Anaerobic Digestion of Petroleum Hydrocarbon (PHC) Waste

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Outline

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2. Overview
3. Methodology
4. Material characterization
5. Theoretical Estimation of landfill-gas
6. Experimental
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Introduction

- United Arab Emirates represents the seventh proven reserve of oil & gas worldwide and tenth largest producers of crude oil and natural gas. Crude oil exports amounted to 2,794 million barrels per day (bpd) and 54,245 million cubic meter natural gas in 2015
- Estimates show that daily production of 200–500 barrels of petrochemicals generates nearly 10,000 m^3 annually of sludge which creates environmental stress and pollution [1]
- The oily sludge is described as a remnants obtained from the water, oil, fat , solids and organic compounds.
- Different treatment methods, such as incineration, pyrolysis, landfilling, and biodegradation have been explored to deal with such oily sludge waste
- In Abu Dhabi, BeAAT a specialized treatment facility for petroleum waste, was established to safely receive, manage, treat and dispose hazardous waste generated by ADNOC Group and to ensure that human health and the environment are adequately protected
- BeAAT methods of treatment focus on thermochemical and stabilize landfilling. This work focus on the anaerobic PHC decomposition in bioreactor for the generation of landfill gas side to/or an alternative to the thermal method

[1]A. Gafarov, A. Panov, A. Filonov, and A. Boronin, "Change in the composition of a bacterial association degrading aromatic compounds during oil sludge detoxification in a continuous-flow microbial reactor," *Applied Biochemistry and Microbiology,* vol. 42, pp. 160-165, 2006.

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Introduction (Cont'd)

Petroleum Waste in Abu Dhabi is processed by BeAAT which is a subsidiary of Takreer, the national refinery company of Abu Dhabi, BeAAT is specialized in the treatment of hazardous waste. On a yearly basis they receive:

- Drill cuttings from Off-shore: ~ 2500 tons/year
- Contaminated Soil from On-shore: ~ 4500 tons/year

Treatment Method	Quantity	Characteristics
Solidification	10,000 tones / year	Spent catalyst, ceramic balls, inorganic wastes
Centrifugation	5,000 tones / year	Wastewater treatment sludge, PHC sludge, API separator sludge
Thermal Desorption	7,000 tones/year	Drill cuttings, contaminated soil
Incineration	5,500 tones / year	Organic wastes
Physical/Chemical Treatment	35 tones / year	Acidic and alkaline waste
Mercury Distillation	50 tones /year	Mercury
Landfill Class I & II	85,000 m^3 total capacity	All wastes treated by other units
Evaporation Pond	3,000 m3 total capacity	Drill cuttings
TOTAL throughput (design)	25,000 t/year	All the above

A. R. A. Hosni, "An overview of beaat plant," *Japan environment symposium,* 2013.

Overview

Literature Review

- Bioreactor landfilling is the state of the art technique of landfilling that speeds up the degradation of solid wastes by controlling the moisture content via leachate recirculation and water addition.

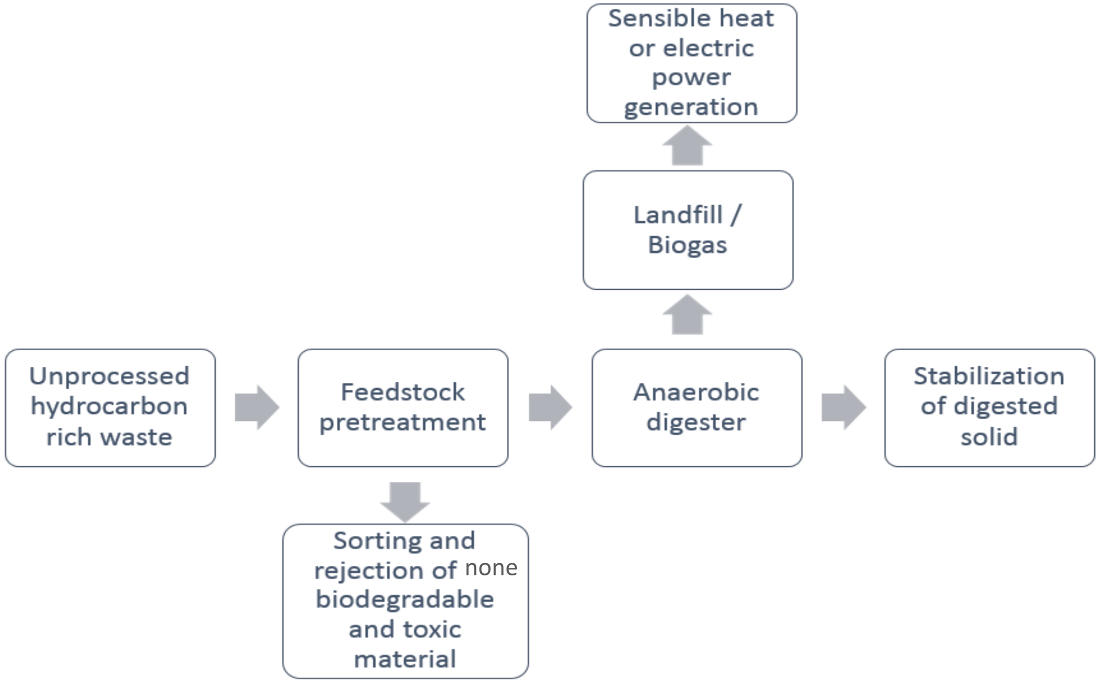
- While, the conventional landfill (dry tomb) works by reducing the moisture content of the landfill in order to lower its leachate and LFG emissions albeit it still persist at low rates, causing slowness in the degradation of wastes and occupying more space than bioreactor landfills.

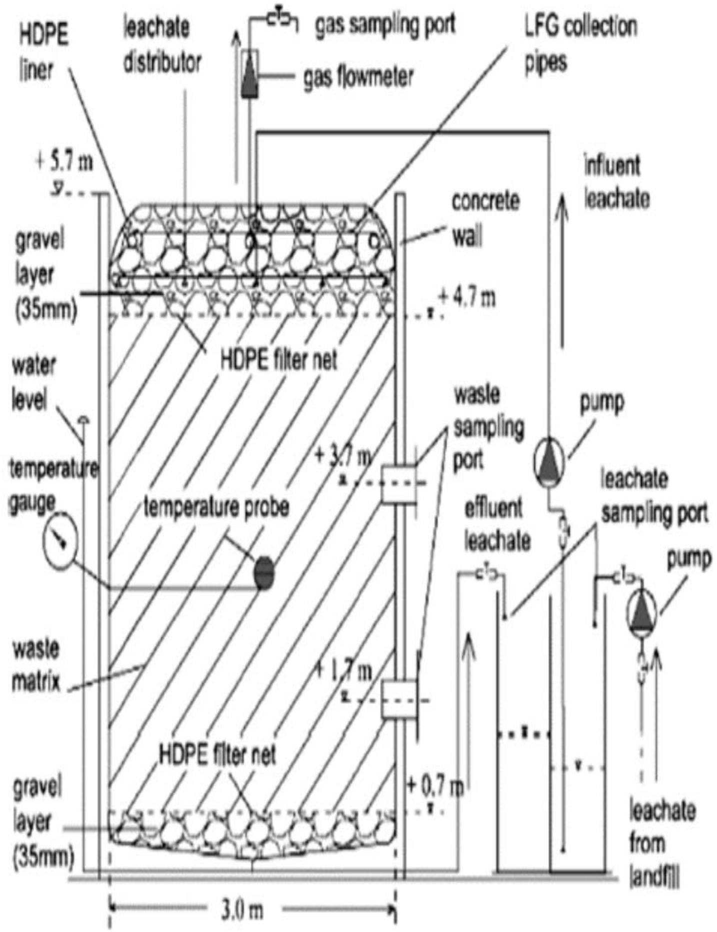
- Anaerobic digestion has been the best waste management practice used for both pollution control and energy recovery. Many agricultural and industrial wastes contain high levels of easily biodegradable materials and thus are ideal for anaerobic digestion

Type of Anaerobic Digestion	Temperature	Substrate	SMY (L kg^{-1})	Reference
Mesophilic & Thermophile	35-65	Cattle manure	240-280	Varel (1980) [7]
Physrophelic	20	Cow feces	184.5 ± 24	Saady and Masse (2014) [6]
Thermophile	65	Cattle manure	165	Ahring (2001)[8]
Mesophilic	30	Dairy cattle manure	164	Shyam (2002)[9]
Mesophilic	35	Dairy cattle feces	148 ± 41	Moller (2004) [10]
Mesophilic	30	Dairy cattle manure	135	Somayaji Khanna (1994)[11]
Physrophelic		Beef cattle manure	85	Schäfer (2006)[5]
Mesophilic	35	Refinery Residuals	-	Nasirpour, N. et al. [12]

[5] Schäfer, W., Lehto, M., Teye, F., 2006. Dry anaerobic digestion of organic residues onfarm – a feasibility study. Agrifood Research Reports 77. MTT Agrifood Research Finland. <http://www.mtt.fi/met/pdf/met77.pdf>.
[6] Massé, D., Saady, N. (2014). Psychrophilic dry anaerobic digestion of dairy cow feces: Long-term operation. Waste Management, 36(2015), 86–92-86–92.
[7] Varel, V.H., Hashimoto, A.G., Chen, Y.R., 1980. Effect of temperature and retention time on methane production from beef cattle waste. Appl. Environ. Microbiol. 40, 217–222.

Methodology

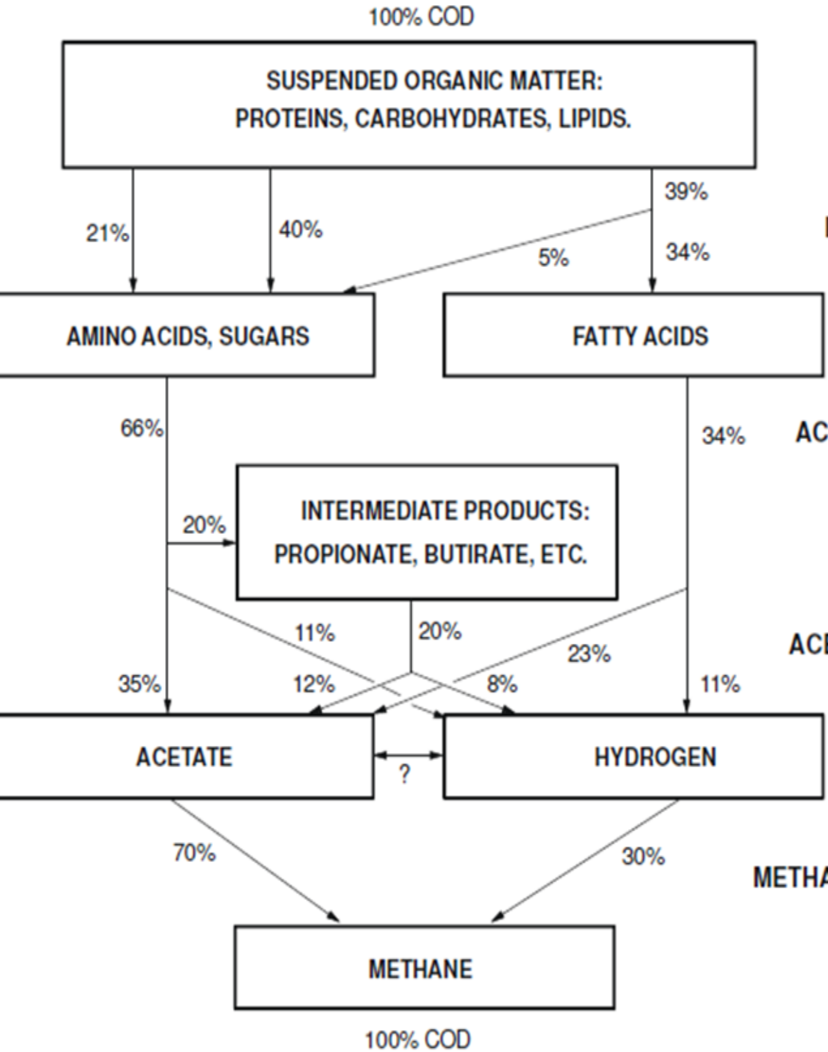




- Bioreactor landfill has the potential to fully degrade waste in ten years instead of many decades as the case of classical dry tomb landfill. It generates faster Landfill gas (LFG) for fuel utilization.

Methodology

Theoretical



HYDROLYSIS In the hydrolysis step, the complex organic compounds are solubilized and converted into smaller sized organic compounds by extracellular enzymes.

$$(C_6H_{10}O_5)n + n\ H_2O \rightarrow n\ C_6H_{12}O_6$$

$$C_6H_{12}O_6 \rightarrow CH_3\ (CH_2)2\ COOH + 2H_2 + 2\ CO_2$$

ACIDOGENESIS The organic acids are then broken into acetic acid.

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2\ CH_3CH_2COOH + 2H_2O$$

$$C_6H_{12}O_6 + 2\ H_2O \rightarrow 2CH_3COOH + 4H_2 + CO_2$$

ACETOGENESIS In this stage, conversion of propionic and butyric acids into acetic acid occurs as described in the following reactions

$$CH_3(CH_2)_2COOH + 2H_2O \rightarrow 2\ CH_3COOH + 2\ H_2$$

$$CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + 3\ H_2 + CO_2$$

METHANOGENESIS Final conversion stage in which the formation of methane gas either from acetate or carbon dioxide reduction, it takes place following these equations

$$CH_3COOH \rightarrow CH_4 + CO2$$

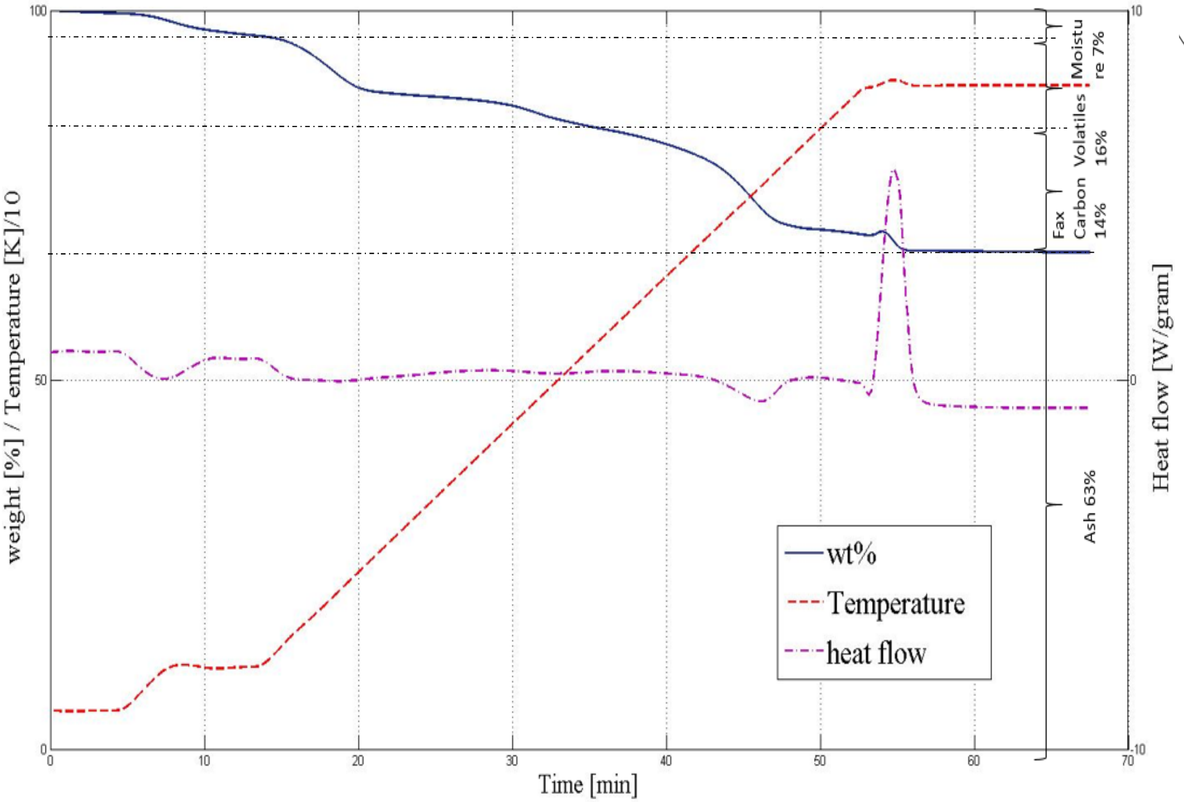
$$4H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O_2$$

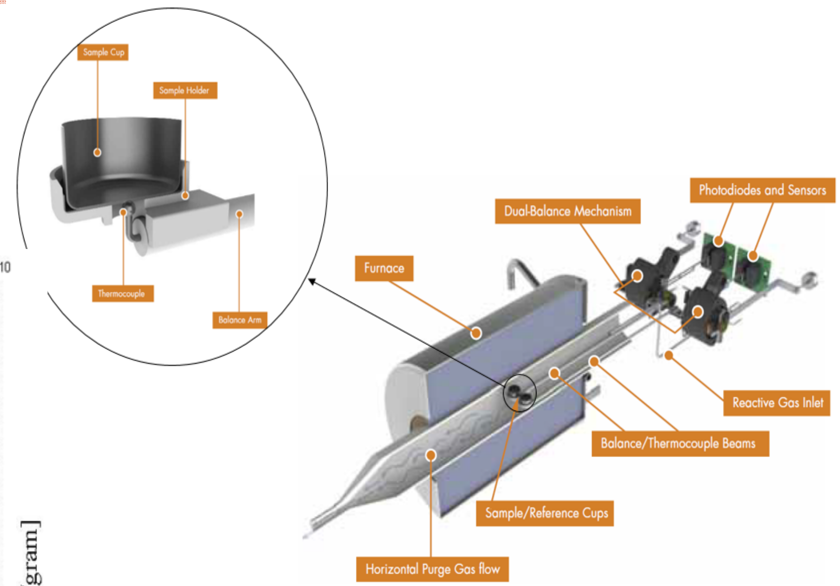
Material characterization

Proximate analysis

Thermo-Gravimetric Analysis (TGA)

- 4 different batches tested 3 times.

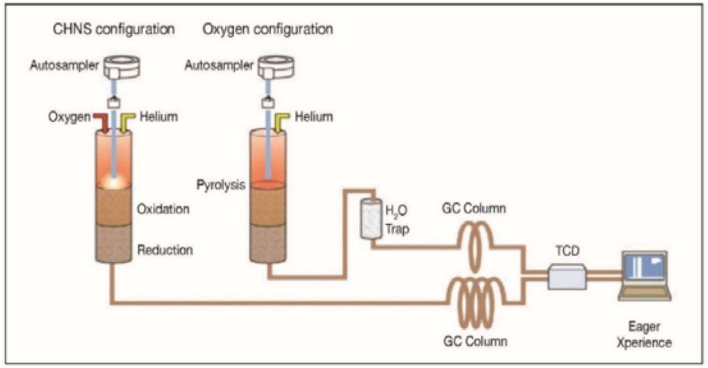




Batch	Moisture [wt%]	Volatiles [wt%]	Fixed carbon [wt%]	Ash [wt%]
Sample 1	7	16	14	63
Sample 2	6	16	13	65
Sample 3	10	21	17	52
Sample 4	12	18	14	56
Average	9	17	14	60
St. Dev. σ	2.63	2.34	1.92	6.34

Material characterization
Ultimate analysis

The volatile matter of the petroleum waste consisted primarily of five elements: carbon, hydrogen, nitrogen, oxygen and sulfur



Account for H_2 Weight Fraction in Moisture:

$$MF_H = WF_{H_2O} \frac{2M_H}{M_{H_2O}} * W\,F_{moisture}$$

O_2 found by difference:

$$WF_O = 1 - WF_C - WF_H - WF_N - WF_S - WF_{moisture} - WF_{ash}$$

Molar Composition:

$$MC_i = \frac{MC_i}{MC_C}$$

Normalizing for Carbon:

$$MC_{1,norm} = \frac{MC_1}{MC_c}$$

Element	Sample 1	Sample 2	Sample 3	Sample 4	Average
C [wt.%]	14.4	13.1	18.3	20.2	16.5
H [wt.%]	1.4	1.3	1.2	1.4	1.3
O [wt.%]	9.2	14.0	17.9	9.7	12.7
N [wt.%]	0.1	0.0	0.0	0.2	0.1
S [wt.%]	1.1	0.6	0.3	0.2	0.6
H2O [wt.%]	7.1	5.7	10.2	12.0	8.6
Ash [wt.%]	63	65.2	52.1	56.1	60.2
Molecular Formula	$CH_{1.138}O_{0.477}N_{0.004}S_{0.029}$	$CH_{1.151}O_{0.802}N_{0.003}S_{0.016}$	$CH_{0.749}O_{0.730}N_{0.001}S_{0.007}$	$CH_{0.821}O_{0.361}N_{0.007}S_{0.007}$	$CH_{0.965}O_{0.593}N_{0.004}S_{0.015}$
M [kg/kmol]	21.77 2	6.53	24.66	18.93	22.97

Theoretical Estimation of landfill-gas

To estimate the rate of production of methane Numerous samples of the PHC sludge from BeAAT were obtained and subjected to homogenization. This is followed with TGA proximate and Flash200 elemental analyses. The estimated theoretical yield follows the biodegradation stoichiometric following equation:

$$C_aH_bO_cN_d + \left(\frac{4a-b-2c-3d}{4}\right)H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right)CH_4 + \left(\frac{4a-d+2c+3d}{8}\right)CO_2 + dHN_3$$

Waste Stream	Molecular formula	Moisture	Volatiles solid	Ash
PHC	$CH_{0.965}O_{0.593}N_{0.004}$	9%	17%	60%
WWTS	$CH_{0.091}O_{0.565}N_{0.2}$	62%	27%	5%
MSW	$CH_{1.58}O_{0.63}N_{0.016}$	12%	58%	22%

Anaerobic Gas Yield	PHC	WWTS	MSW	60% PHC & 40% WWTS
Weight of the methane (kg)	11.57	8.8	22.1	10.46
Weight of carbon dioxide (kg)	35.56	41.55	51.67	37.95
Volume of the methane (m^3)	7.32	5.56	13.97	6.61
Volume of carbon dioxide (m^3)	8.15	9.53	11.85	8.70
Percentage of the methane %	47.29	36.87	54.11	43.12
Percentage of carbon dioxide %	46.65	46.65	46.65	46.65
Total theoretical amount of landfill-gas generate (L kg^{-1})	13.4	49.027	111.2	27.65
Specific methane yield (N L CH_4 kg^{-1})	6.34	18.07	60.17	11.92

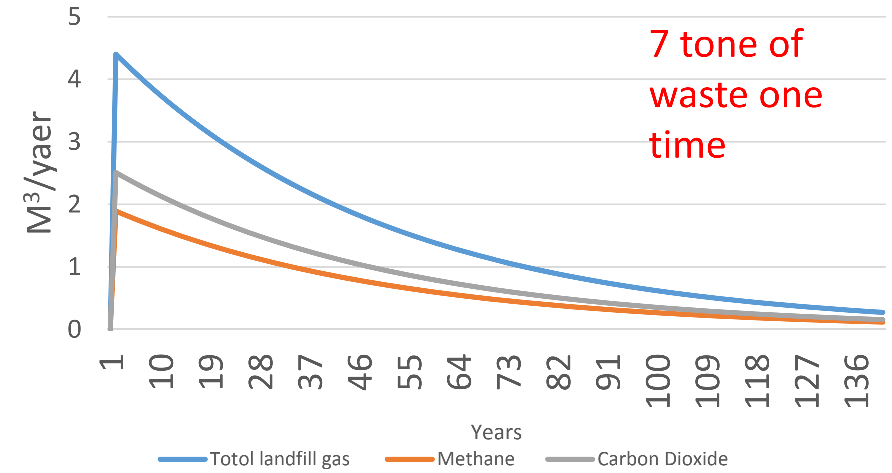
Theoretical Estimation of landfill-gas

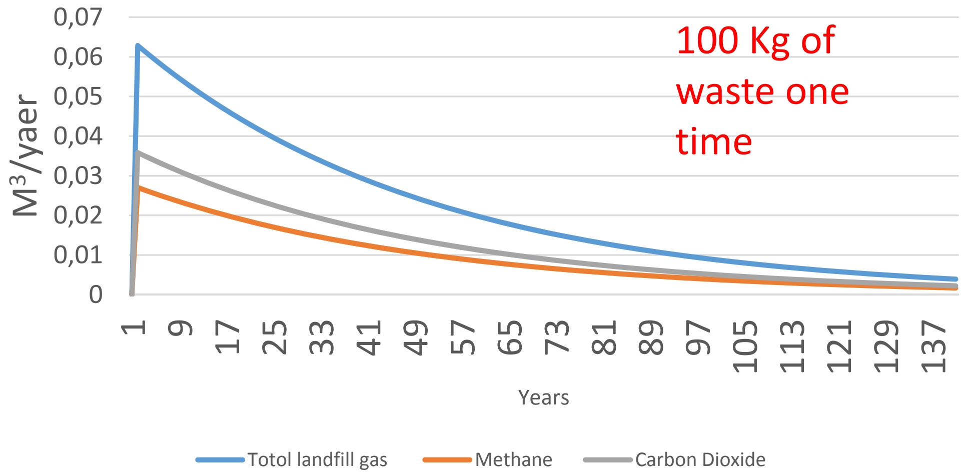
Landfill Gas Emissions Model

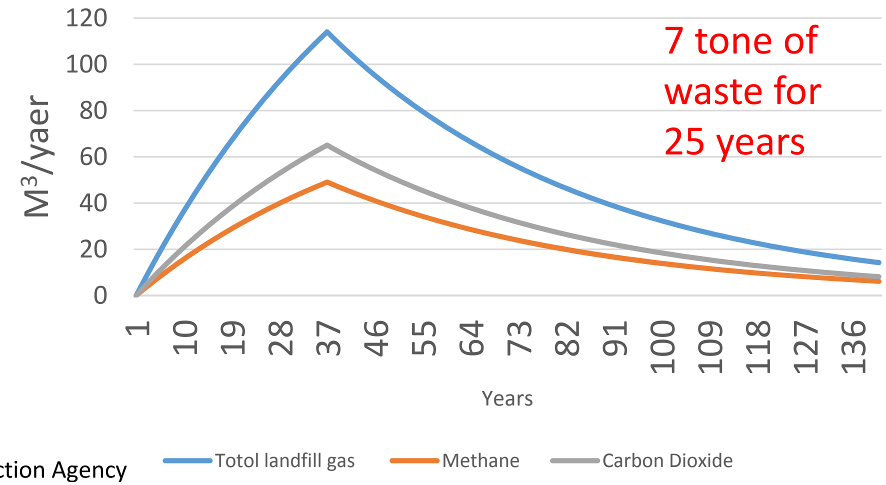
Landfill gas emissions model is used to simulate the gas generation as time elapsed in years or decades to come [13]. Theoretically obtained amount is compared to the landfill generation model created by USEPA.

Methane Generation Rate, k	0.02	year-1
Potential Methane Generation Capacity, Lo	15	m^3/Mg
NMOC Concentration	8000	ppmv as hexane
Methane Content	43	% by volume

$$Q_{CH_4} = \sum_{t=1}^{n} \sum_{j=0.1}^{1} K L_o \left[\frac{M_i}{10}\right] e^{-kt_{ij}}$$



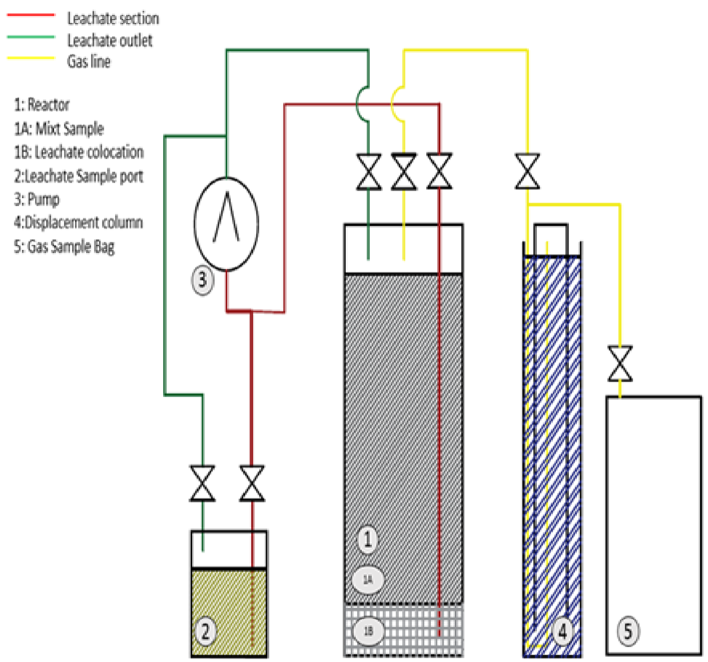


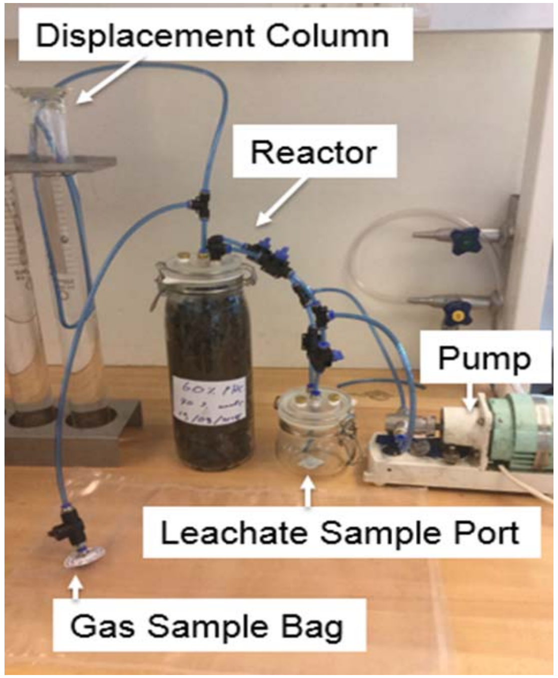


[13]Landfill Gas Emissions Model (LandGEM) Version 3.02, EPA United States Environmental Protection Agency

Experimental

Reactor Design EX1 and Set Up



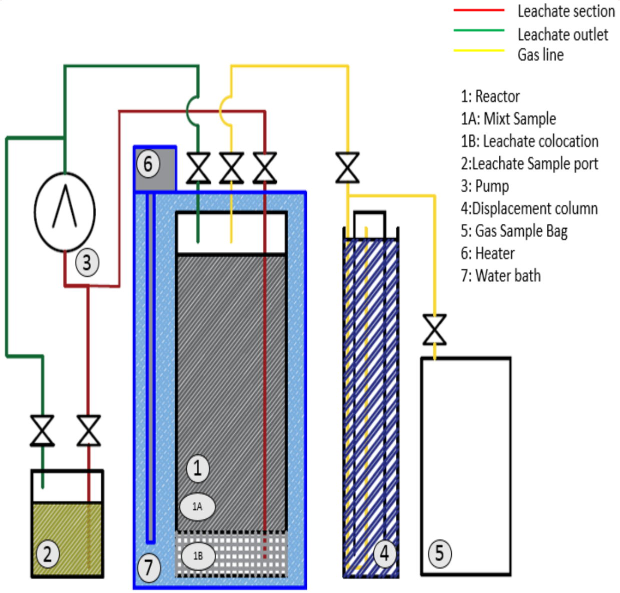


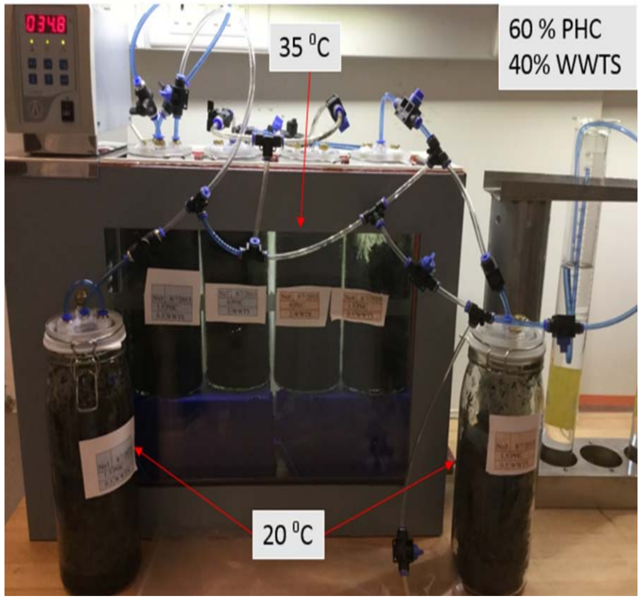
- Reactor design: Simple and low cost with three accessible inlets (leachate, moisture, gas)
- Displacement column design: Due to low mass flow ml/min improvising is needed
- Gas Analysis using Teflon toddler bags which directly fed to the GC/MS and Gasboard gas analyzer for appropriate species detections O_2, H_2S, CH_4, CO_2

Experiment	Reactor No	Addition Water L	PHC %	WWTS %	total weight kg	Weight of PHC kg	Weight of WWTS kg	Temperature °C
No 1	EX1R1	0	100	0	2.3	0	2.3	20
	EX1R2	0	70	30	2.3	1.61	0.69	20
	EX1R3	0	60	40	2.3	1.38	0.92	20
	EX1R4	0	50	50	2.3	1.15	1.15	20

Experimental

Reactor Design EX2 and Set Up



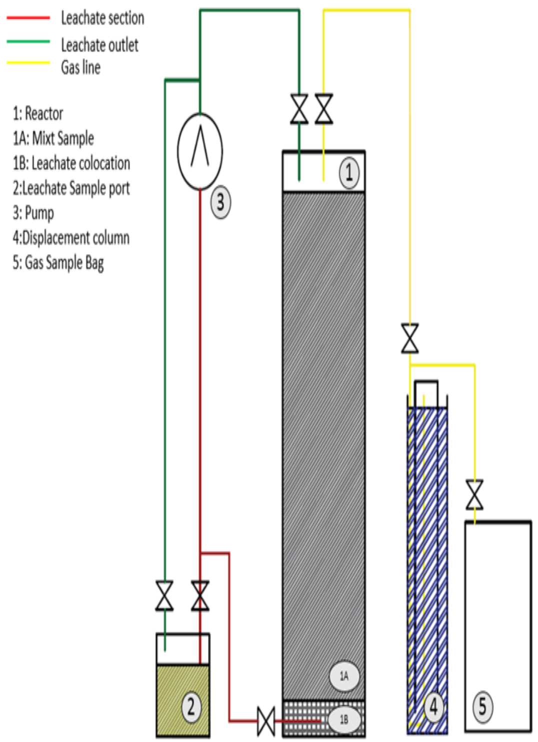


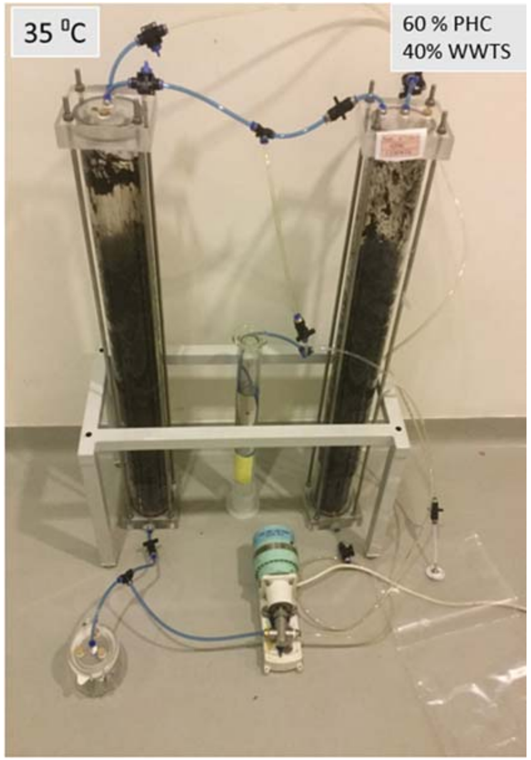
- Reactor design: Simple and low cost with three accessible inlets (leachate, moisture, gas)
- Displacement column design: Due to low mass flow ml/min improvising is needed
- Gas Analysis using Teflon toddler bags which directly fed to the GC/MS and Gasboard gas analyzer for appropriate species detections O_2, H_2S, CH_4, CO_2

Experiment	Reactor No	Addition Water L	Ratio		total weight kg	Weight of PHC kg	Weight of WWTS kg	Temperature °C
			PHC %	WWTS %				
No 2	EX2R1	1	60	40	2.3	1.38	0.92	20
	EX2R2	0	60	40	2.3	1.38	0.92	20
	EX2R3	1	60	40	2.3	1.38	0.92	35
	EX2R4	0	60	40	2.3	1.38	0.92	35
	EX2R5	1	0	100	2.3	0	2.3	35
	EX2R6	0	0	100	2.3	0	2.3	35

Experimental

Reactor Design EX3 and Set Up

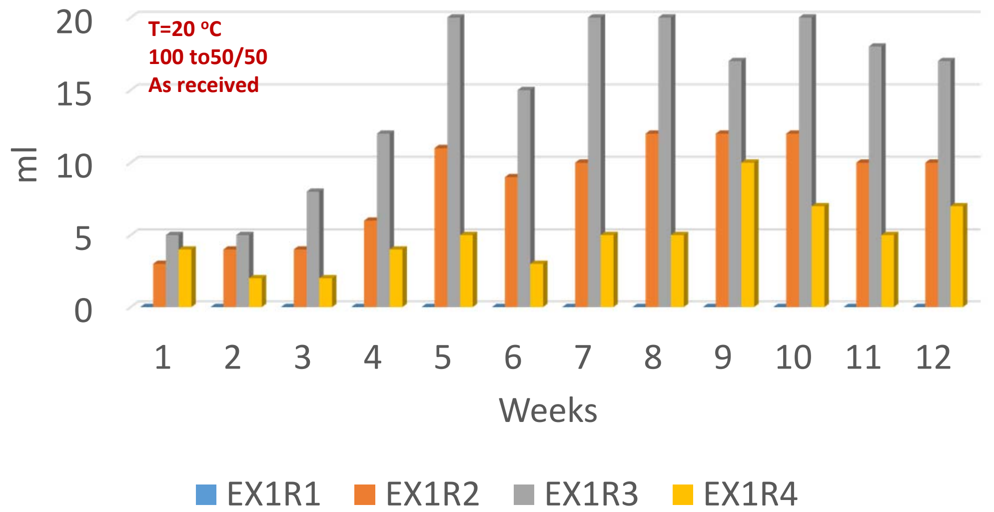


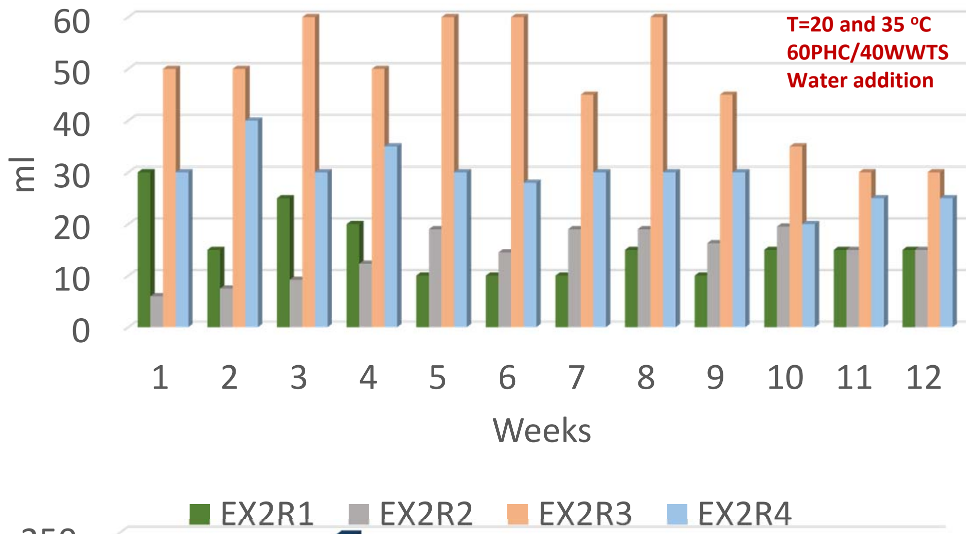


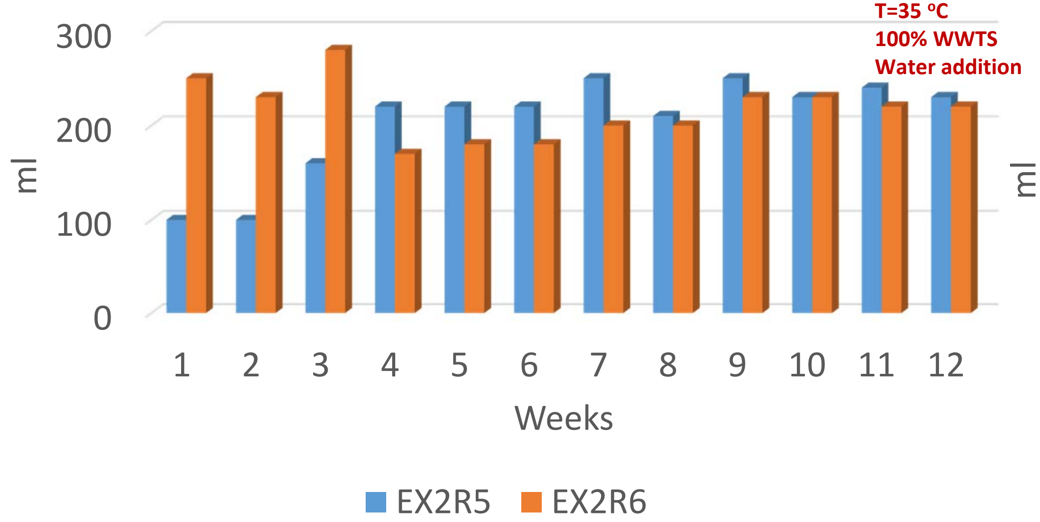
- Reactor design: Simple and low cost with three accessible inlets (leachate, moisture, gas)
- Displacement column design: Due to low mass flow ml/min improvising is needed
- Gas Analysis using Teflon toddler bags which directly fed to the GC/MS and Gasboard gas analyzer for appropriate species detections O_2, H_2S, CH_4, CO_2

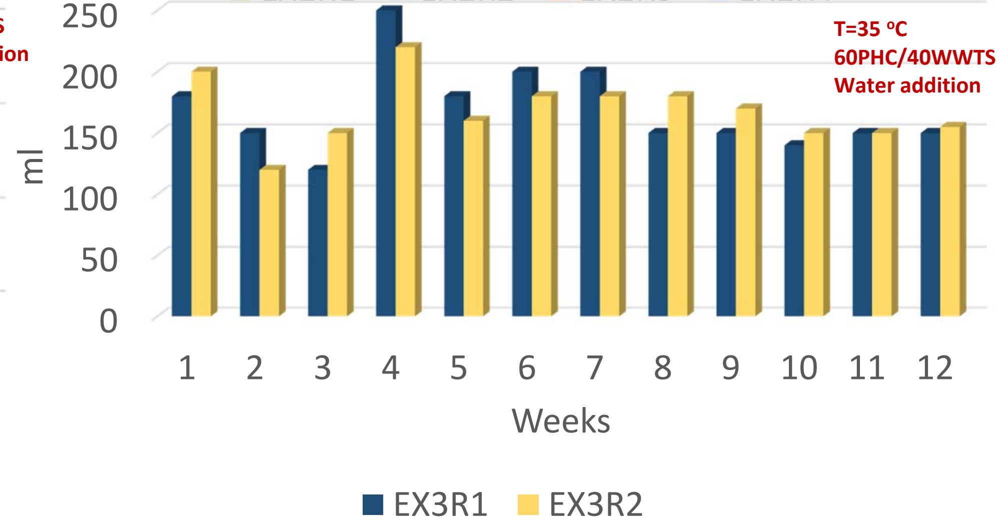
Experiment	Reactor No	Addition Water L	Ratio		total weight kg	Weight of PHC kg	Weight of WWTS kg	Temperature °C
			PHC %	WWTS %				
No 3	EX3R1	2.2	60	40	5.3	3.2	2.1	35
	EX3R2	0	60	40	5.3	3.2	2.1	35

Results
Landfill Gas production





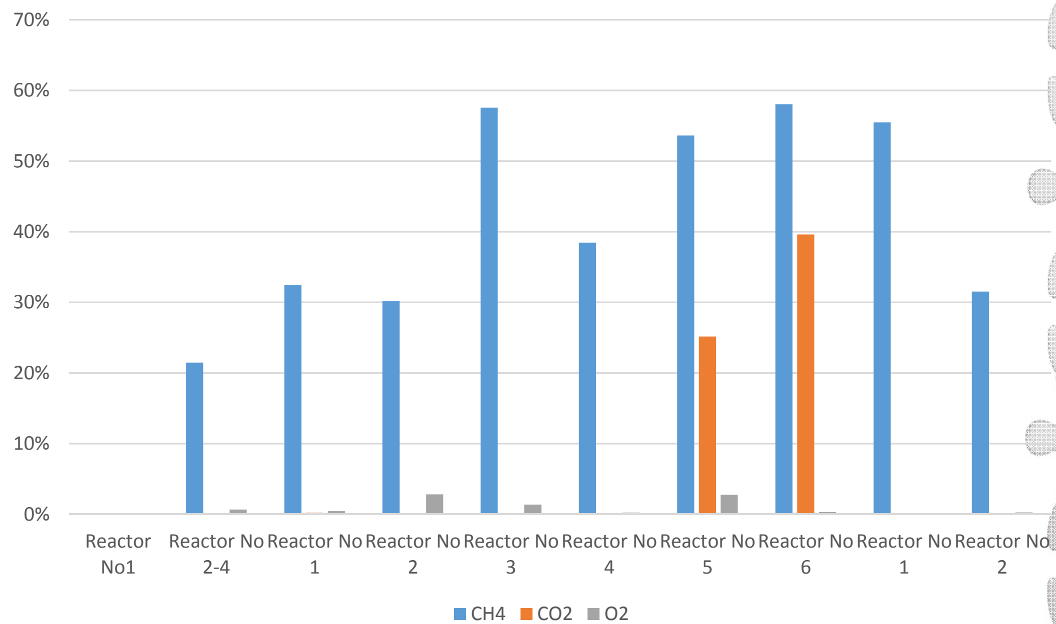




Results
Gas Analysis

Biogas volume produced was measured weekly using displacement column while gas analysis (Gasboard-3100P: CH_4, O_2, H_2S, CO_2) were measured monthly. Methane production is reported in normalized liters (N L CH_4).

Experiment	Reactor	CH_4	CO_2	O_2	H_2S
No 1	EX1R1	0%	0%	0%	0 PPM
	EX1R2-4	21.46%	0.16%	0.66%	17 PPM
No 2	EX2R1	32.47%	0.20%	0.43%	1 ppm
	EX2R2	30.18%	0.03%	2.82%	1 ppm
	EX2R3	57.56%	0.09%	1.36%	89 ppm
	EX2R4	38.45%	0.04%	0.23%	14 ppm
	EX2R5	53.61%	25.15%	2.74%	894 ppm
	EX2R6	58.05%	39.60%	0.29%	8580 ppm
No 3	EX3R1	55.47%	0.03%	0.03%	245 ppm
	EX3R2	31.51%	0.04%	0.25%	0 ppm



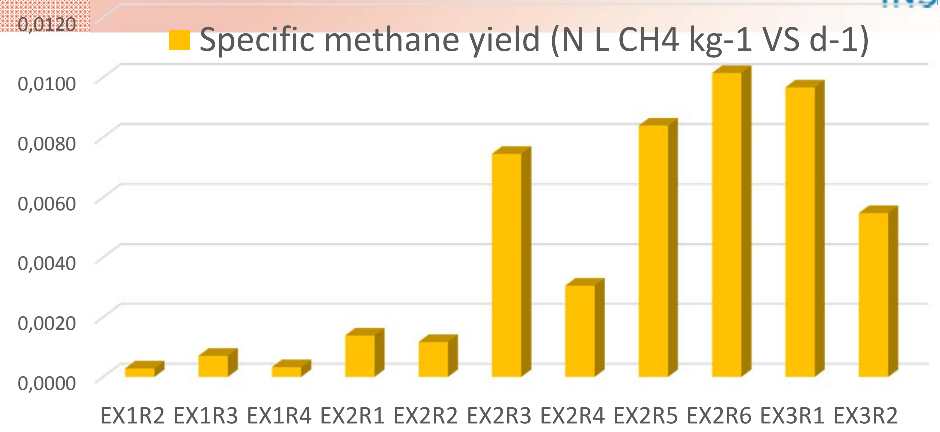
- No gas production at low temperature for 100%WWTS reactor
- Increase of weekly production following the induction period

Results

Specific methane yield (SMY)

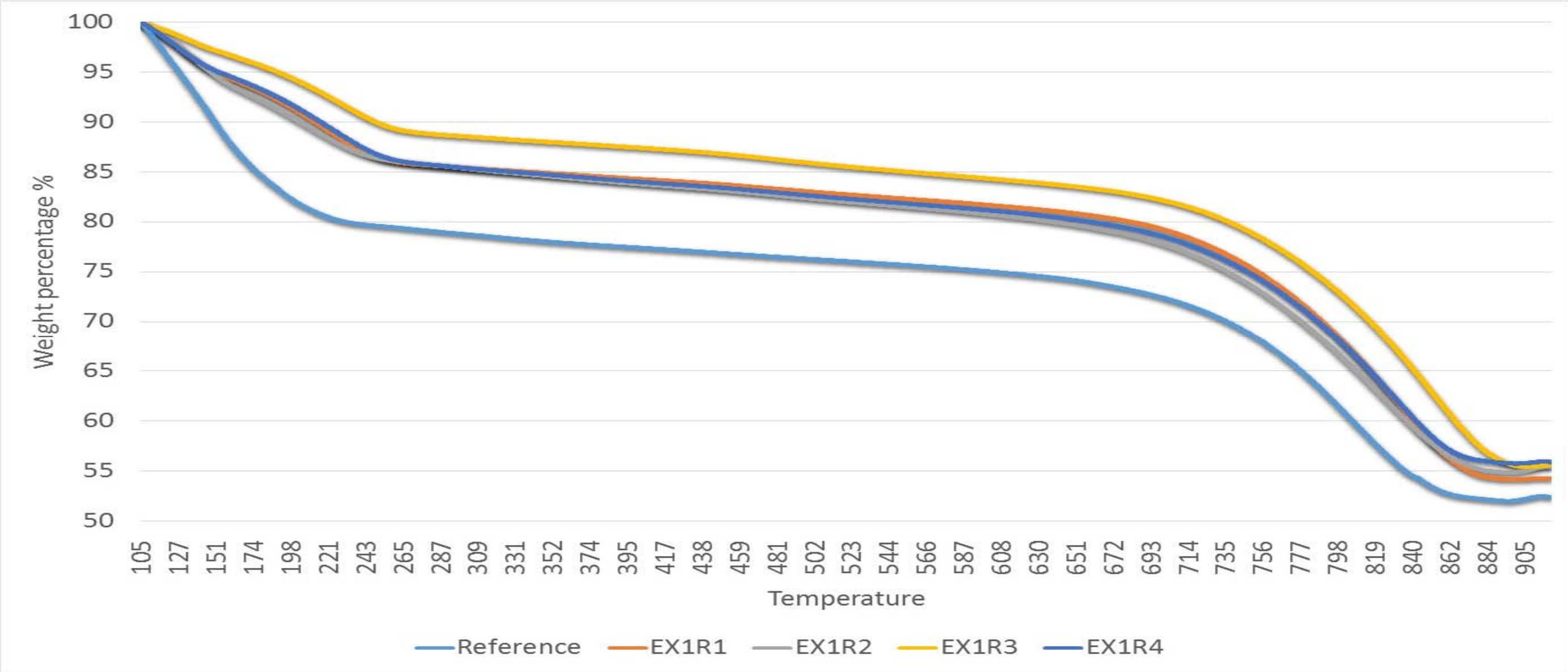
methane production is stated in normalized liters (N L CH4) total cumulative CH_4 yield was conventional. Specific CH_4 yield was calculated for each feed as the ratio of CH_4 produced over the mass of volatile solids (VS) fed to the reactor at the beginning of the cycle.

$$SMY = \frac{CH_4\ produced\ (liter)}{mass\ of\ volatile\ solids\ (kg)}$$



Experiment	Reactor Designation	Total Weight (kg)	Volatile solid (KG)	Bio-gas yield (L kg-1)	Specific methane yield (N L CH4 kg-1)	Specific methane yield VS (N L CH4 kg-1 VS)	Specific methane yield VS d-1 (N L CH4 kg-1 VS d-1)
N0 1	EX1R2	2.3	0.92	0.0448	0.0096	0.0240	0.0003
	EX1R3	2.3	0.621	0.0748	0.0160	0.0594	0.0007
	EX1R4	2.3	0.46	0.0257	0.0055	0.0275	0.0003
No 2	EX2R1	2.3	0.529	0.0826	0.0268	0.1166	0.0014
	EX2R2	2.3	0.529	0.0749	0.0226	0.0983	0.0012
	EX2R3	2.3	0.529	0.2500	0.1439	0.6257	0.0074
	EX2R4	2.3	0.529	0.1535	0.0590	0.2566	0.0031
	EX2R5	2.3	1.955	1.1174	0.5990	0.7047	0.0084
	EX2R6	2.3	1.955	1.2478	0.7244	0.8522	0.0101
No 3	EX3R1	5.3	1.38	1.1174	0.6198	1.0330	0.0074
	EX3R2	5.3	1.38	1.2478	0.3932	0.6553	0.0047

Results
PHC Bio-degradation



Proximate	Reference	EX1R1	EX1R2	EX1R3	EX1R4
Volatiles	23.16	16.16	16.86	13.21	15.27
Volatiles disintegration	---	30.22%	27.20%	42.96%	34.07%
Fix carbon	24.47	29.52	27.69	31.18	30.15
Ash	52.37	54.22	55.45	55.61	54.2
TPH disintegration		4%	5%	7%	5%

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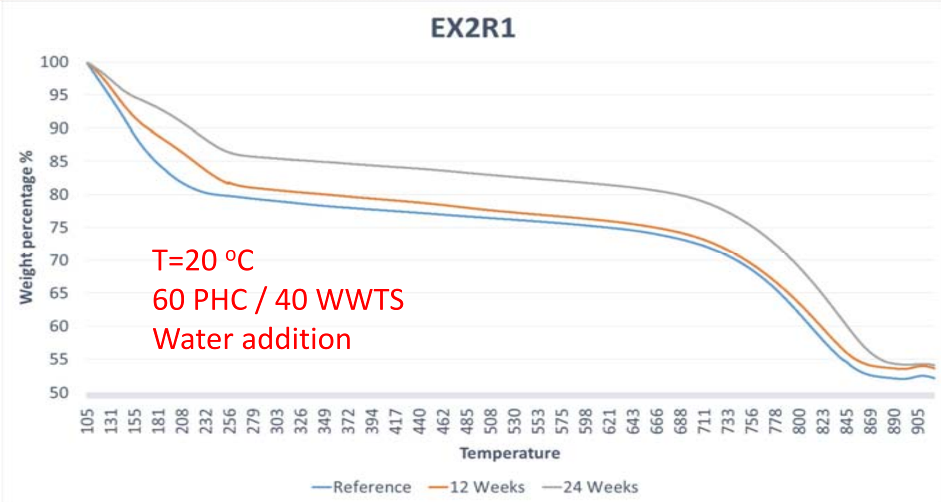
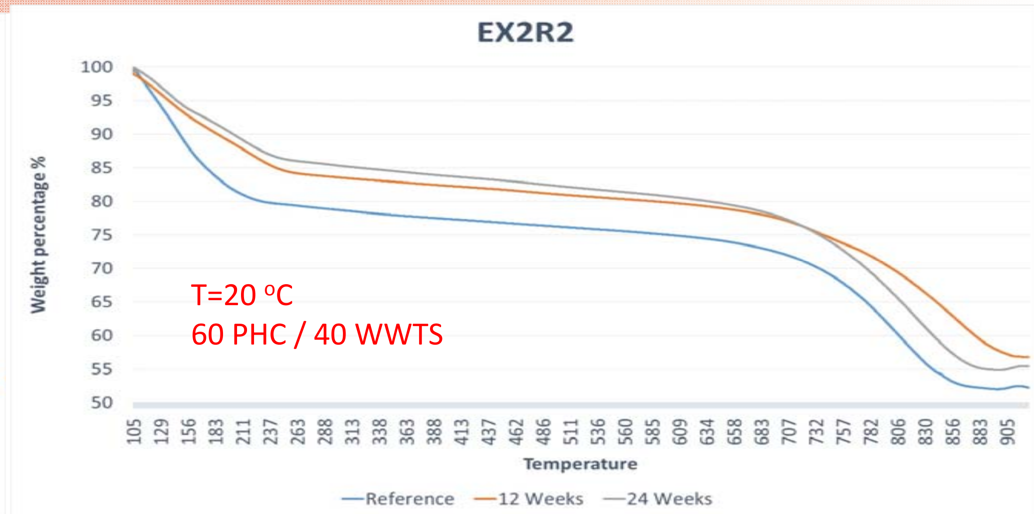
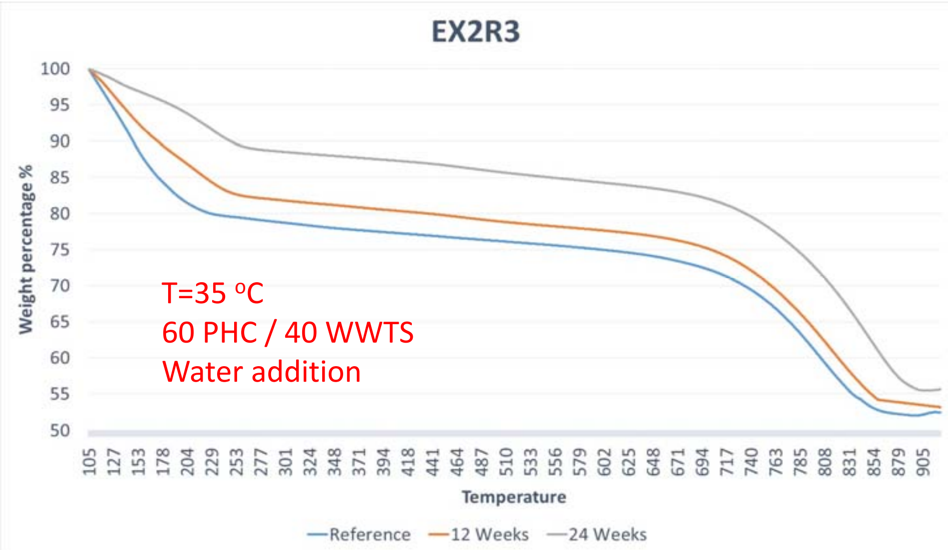
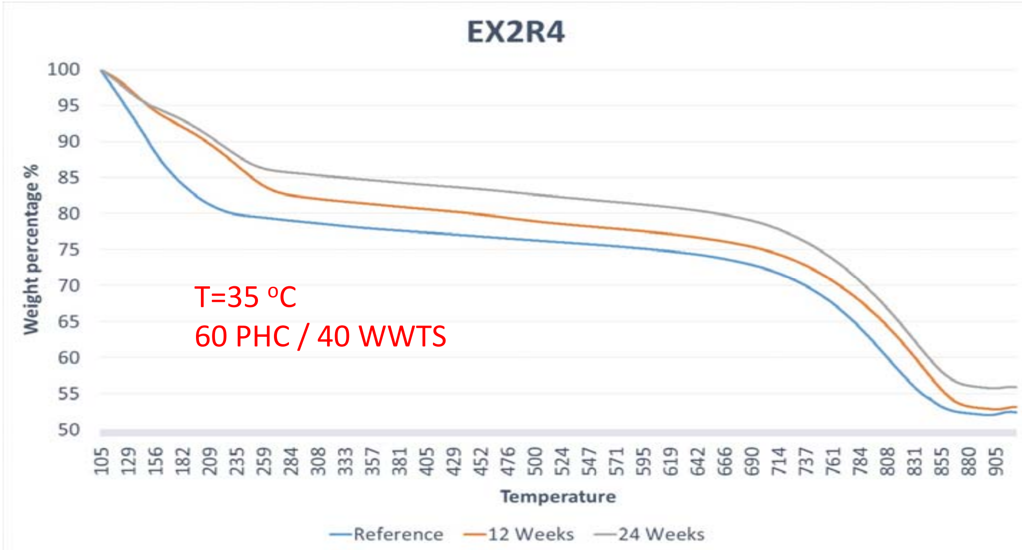
Results

PHC Bio-degradation Vs Time

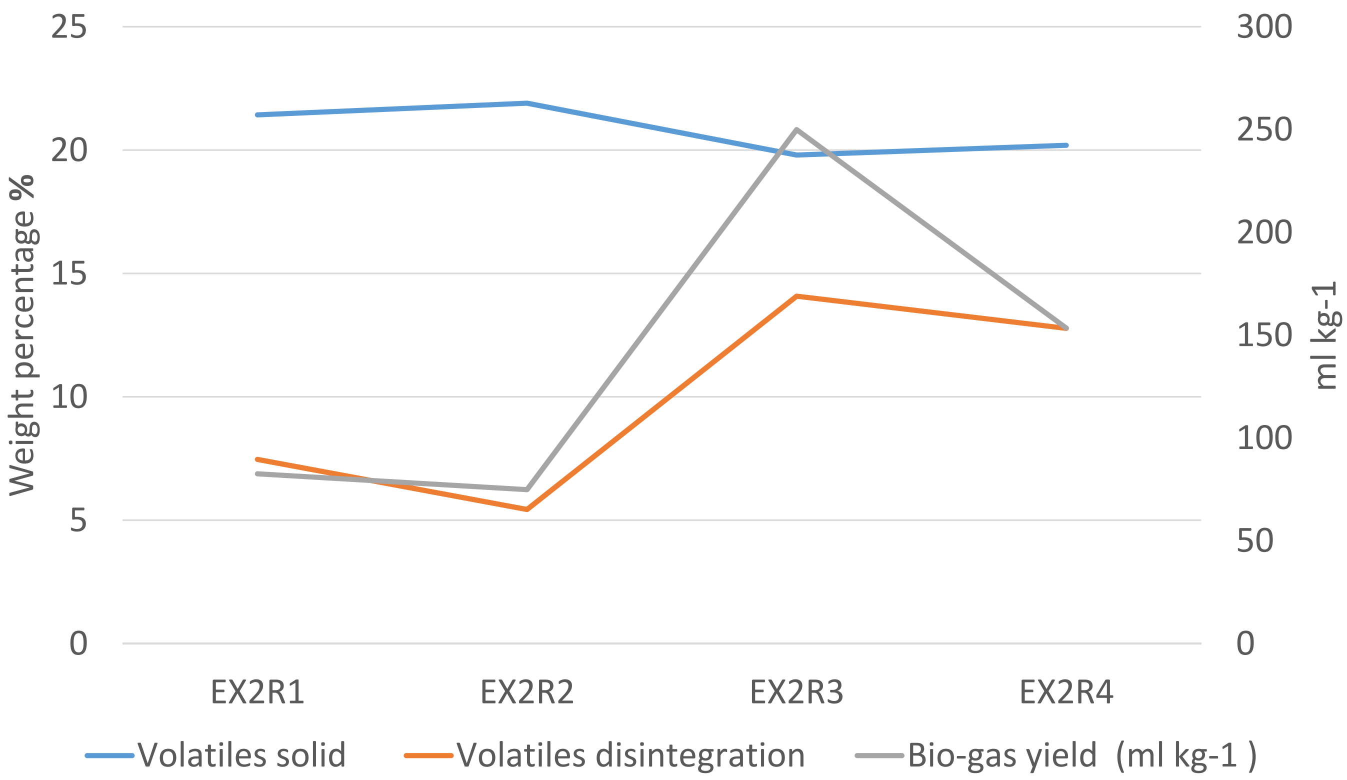








Results
PHC Bio-degradation Vs Gas production



Proximate	EX2R1	EX2R2	EX2R3	EX2R4
Volatiles solid	21.43	21.90	19.8	20.20
Volatiles disintegration	7.47%	5.44%	14.08%	12.78%
Bio-gas yield (ml kg-1)	82.6	74.9	250	153.5

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Conclusion and Future Work

- Estimation of landfill gas due to the anaerobic digestion of PHC waste is evaluated, which otherwise is destined to the landfill or thermochemical treatment pathways.
- Due to the low nutritional value of PHC co-digestion is required for practical reason.
- The co-digestion of PHC with MSW would enhance the biodegradation and the yield, the co-digestion with WWTS only enhances the biodegradation
- Preliminary Experimental results show that:
  - CH_4 is highest at 60%PHC and 40%WWTS
  - Mesophilic (~35 ^{o}C) achieves higher degradability than Physrophelic (~ 20 ^{o}C)
  - Larger reactor results in a higher specific Bio-gas yield.
  - Disintegration of PHC is 7% and volatiles disintegration 42.96% in higher Mesophilic (~35 ^{o}C) with 60%PHC and 40%WWTS
  - 63.3% efficiency of Landfill Gas Emissions Model (LandGEM) and 1.4% efficiency to theoretical estimation of landfill-gas in first three months
- The best SMY achieved was at 0.6198 (L CH_4 kg^{-1}), this however considered very small compared to the sited literature although for different feed.

Future work

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- Future work is concerned with maximizing the degradability of the PHC using:
  - Assess the feedstock as Inhibiters
  - New cultivated bacterial
  - Bio-stimulation
  - Electrostimulation
  - More expanded conditions of co-digestion, temperature, and water addition

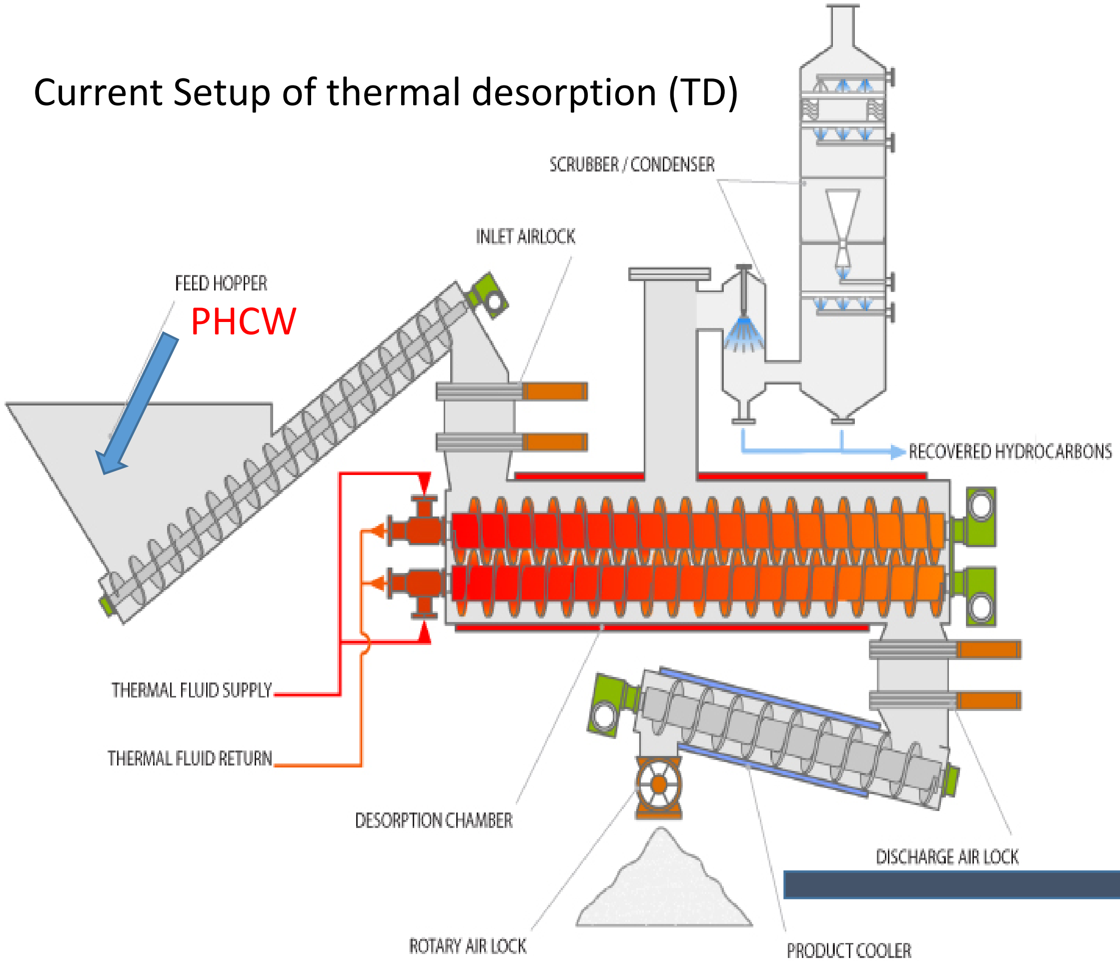
1 2 3 4 5 6 7 8

Thank You

Backup Slides

Overview
Thermal Desorption

Current Setup of thermal desorption (TD)

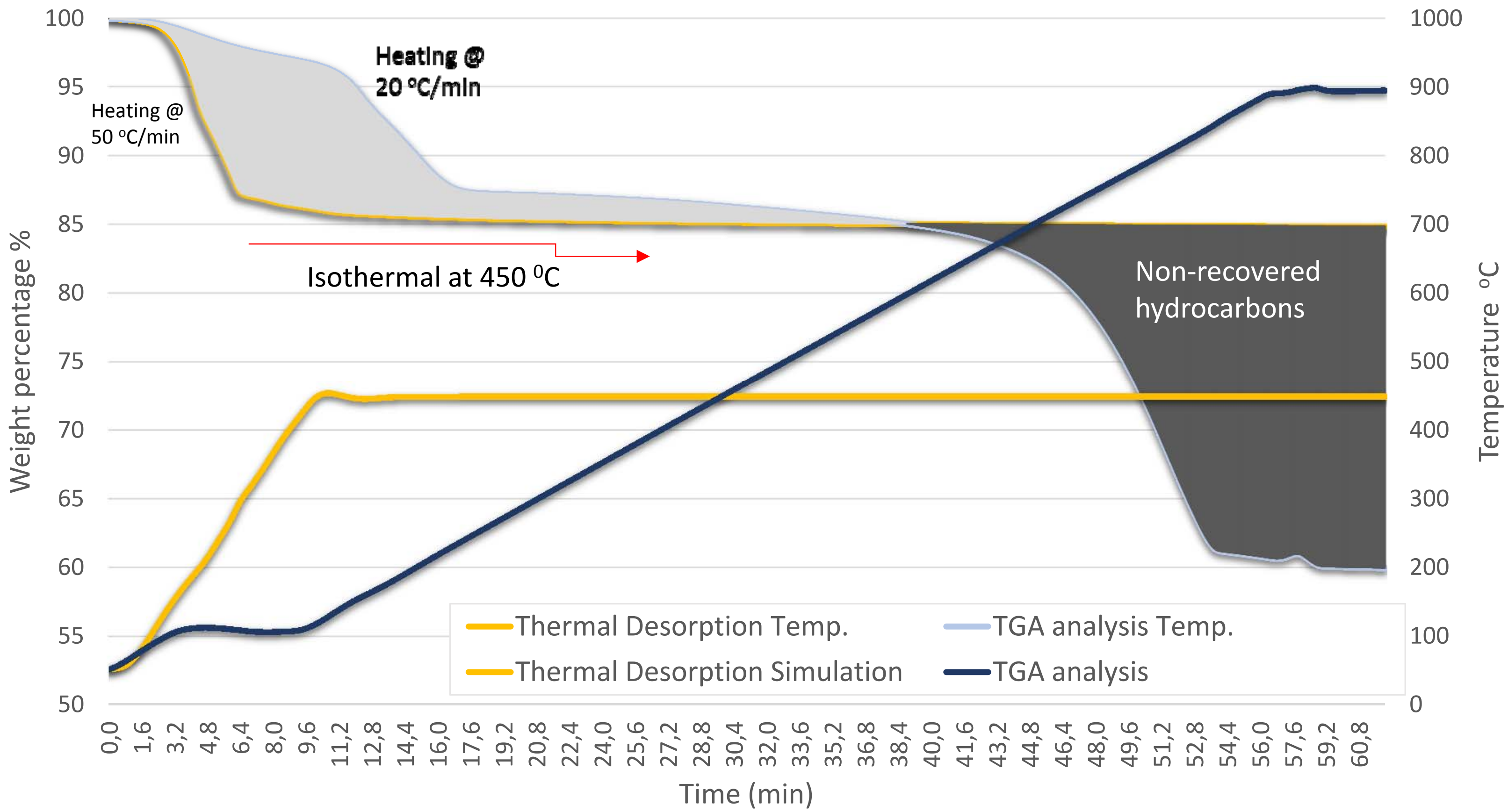


- Drill cuttings and Contaminated soil are mixed before entering the TD unit
- Anaerobic heating in a rotating drum at 450 ^{o}C
- Devolatilized gases are condensed to produce fuel oil
  - Non-condensable gases are fed to the Diesel burners
- Solids are solidified for stabilization and disposed in landfill

Typical Applications. (n.d.). Retrieved March 22, 2016, from http://www.therma-flite.com/ThermalDesorption.php

Overview

Simulation of Thermal Desorption Procedure



More then half of the organic matter is left unrecovered

Overview
Literature Review

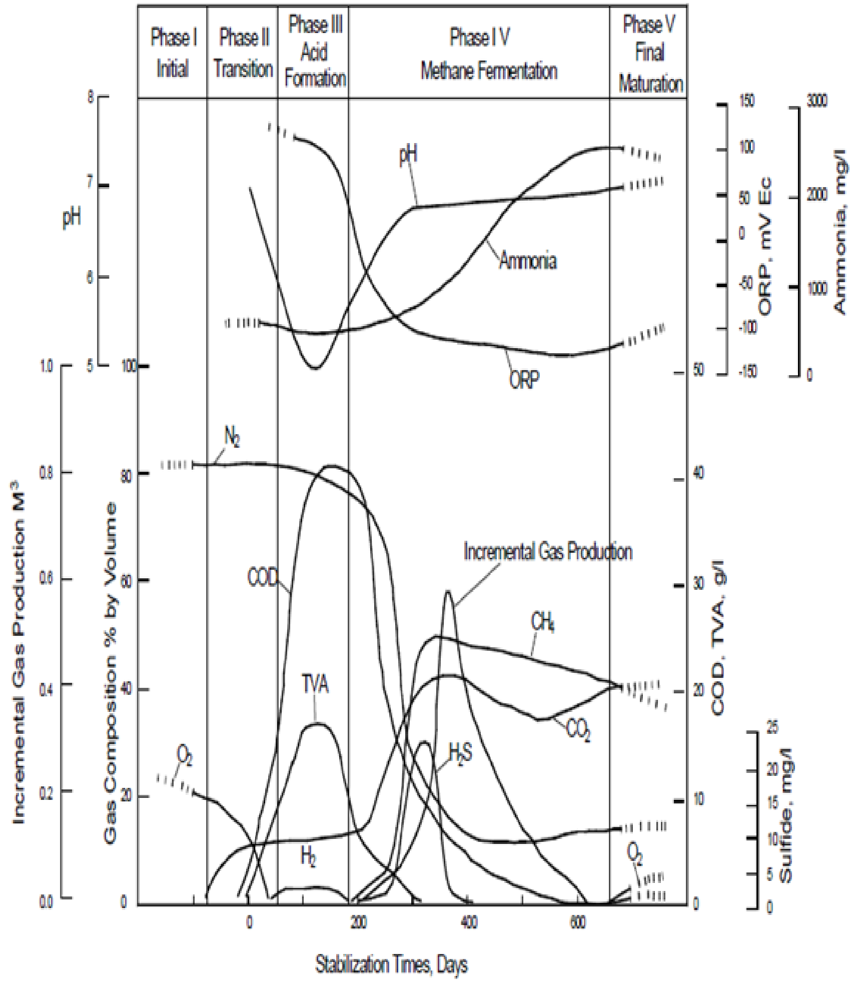
Bioremediation is the process of using microorganisms to remove environmental pollutants, and is commonly employed for the restoration of oil-polluted environments through accelerating the microbial degradation of PHCs. The most intensively studied bioremediation methods include:

- **Land treatment:** Involves the incorporation of wastes into soil and then the use of various processes to degrade contaminants in that soil. Biological activity usually accounts for most of the degradation of organic pollutants [2].
- **Bio-pile**: Involves turning of waste materials into piles (height of 2–4 m) for degradation by indigenous or extraneous micro-organisms. The piles may be static with installed aeration piping, or turned and mixed by special devices [3].
- **Bio-slurry treatment**: Reported to have faster pollutant removal than solid-phase treatment (e.g., land-farming and composting), and has been successfully applied to the cleanup of oil contaminated soils [4].

Method	TPH Removal Rate	Time Period	Capital cost	energy consumption
Land treatment	80%	12 months	Low	Low
Bio pile/composting	62%	12 month	Low	Low
Bio.slurry treatment	50%	One week	high	high

[2] J.A. Marin, T. Hernandez, C. Garcia, Bioremediation of oil refinery sludge by land farming in semiaridconditions: Influence on soil microbial

- The aerobic digestion stage takes place in a short period of time, its duration being determined by the amount of oxygen that is present in the waste. In turn. In this stage, the organic waste reacts with oxygen in the presence of aerobic bacteria to produce carbon dioxide, water, biomass and heat
- The first stage of the anaerobic biodegradation is hydrolysis. In the hydrolysis step, the complex organic compounds are solubilized and converted into smaller sized organic compounds by extracellular enzymes.
- The acidogenic process begins and the end products of hydrolysis are oxidized to organic acids. The organic acids are then broken into acetic acid.
- The formation of acetic acid in the acidogenic process marks the beginning of the acetogenesis stage. In this stage, conversion of propionic and butyric acids into acetic acid occurs as described in the following reactions
- The final stage, methanogenesis, involves the formation of methane either from acetate or carbon dioxide reduction with hydrogen, as shown in the following reactions



Overview
Inhibition of anaerobic digestion process

The main inhibitors present in an anaerobic process include:

1. **Ammonia**: is delivered by the organic debasement of the nitrogenous matter, for the most part as proteins and urea A few systems for ammonia inhibition have been proposed, for example, an adjustment in the intracellular pH, increment of support vitality prerequisite, and restraint of a particular enzyme reaction. To remove ammonia from the substrate, two physical–chemical techniques can be used: air stripping and compound precipitation

2. **Sulfide**: is a typical constituent of numerous industrial wastewaters. In anaerobic reactors, sulfate is lessened to sulfide by the sulfate decreasing microbes (SRB).

3. **light metals:** ions including sodium, potassium, calcium, and magnesium are available in the influent of anaerobic digesters. They may be discharged by the breakdown of organic matter, (for example, biomass), or included as pH alteration chemicals

4. **heavy metals:** can be available in significant amount in municipal sewage and sludge The heavy metals distinguished to be of specific concern incorporate chromium, iron, cobalt, copper, zinc, cadmium, and nickel

The following review provided a detailed summary on the inhibition of the anaerobic process while focusing on inhibition mechanisms, factors affecting inhibition and the problems that waste treatment process encounters. The main inhibitors in the anaerobic process include ammonia, sulfide, light metals, heavy metals and organics.

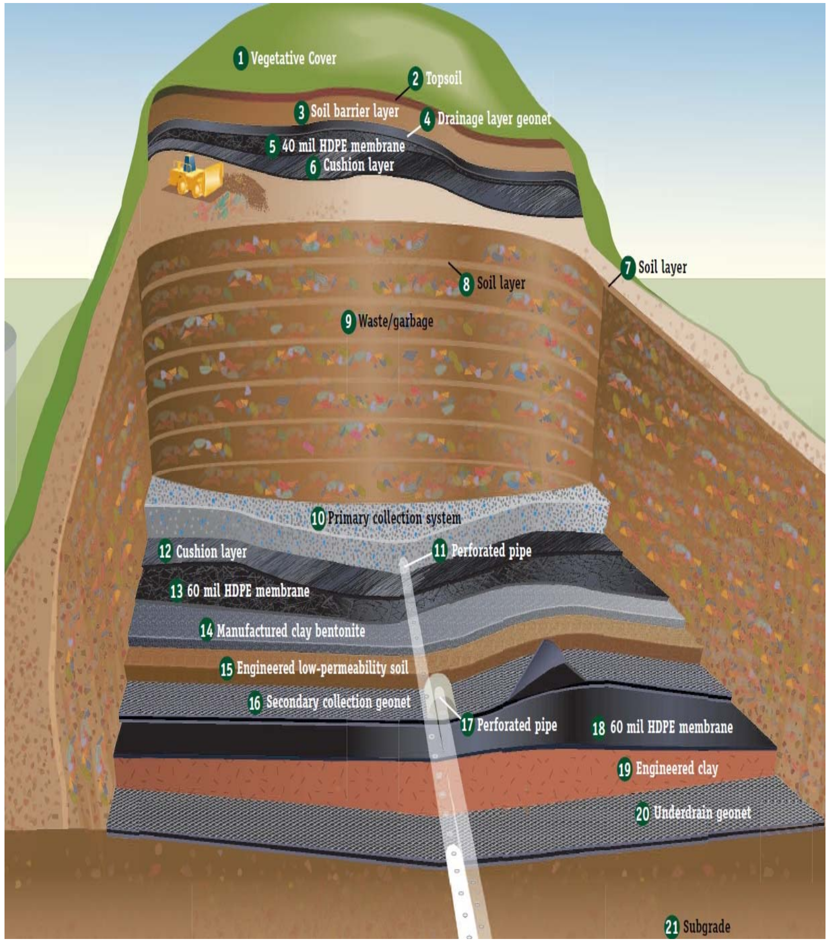
Waste water treatment sludge

40%

Drill cuttings, contaminated soil

60%

Landfill at BeAAT



Landfill Design

Niton™ XL3t GOLDD+ XRF Analyzer

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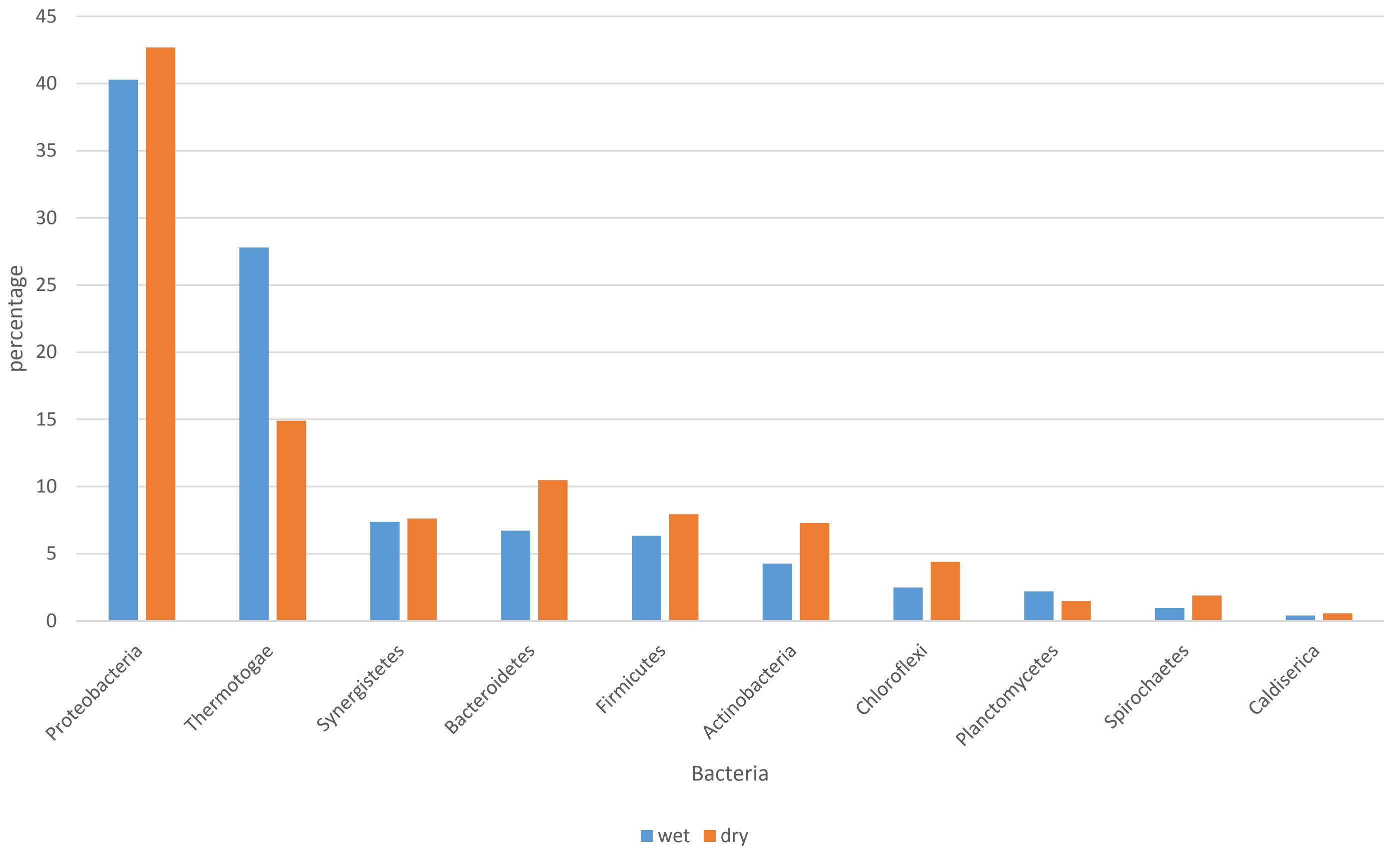
Industries from mining and exploration to scrap metal recycling depend on fast, accurate elemental analysis. The hand-held XRF device used was a Thermo Scientific Niton XL3t with the measurement of up to 25 simultaneous elements in the analytical range between sulphur (atomic number 16) and uranium (atomic number 92) as well as light elements (Mg, Al, Si, P, S and Cl).

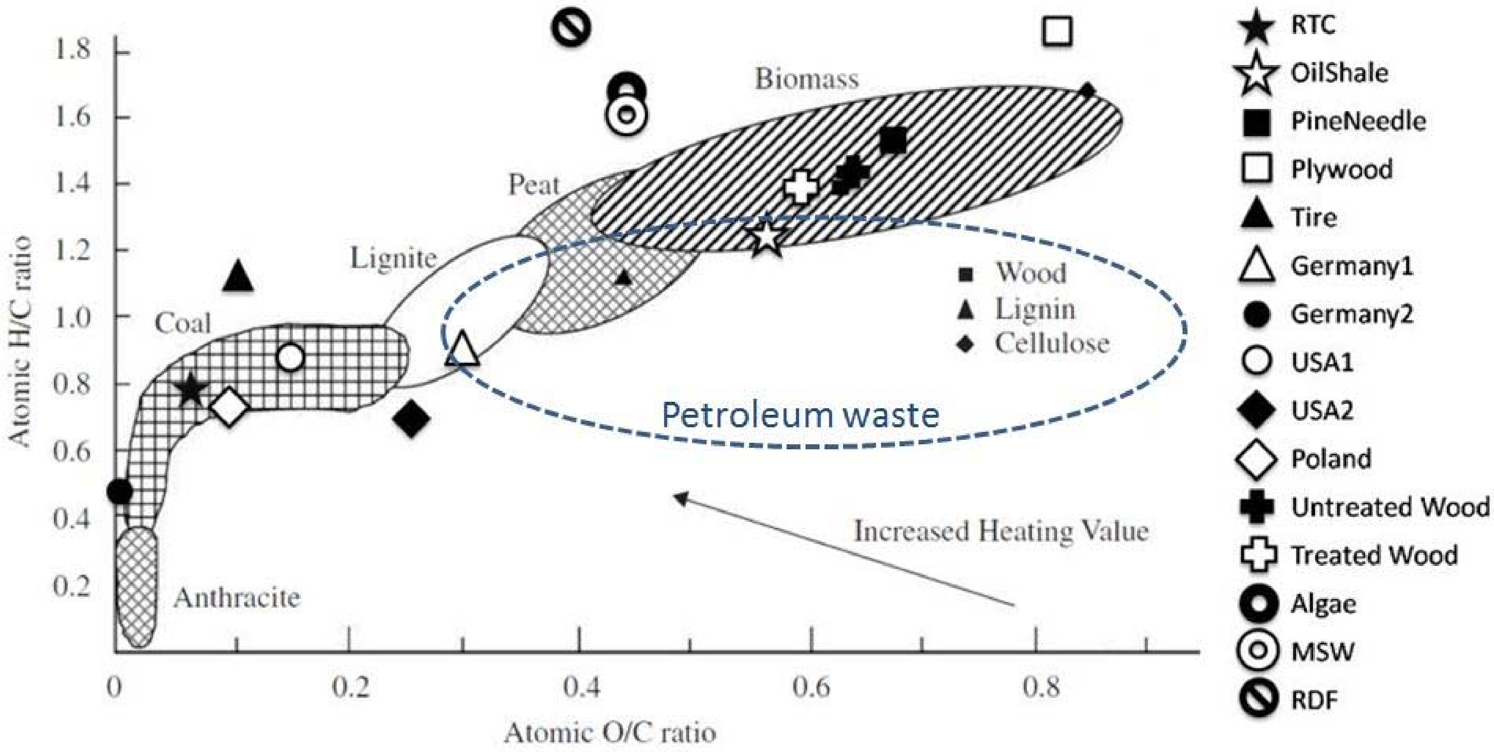
Elements		percentage
Barium	Ba	0.37%
Aluminum	AL	0.19%
Silicon	Si	0.12%
Sulfur	s	0.04%
Chlorine	Cl	0.02%
Potassium	K	948 PPM
Calcium	Ca	0.21%
Chromium	Cr	147 PPM
Manganese	Mn	0.02%
Iron	Fe	0.02%

Bacteria

	wet	dry
Proteobacteria	40.29	42.69
Thermotogae	27.8	14.89
Synergistetes	7.37	7.61
Bacteroidetes	6.71	10.48
Firmicutes	6.33	7.94
Actinobacteria	4.25	7.28
Chloroflexi	2.48	4.39
Planctomycetes	2.19	1.47
Spirochaetes	0.96	1.89
Caldiserica	0.39	0.56



Comparing Petroleum Waste to other Feedstock



Theoretical Estimation of Landfill-Gas VS Experimental Results Landfill-Gas

Anaerobic Gas Yield	PHC	WWTS	60% PHC & 40% WWTS
Theoretical amount of landfill-gas generate (L kg-1)	13.4	49.027	27.65
landfill-gas generate (L kg-1)	0	1.25	0.381
Percentage	0	2.5%	1.4%
			63.5

Material characterization

Ultimate analysis

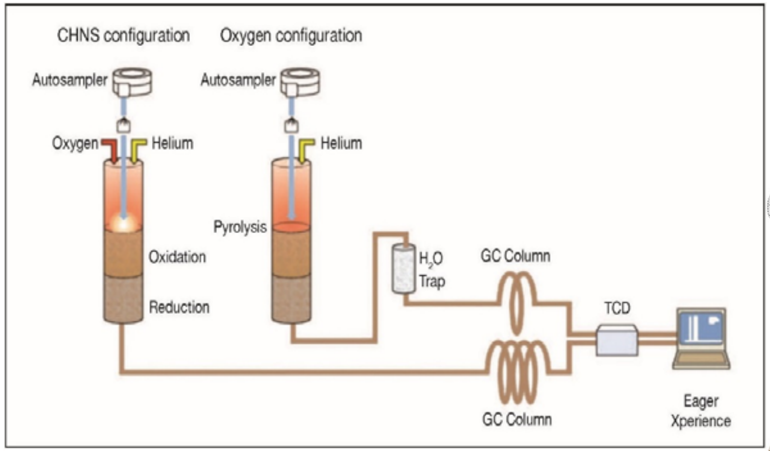
CHNS Flash Analysis

4 different batches each tested 6 times.

Gross Calorific Value (cal/kg) is estimated by a mathematical formulation:

$GCV = x_1 \, C + x_2 \, H + x_3 \, S - x_4 \, N$

GCV is converted into the Higher Heating Value (MJ/kg)



Batch	Carbon [wt%]	Hydrogen [wt%]	Nitrogen [wt%]	Sulphur [wt%]	HHV [MJ/kg]
Sample 1	14.42%	2.07%	0.06%	1.13%	8.05%
Sample 2	13.14%	1.90%	0.04%	0.56%	7.30%
Sample 3	18.34%	2.28%	0.03%	0.32%	9.60%
Sample 4	20.22%	2.72%	0.17%	0.40%	10.89%
Average	17.14%	2.67%	0.12%	0.44%	9.77%
Standard Deviation (σ)	2.6	0.72	0.11	0.35	1.75

Experimental

Several experiments carried out to simulate the biodegradation of the PHC in anaerobic conditions. These are divided into three sets according to the applied conditions and utilized size, namely being psychrophilic or mesophilic in a small jar or large and long jar.