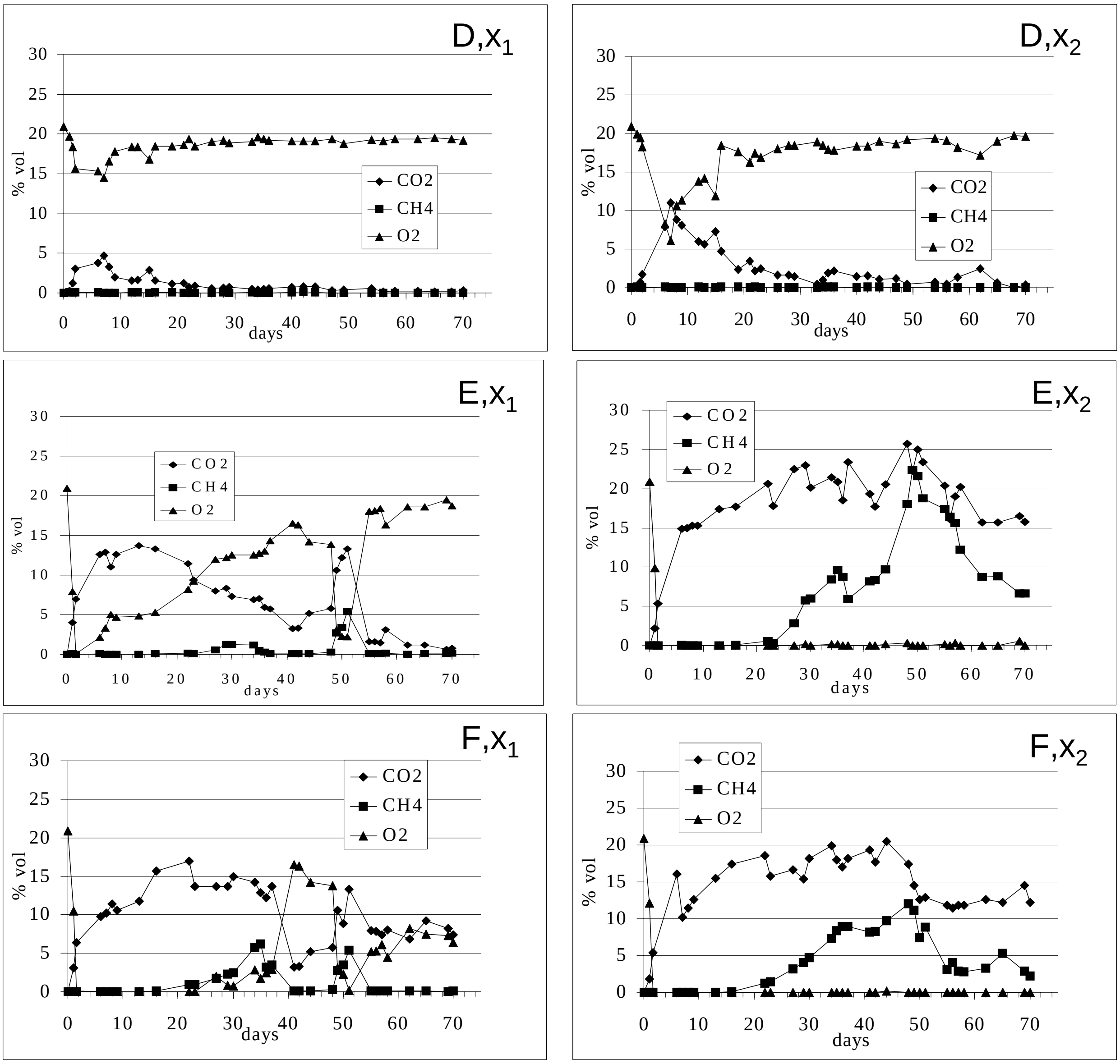

Figure 10. Evolution of gas composition at the two measuring points along the height of the three aerobic columns (D,E,F). x1 and x2 are the two measuring points of the columns, the first close to the head and the second close to the bottom of the individual column.

4. CONCLUSIONS

A comparison of the emissions from the six lab columns, operating according to different landfill concepts, and from a large lysimeter operating according to the PAF (Preatreated Aerobic Flushing) model indicate the following:

- the traditional anaerobic landfill with unprocessed waste shows the highest level of emissions, with high concentrations of BOD, COD and ammonia. Biogas production is delayed by the initial acid phase of biodegradation;
- MBP waste under anaerobic conditions presents a reduction of BOD_5, COD and ammonia, although concentrations observed still remain high (BOD_5 = 1500 mg/l);
- Methanogenesis is accelerated and the total gas production much higher than that generally observed with unprocessed waste;

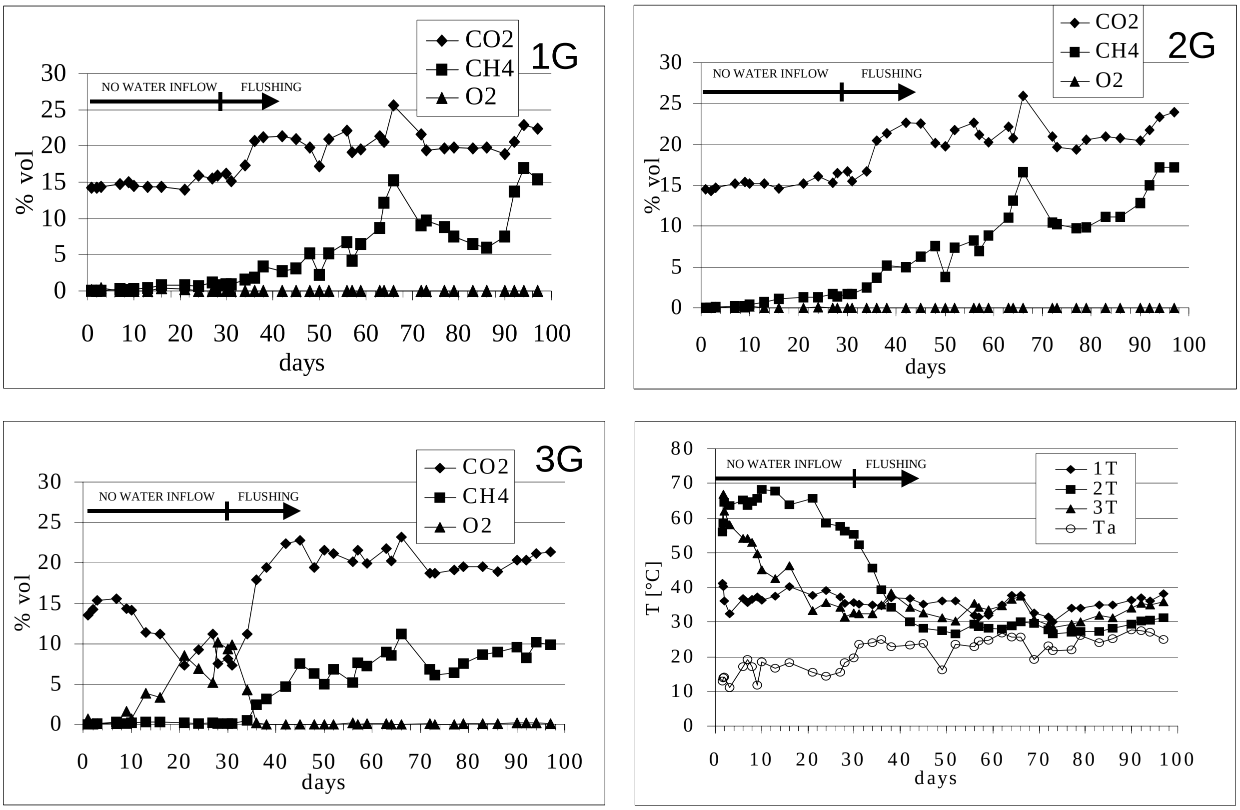

Figure 11. Evolution of gas composition and temperature at the three measuring points along the height of the lisymeter (Ta = ambient temperature).

- Flushing of MBP waste rapidly reduces the level of emissions for all parameters tested
- Aeration of the waste mass, either with forced aeration and in “semi-aerobic like” conditions, produces a rapid and marked oxidation of organics and nitrogen
- The combination of Pre-treatment, semi-aerobic conditions and flushing (PAF model), seems to optimize the advantage presented by the different individual options, achieving a more marked and quicker reduction of the concentrations and mass reduction in the residual waste. The two phases (semiaerobic conditions with flushing) should be careful balanced.
- Further studies are in progress in order to optimize the operational conditions of the PAF model, as well as to investigate the mechanical and hydraulic properties and fluidodynamic behaviour of the deposited waste mass.

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