Effect of salinity on biodegradation of MSW in bioreactor landfills

By

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Abstract

Bioreactor landfills require sufficient moisture to optimize the biodegradation processes and methane generation. In arid regions, this is problematic given the lack of fresh water supplies. Saline water can be used but may inhibit the biodegradation of the municipal solid waste (MSW) in landfills. Sludge may be used to enhance the biodegradation of MSW under saline conditions.

For this research, two groups of laboratory scale bioreactor cells were used to study the impact of saline water and sludge addition on the biodegradation of MSW in bioreactor landfills. The first group (R1-R4) operated without sludge addition. The second group (R5-R8) operated with addition of sludge. The salt concentrations in the two groups were 0%, 0.5%, 1%, and 3% (w/v) respectively. All bioreactors were operated at neutral pH levels with leachate recycle.

The methane yield was 70.6, 61.7 and 47.5 L/kg dry waste for bioreactors R1, R2 and R4, respectively; and 84.7, 78.7, 72.6 and 59.0 L/kg dry waste for bioreactors R5, R6, R7 and R8, respectively. The high salt content (3%) inhibited the MSW biodegradation as evidenced by the methane yield, the percentage peak reduction in leachate concentration and the settlement that occurred during the study. Sludge addition was able to improve the methane yield at all salt contents.

A mathematical model was developed to simulate the biodegradation of the MSW in bioreactor landfills operating under saline conditions and to predict the leachate strength (aqueous organic acid and volatile fatty acid (VFA)), and the volume of landfill gas (CH_4

and CO_2) produced. Sensitivity analysis indicated that the hydrolysis rate constant, methanogenic parameters (μ_M, k_{dM}, K_{SM}), and initial concentration of methanogenic biomass had a significant impact on peaks of the VFA and daily methane produced, as well as the time required to reach them.

The model has been calibrated by comparing the simulation results to the experimental 1D bioreactor measurements. The results of methane production showed good agreement between the model and experimental data. Both the model parameters and the salt inhibition constants (K_I and m) were determined from these simulations.

- To my parents and my family

-To the memory of H.H. Sheikh Zayed bin Sultan Al Nahyan, Former President of the United Arab Emirates

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Nomenclature

COD: Chemical oxygen demand

BOD: Biochemical oxygen demand

VFA: Volatile fatty acids

BMP: Biochemical methane potential

C^g: generation rate of aqueous organic acids carbon concentration (M/L^3)

C^d: depletion rate of aqueous organic acids carbon concentration (M/L^3)

$C_{(S)}$: solid organic carbon (M/ L^3)

$C_{(aq)}$: aqueous organic carbon (M/ L^3)

$C_{(XA)}$: acidogenic biomass carbon (M/ L^3)

$C_{(VFA)}$: VFA carbon concentration (M/ L^3)

$C_{(XM)}$: methanogenic biomass carbon (M/ L^3)

$C_{(CH4)}$: methane carbon concentration (M/ L^3)

$C_{(CO2)}$: carbon dioxide concentration (M/ L^3)

k_h: hydrolysis rate constant (T^{-1})

μ_A: maximum specific growth rate constant of acidogenic biomass (T^{-1})

K_{SA}: half saturation constant of acidogenic biomass (M/ L^3)

k_{dA} : decay rate constant of acidogenic biomass (T^{-1})

Y_A: mass of acidogenic biomass formed per mass of carbon utilized (M/ M)

μ_M: maximum growth rate constant of methanogenic biomass (T^{-1})

K_{SM}: half saturation constant of methanogenic biomass (M/L)

k_{dM} : decay rate constant of methanogenic biomass (T^{-1})

Y_M: mass of methanogenic biomass formed per mass of VFA utilized (M/ M)

Y_{CH4}: methane carbon fractional formation yield coefficient (M/M)

Y_{HAC}: VFA carbon fractional formation yield coefficient (M/M)

I: salt content concentration %(w/v)

K_I: inhibition constant due to salt content (same concentration unit as I)

m: inhibition constant due to salt content (dimensionless)

C_{bk}: biodegradable carbon in the k component of waste (M biodegradable carbon /M dry k component of waste)

C_k: carbon content in the k component of waste (M carbon / M dry k component of waste)

BF_k: biodegradable fraction of carbon content (M biodegradable carbon / M carbon)

M_k: dry mass of k component (M dry k component)

Chapter 1
Introduction

Landfills have been widely used for municipal solid waste (MSW) disposal all over the world. Landfill disposal is the most commonly used waste management method in many countries. The chemical, biological and physical processes that take place in the landfill promote the biodegradation of waste and result in the production of leachate and landfill gas (LFG). Leachate can cause contamination of groundwater and surface water and the landfill gases (CH_4 & CO_2) are green house gases, which can absorb heat and prevent it from escaping from the atmosphere thereby contributing to causing global climate change.

The conventional landfill (dry tomb) is designed to minimize problems associated with the production of leachate and gas emissions by controlling the water flow using barrier liners and low permeability covers. The low moisture content in the conventional landfill can result in a slow biodegradation rate, which extends landfill life and leads to long term monitoring. The cost of monitoring and long term care of the landfill can be very high. Leachate that is produced must be collected and stored or treated if it is to be discharged from the site. In addition, the landfill gases must be controlled to reduce the problems associated with gaseous emissions and odor problems (Reinhart, 1996).

The process based approach that promotes waste biodegradation and uses the landfill space as a treatment method rather than a storage method is the landfill bioreactor. The basic concept of a bioreactor landfill is to accelerate the biodegradation of the MSW in the landfill by controlling the moisture content and providing the required nutrients for

the microorganisms to degrade the organic components. One method to control the moisture content in MSW is by recycling leachate. The bioreactor not only enhances the biodegradation but also stabilizes the landfill as quickly as possible (Warith et al., 1999). Acceleration is accomplished through the addition of water in order to bring the moisture content to an approximate range of 35 to 60 percent (weight basis). The bioreactor landfill thereby avoids the concerns related to future liner failure and leachate contamination because the waste decomposes within 5 to 10 years, which is considerably less than the typical service life of these systems. Landfill stabilization means that the environmental performance measurement parameters (i.e. landfill gas composition and generation rate, waste temperature and leachate concentrations) remain at steady levels, and should not increase if there is any failure beyond 5 to 10 years of bioreactor process implementation (Barlaz et al., 1990; Warith, 2003).

Bioreactor landfills and accelerated waste biodegradation systems have several advantages over conventional landfills. Increased methane production can result when biological processes in the landfill are accelerated. Bioreactor landfills can produce elevated amounts of methane in short periods of time, making it a valuable source of energy. Methane gas could then be collected and used to improve the cost-effectiveness of landfill gas recovery and utilization. Leachate recirculation not only reduces the cost of treatment, but also lowers the strength of leachate, which lessens its potential for soil and groundwater contamination, a process referred to as "in situ treatment". Finally, bioreactor landfills have great economic benefits due to the reduction of cost associated with avoiding long term monitoring and maintenance and the reduction in the delay of the final site utilization after closure (Reinhart et al., 2002).

Enhancement technologies that can be used to increase the biodegradation rate in landfill bioreactors include leachate recycling, control of moisture content and moisture flow, buffering, sludge addition, nutrient addition, temperature control, shredding and lift design (Komils et al., 1999).

The bioreactor landfill offers great advantages in the biodegradation of MSW, which could be employed in arid and semi-arid regions. However, bioreactor landfills require a certain amount of moisture to initiate the biodegradation process, which is problematic in arid and semi-arid regions where fresh water supplies are scarce. It is therefore the purpose of this study to examine the utilization of saline water, readily available in many arid areas, to control the moisture content in the landfill, thereby facilitating the use of this new bioreactor technology in those regions. To date, experimental studies on the impact of saline water on the biodegradation of MSW in landfills have not been reported. It is the hope that this study will serve as a steppingstone to future research in this field.

Laboratory scale 1D bioreactor experiments were run with recycled leachate, pH control by addition of buffer to the leachate recycle, and with or without sludge addition. The 1D bioreactor experiments were designed to estimate the effect of using saline water on the biodegradation of MSW and to enhance the performance of bioreactor landfills operating under saline conditions by sludge addition.

BMP assays were designed to estimate the hydrolysis rate constant of MSW at different salt contents.

1.1 Problem statement

The United Arab Emirates (UAE) lies in the eastern corner of the Arabian Peninsula. It is an arid country with a mean annual rainfall of 80 – 160 mm and very limited sources of useable groundwater. The climate is characterized by long hot summers (45-50°C) and short cool winters (14- 23°C) (www.alain-airport.gov.ae).

The rapid urban and industrial developments of the UAE in recent years have caused an increase in MSW generation, thereby creating a demand in landfill construction, as shown in Figure 1.1.

Landfilling is still the primary method of MSW disposal in arid countries. However, bioreactor landfills would offer greater advantages, as discussed earlier.

The bioreactor landfill is a sanitary landfill in which moisture content, temperature, nutrients, and inoculums are managed in a controlled manner to achieve rapid biodegradation of MSW. To optimize the rapid MSW biodegradation, moisture content of the waste must be established and maintained at field capacity which is problematic in countries of the Arabian Peninsula that face shortages of fresh water supplies, as shown in Table 1.1. One solution to this problem is to use brackish water which is available in the area and has a salt content in the range of 500 to 20,000 ppm (www.unu.edu).

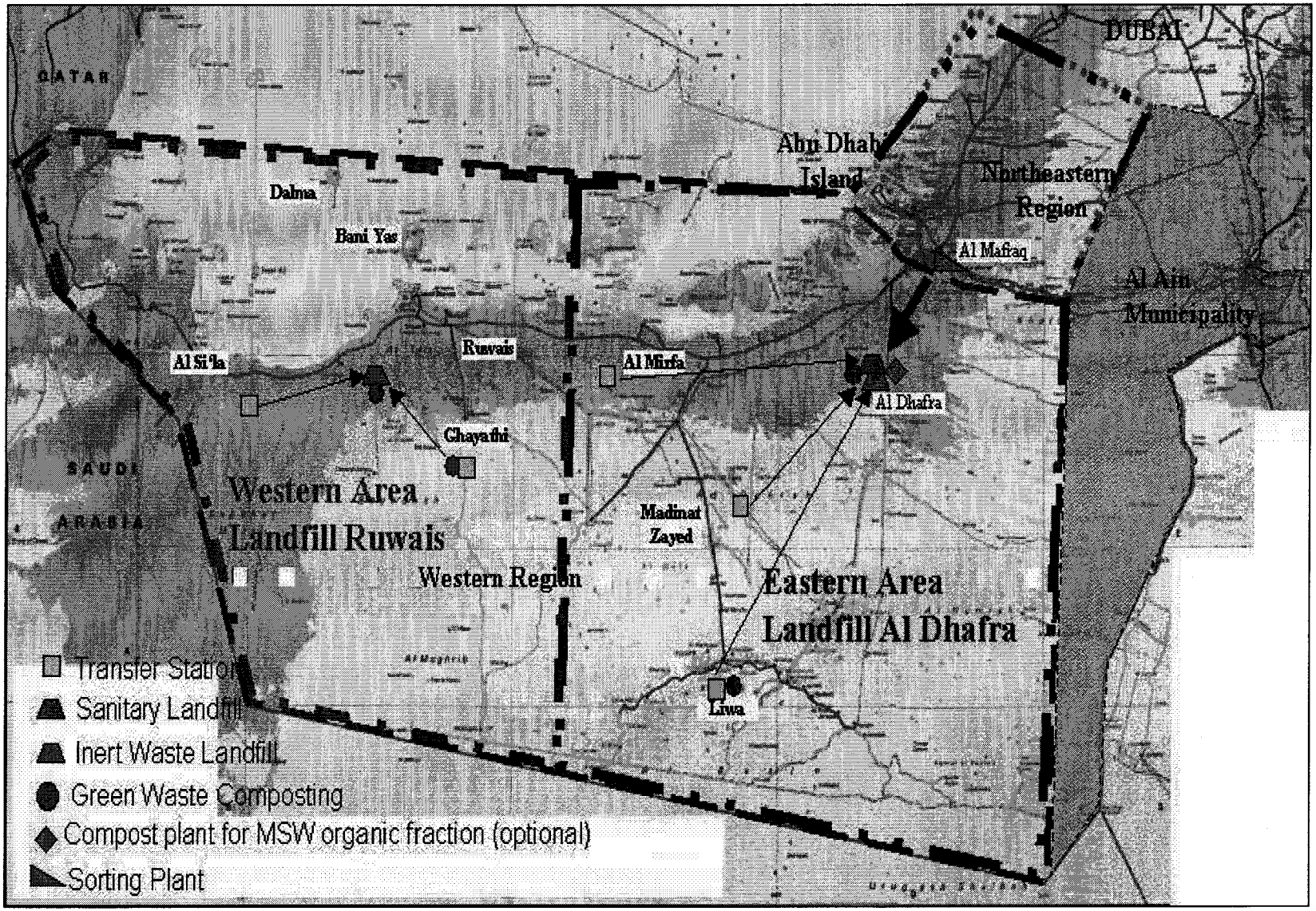


Figure 1.1: Overview on proposed Solid Waste Management facilities and sites in Abu Dhabi. (Abu Dhabi Municipality).

Table 1.1: Water resources in Arabian Peninsula countries

Country	Average annual rainfall (mm)	Groundwater recharge (mcm) [1]	Groundwater use (mcm)[1]
Saudi Arabia	33-550	3,850	14,430
Kuwait	30-140	160	80
Bahrain	30-140	100	166
Qatar	20-150	50	190
UAE	**80-160**	**125**	**900**
Oman	80-400	550	645

(1) Million cubic meter

1.2 Contribution

This study aims at contributing to research in bioreactor landfills in the following areas:

1. Examine the effect of salinity on the biodegradation of municipal solid waste under different operational conditions.
2. Enhance the performance of bioreactor landfills operating under saline conditions by sludge addition.
3. Develop a mathematical model to simulate the long term performance of bioreactor landfills operating under saline conditions and to estimate the parameters needed for the model.

1.3 Thesis organization

The thesis contains six chapters.

Chapter 1: Offers a general introduction to this research, the problem statement and the objectives.

Chapter 2: Presents a literature review on the following topics: characteristics and biodegradation of MSW in landfills, treatment of saline wastewater, previous models (leachate and gas), hydrolysis process and methods used to estimate the hydrolysis rate constant.

Chapter 3: Provides the methodology used to address the objectives of this study, as well as the experimental setup and analytical method used to measure the parameters.

Chapter 4: Presents the model development, assumptions and derivation, as well as the model sensitivity to hydrolysis rate constant, kinetics of biomass and initial conditions.

Chapter 5: Provides the results obtained from 1D bioreactor and BMP assay experiments. Results from 1D bioreactors include moisture content, temperature, settlement, biogas produced, effluent COD, BOD, VFA, pH, TVS, TS, salinity, vertical concentration profile in the bioreactors, and an evaluate of potential shortcircuiting. Results from BMP assays are presented in terms of methane concentration and daily production. This chapter also include the results of the determination of the hydrolysis rate constant and model calibration. In addition, statistical analysis for these results are provided.

Chapter 6: Presents a summary, conclusions and suggestions for future studies that could be used to improve and build upon this research.

Chapter 2

Literature review

The purpose of this chapter is to offer a background on landfill systems in order to illustrate the processes taking place during the biodegradation of MSW. The first section covers the characteristics of MSW. Section two deals with the biodegradation of MSW in landfills. The third and fourth sections present studies conducted on saline wastewater treatment and a review of previous models, respectively. The last section of this chapter covers the hydrolysis process and methods used to estimate the hydrolysis rate constant.

2.1 MSW characteristics

2.1.1 MSW composition

The term MSW is commonly used to describe the waste originating in residential, commercial, institutional and, in some cases, industrial sources (Franklin, 2002). Primary MSW consists of organics, paper, plastics, textiles, metals and glass. There are many factors affecting the composition of MSW such as consumer habits, lifestyle and income; MSW management; the weather and seasons. As a result, the composition of MSW can vary from one area to another and from country to country, as shown in Table 2.1.

2.1.2 Properties of MSW

It is important to know the physical, chemical, and biological properties of MSW, since these properties are useful in the design and alternative operations of landfills (e.g. expected quality of leachate produced and the theoretical yield of gas generated per kg of waste).

Table 2.1: Waste composition in different countries

Country	Organic	Paper	Plastic	Glass	Metal	Other
Canada[1]	34	28	11	7	8	13
Mexico[1]	52	14	4	6	3	20
USA[1]	23	38	9	7	8	16
Japan[1]	26	46	9	7	8	12
Australia[1]	50	22	7	9	5	8
Denmark[1]	37	30	7	6	3	17
Finland[1]	32	26	0	6	3	35
France[1]	25	30	10	12	6	17
Greece[1]	49	20	9	5	5	13
Luxembourg[1]	44	20	8	7	3	17
Netherlands[1]	43	27	9	4	5	8
Norway[1]	18	31	6	4	5	36
Portugal[1]	35	23	12	5	3	22
Spain[1]	44	21	11	7	4	13
Switzerland[1]	27	28	15	3	3	24
Turkey[1]	64	6	3	2	1	24
Kuwait[2]	58	18	12	4.5	5	2.5
Average	**38**	**26**	**8**	**6**	**5**	**18**

(1) World Bank
(2) Al-Yaqout et al. (2005)

2.1.2.1 Physical properties of MSW

The most important physical properties of MSW are moisture content, density, field capacity and hydraulic conductivity.

- Moisture content and density

There are different factors affecting the moisture content of MSW such as the waste composition, humidity and rain, and season of the year (Dixon et al., 2005). The moisture content of waste can be measured by using either the volumetric or weight basis methods.

Oweis et al. (1990) stated that the initial moisture content in the waste is in the range of 10%-20% by volume. The initial moisture varies from 15% to 40% by weight (Tchobanouglous et al., 1993).

Tchobanouglous et al. (1993) found that the dry density of MSW in the delivered vehicles varied on average from 180 to 415 kg/m^3 and that it would increase to 800 kg/m^3 after compaction was performed in the landfill site.

- Field capacity

The field capacity of MSW is the upper limit of moisture that can be held in the waste before gravity drainage (Oweis et al., 1990). Generally speaking, there will be no leachate generation until the field capacity of the waste is exceeded. The field capacity is a function of the waste density, porosity, and the stage of waste decomposition (Tchobanouglous et al., 1993).

Oweis et al. (1990) stated that the field capacity of waste is commonly in the range of 20%-35% by volume. Tchobanouglous et al. (1993) reported that the field capacity of uncompacted waste from residential and commercial sources is in the range of 50% to 60% by weight, or 30% by volume.

- Hydraulic conductivity

Waste hydraulic conductivity is important to landfill designers because it affects the leachate pressure distribution in waste layers (Dixon et al., 2005). The hydraulic conductivity of MSW varies from upper to lower layers within a landfill and it is dependent upon the type of waste, moisture content, effective stress and density of waste

or compaction. Fang (1983) found, based on laboratory tests, that the hydraulic conductivity for dense waste was $7 \cdot 10^{-4}$ cm/s and $15 \cdot 10^{-3}$ cm/s for loose waste.

Based on core samples collected from the Keele Valley landfill, Bleike et al. (1995) found that as the density of waste increased with the depth of landfill from 500 to 1250 kg m^{-3}, the hydraulic conductivity decreased from $2 \cdot 10^{-3}$ to $2.5 \cdot 10^{-5}$ cm/s. Also, they reported that as the effective stress increased from 0 to 1150 kPa, the hydraulic conductivity decreased from $2 \cdot 10^{-3}$ to $2 \cdot 10^{-5}$ cm/s. This agreed with results presented by Oweis et al. (1986) and Powrie et al. (1999). Oweis et al. (1986) found that by increasing the unit weight from 600 to 1200 kg m^{-3}, the hydraulic conductivity decreased from $10^{-2.8}$ to 10^{-5} cm/s. Powrie et al. (1999), on the other hand, found that the hydraulic conductivity of fresh waste decreased by three orders of magnitude to approximately 10^{-5} cm/s after placement and burial to a depth of 60 m due to compression.

Based on a leachate pumping test for MSW landfill, Oweis et al. (1998) found that the hydraulic conductivity is approximately 10^{-3} cm/s. Also, they concluded that in the absence of site-specific data, the reasonable value for hydraulic conductivity is 10^{-3} cm/s for good compaction.

2.1.2.2 Chemical properties of MSW

Knowing the chemical composition of the MSW constituents is an important factor in selecting the optimum treatment process (e.g. landfilling, or combustion) and estimating the theoretical amount of biogas to be produced in the landfill.

Several methods are used to characterize the chemical composition of MSW. These are proximate analysis (for organic and inorganic, as well as easy, moderate and hard

biodegradable matter); chemical compounds (for lipids, carbohydrates, lignin and protein); and ultimate analysis (for carbon, hydrogen, oxygen, nitrogen and sulphur) (Tchobanouglous et al., 1993). Table 2.2 shows the chemical composition of MSW in terms of organic, inorganic and ultimate analysis methods. Table 2.3 shows the biodegradable fraction of selected components based on lignin content (Tchobanouglous et al., 1993).

Table 2.2: Chemical composition of MSW

Components	% dry weight basis					
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash
Food waste	48	6.4	37.6	2.6	0.4	5
Yard waste	47.8	6	38	3.4	0.3	4.5
Paper waste	43.5	6	44	0.3	0.2	6
Textile waste	55	6.6	31.2	4.6	0.15	2.5
Wood waste	49.5	6	42.7	0.2	0.1	1.5
Plastics waste	60	7.2	22.8	-	-	10
Metals waste	4.5	0.6	4.3	0.1	-	90.5
Glass waste	0.5	0.1	0.4	0.1	-	98.9
Ash/dirt/fines	26	3	2	0.5	0.5	68
Leather waste	60	8	11.6	10	0.4	10
Rubber waste	78	10	-	2	-	10

Table 2.3: Biodegradable fraction of selected components based on lignin content

Components	Moisture content % (w/w)	VS, percent of TS	Lignin content, percent of TS	Biodegradable fraction (BF)
Food	50-80	95 – 98	0.4	0.82
Paper				
Newsprint	4-10	96 – 99	21.9	0.22
Office paper	4-8	90 – 95	0.4	0.82
Plastics	1-4	-	-	0
Textile	6-15		4.1	0.72

2.1.2.3 Biological properties of MSW

The organic content of MSW can be converted into biogas and intermediate products as a result of a series of biological reactions taking place in the landfill. The following section covers the mechanisms and bacteria groups involved in the biodegradation of MSW.

2.2 Biodegradation of MSW in landfill

This section covers the following topics: stages and phases involved in the biodegradation process, production of leachate and biogas, factors controlling the biodegradation process, enhancement methods and case studies. The biodegradation of solid waste has been studied by Barlaz et al. (1989); Pohland et al. (1999); Christensen et al. (1989); Warith (2003); Reinhart (1996) and Tchobanouglous et al. (1977, 1993).

2.2.1 Stages of MSW biodegradation

The biodegradation of MSW in the landfill occurs over two stages (aerobic and anaerobic), each stage containing its own bacteria groups and products.

2.2.1.1 Aerobic stage

The aerobic 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, the amount of oxygen present in the waste is dependent on the permeability of the soil cover and waste compaction.

In this stage, the organic waste reacts with oxygen in the presence of aerobic bacteria to produce carbon dioxide, water, biomass and heat (Tchobanouglous et al., 1977). After a short time, the activity of the aerobic bacteria will decline due to depletion in oxygen concentration, causing the landfill to shift to the anaerobic stage.

2.2.1.2 Anaerobic stage

The anaerobic biodegradation of MSW follows three sequenced biochemical reactions involving three different groups of anaerobic bacteria. In the anaerobic stage, bacteria groups convert waste into biogas (CH_4, CO_2) as end products, and organic acids as intermediate products, as shown in Figure 2.1.

Three groups of anaerobic bacteria are mainly involved in the biodegradation of solid waste in the landfills. These groups are:

- Fermentative and hydrolytic bacteria.

  Ferments are large, heterogeneous bacteria. The role of these bacteria is to solubilize and convert complex wastes to smaller, more soluble compounds. The hydrolysis process is caused by extracellular enzymes which are produced by these bacteria (Christensen et al., 1989).

- Acidogenic bacteria.

  These are also large, heterogeneous bacteria. The role of these bacteria is to produce VFA (volatile fatty acids), H_2, and CO_2. The acidogenic bacteria are relatively tolerant to low pH and have a much higher rate of growth than the methanogenic bacteria (Barlaz et al., 1989).

- Methanogenic bacteria.

  The methanogenic bacteria are sensitive to changes in pH and require very low redox potential and hydrogen concentration. This group of bacteria is responsible for the production of CH_4 and CO_2 (Barlaz et al., 1989).

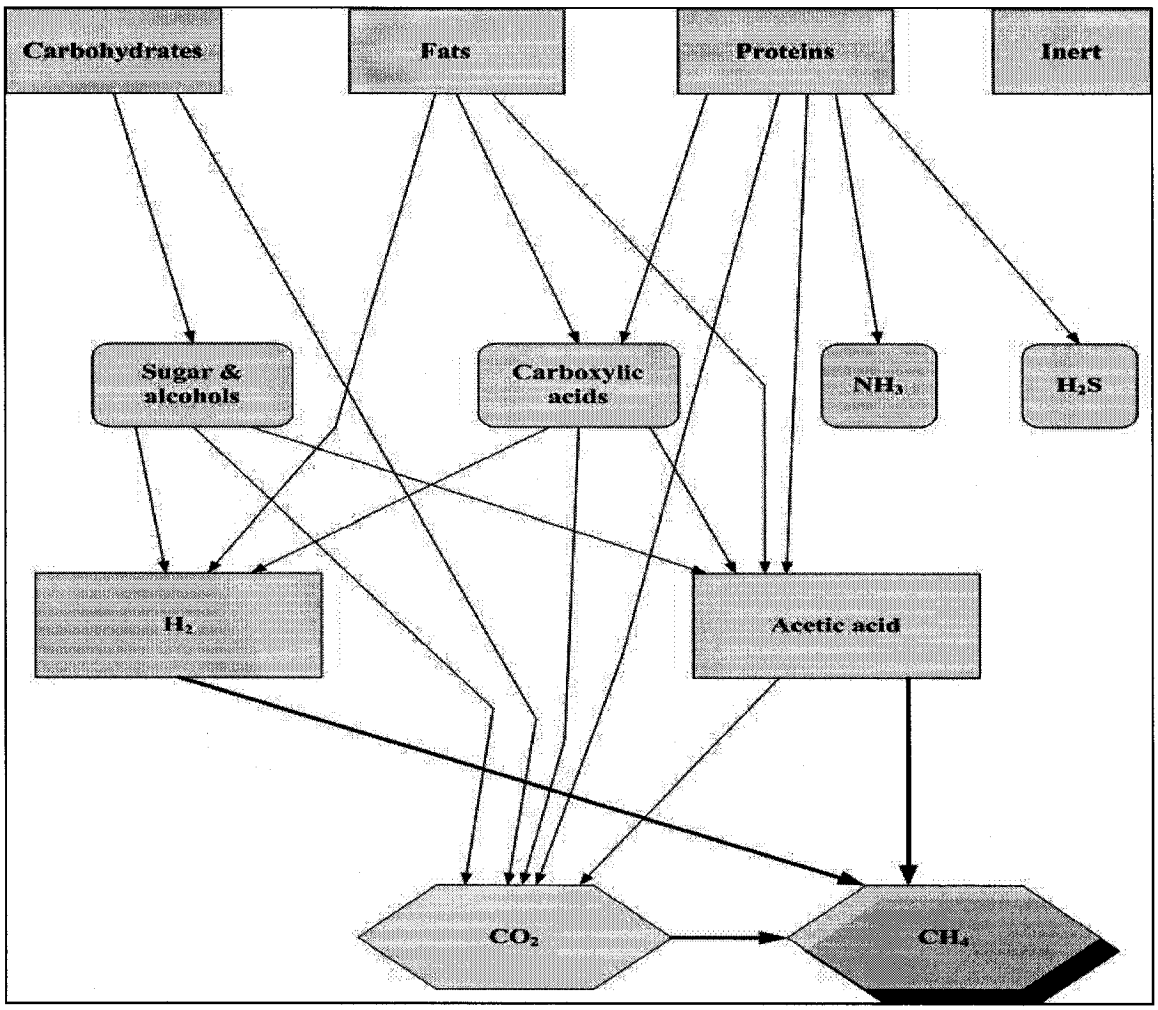


Figure 2.1: Biochemical pathways (adapted from Young, 1989)

There are four steps involved in the biodegradation of MSW to biogas (CH_4 and CO_2): hydrolysis, acidogenesis, acetogenesis and methanogenesis.

- Hydrolysis.

  The hydrolysis process is a very important step in the biodegradation of solid waste in the landfill. In the hydrolysis step, the complex organic compounds are solubilized and converted into smaller sized organic compounds by extracellular enzymes. This step is important because microorganisms cannot deal with large molecules. Only smaller organic molecules can pass through the membrane cell of bacteria (Grady et al., 1999).

The carbohydrate, fats and proteins are reduced to lower molecules as described by the following reactions (White et al., 2004):

$$(C_6H_{10}O_5)_n + H_2O \rightarrow n\ C_6H_{12}O_6 \quad [1]$$

The end results of hydrolysis are solubilization of waste to sugars, alcohols, fatty acids and amino acids, as shown in Figure 2.1

- Acidogenesis.

  In this stage, the end products of hydrolysis are oxidized to organic acids. The organic acids are then broken into acetic acid, as shown in the following reactions (White et al., 2004):

$$C_6H_{12}O_6 \rightarrow CH_3(CH_2)_2COOH + 2H_2 + 2\ CO_2 \quad [2]$$

$$C_6H_{12}O_6 + 2\ H_2 \rightarrow 2\ CH_3CH_2COOH + 2\ H_2O \quad [3]$$

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

There are two major types of acidogenic bacteria. The first bacterium (Hydrogen producing) gains its energy by converting alcohol and longer chain acids into acetic acid and hydrogen in reaction 2. The second bacterium (Hydrogen consuming) produces acetic acid from catabolized carbohydrate, hydrogen and organic compounds as in reactions 3 and 4. It will help to maintain a low partial pressure for hydrogen, which is important for the hydrogen producing bacteria and methanogenesis process. An increase in the partial pressure of hydrogen will reduce the rate of acid formation, thus decreasing the proportion of glucose converted to acetic acid and increasing propionic and butyric acids which reduce the pH and inhibit the methanogenesis process (El-Fadel, 1991).

- Acetogenesis.

  In this stage, conversion of propionic and butyric acids into acetic acid occurs as described in the following reactions (El-Fadel, 1991):

$$CH_3(CH_2)_2COOH + 2H_2O \rightarrow 2CH_3COOH + 2H_2 \quad [5]$$

$$CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + 3H_2 + CO_2 \quad [6]$$

- Methanogenesis.

  Methane is produced either from acetic acid or carbon dioxide reduction with hydrogen, as shown in the following reactions (White et al., 2004):

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad [7]$$

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O_2 \quad [8]$$

2.2.2 Phases of MSW biodegradation in the landfill

The phases and microbial processes of MSW biodegradation in the landfill have been reviewed by a number of researchers (e.g. Veeken et al., 2000; Pohland et al., 1996; 1999; Barlaz et al., 1989,1996; Warith et al., 1998, 2003; Christensen et al., 1989; Reinhart, 1996; White et al., 2004; Zacharof et al., 2004).

The biodegradation of MSW can be divided into five distinct phases, depending on the leachate concentration and landfill gas composition. During each phase, different groups of bacteria are dominant, in accordance with the conditions existing within the landfill (Reinhart, 1996). These phases are:

- Phase I (aerobic). This phase is short and starts after the disposal of MSW. In this phase, easily degradable organic compounds are converted into carbon dioxide, see Figure 2.2 (Phase I).

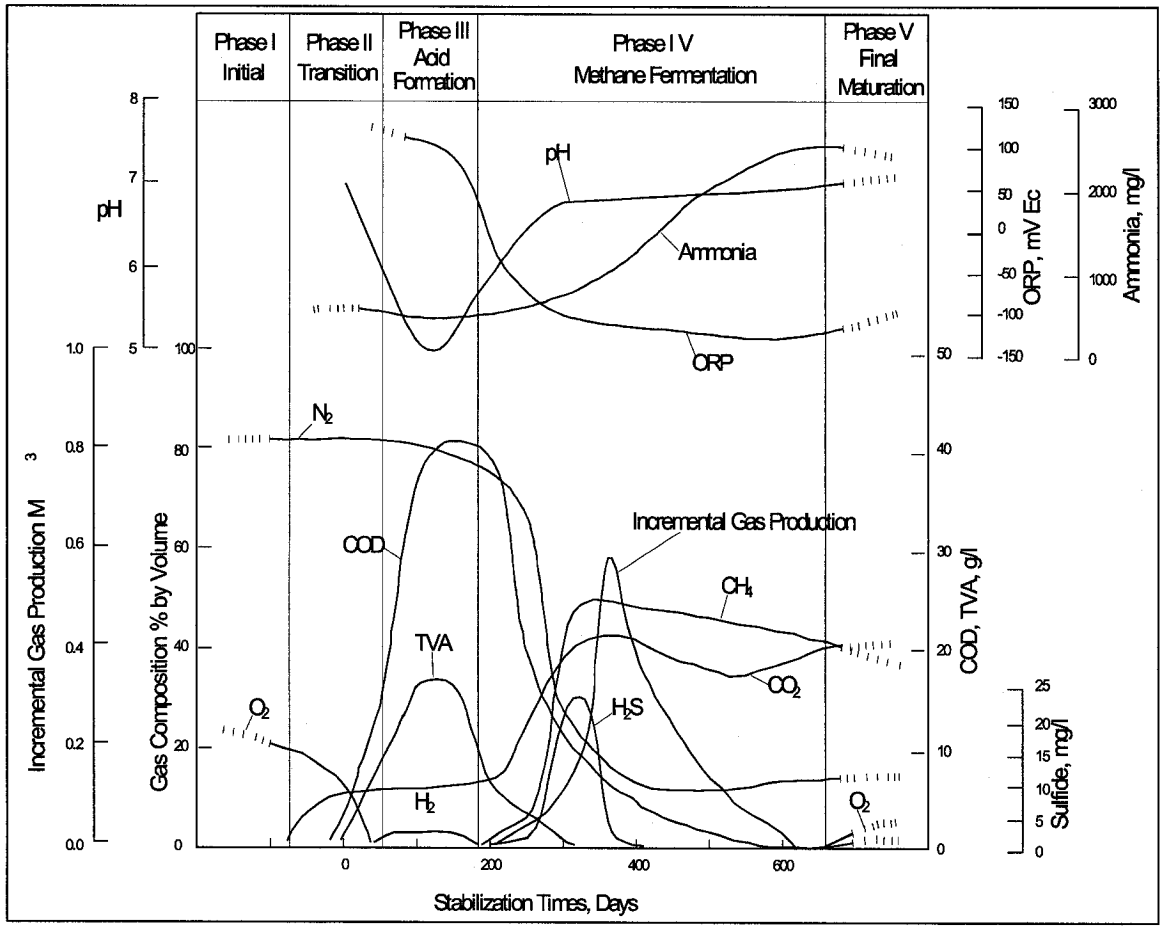


Figure 2.2: Biological decomposition phases in the landfill bioreactor (adapted from Pohland et al., 1996).

- Phase II (transition). It begins with the depletion of O_2 in the waste. The landfill shifted into anaerobic conditions. Two processes occur during this phase: hydrolysis and acidogenesis. The results of these processes are that the volatile fatty acids (VFA) and COD concentrations start to increase at the end of this phase, see Figure 2.2 (Phase II).
- Phase III (acid formation). The acidogenic bacteria become dominant in this phase. The result of that is a rapid generation of (VFA), carbon dioxide, hydrogen and low

pH of leachate. The VFA concentration reaches its maximum concentration, see Figure 2.2 (Phase III).

- Phase IV (methane formation). Low methane generation begins. As methane generation increases, the concentration of VFA decreases and the pH rises. The composition of methane reaches a steady state. The dominant bacteria in this phase are methanogenic. The high rate of methane produced maintains the concentration of VFA at a low value and the pH stabilizes above 7, see Figure 2.2 (Phase IV).
- Phase V (maturation). This phase starts when the rate of methane produced is very low as a result of the removal of nutrients and available biodegradation material.

The duration of each phase is dependent on many factors which will be covered in Section 2.2.5.

2.2.3 Landfill leachate

Leachate is the soluble product of chemical, physical and biological reactions, as well as the washout of fines and colloids (Anderottola, 1992). As mentioned before, leachate is produced when the field capacity of the MSW is exceeded.

2.2.3.1 Landfill leachate generation

Leachate generation from landfills has been studied by Purushottam et al. (1997); Farquhar (1989); Anderottola (1992); Reinhart et al. (1996); Rees (1980) and; El-Fadel et al. (1997a).

The production rate of leachate from a landfill is controlled by several factors, such as initial water content of waste, volume of rainfall entering the waste, site climate and hydrology, site operation and management, pre-treatment and composition, and depth and

density of waste (El-Fadel et al., 1997a; Rees, 1980; Farquhar, 1989). The volume of leachate generation from a landfill site can be estimated by the water budget or HELP (Hydrological Evaluation of Landfill Performance) models (Purushottam et al., 1997).

2.2.3.2 Landfill leachate composition

Landfill leachate typically contains water, heavy metals, organic material as the product of decomposition, and inorganic components such as ammonia, sulphate and metal cations (Reinhart et al., 1996).

Leachate composition is dependent on several factors, namely biological, chemical, and physical processes taking place in the landfill (status of decomposition); the age of the landfill; and initial waste composition. Leachate composition varies according to the following five phases, as shown in Figure 2.2.

- Phase I (aerobic). This phase is short and limited by the presence of O_2 in the landfill. Figure 2.2 (Phase I) shows how in this phase proteins are degraded into amino acids and converted into CO_2, water, nitrate and sulphates. Also, carbohydrates are converted into CO_2 and water, whereas fats are converted into fatty acids which are further degraded into simple catabolics. In reality, this phase is short and no large amount of leachate is generated.
- Phase II (Figure 2.2). In the transition phase, the landfill shifted into anaerobic stage due to the depletion of oxygen and the fact that the anaerobic microorganisms became active. At the end of this phase, the pH drops to less than 6 and the COD and ammonia appears in the leachate.
- Phase III (Figure 2.2). The continuation of the hydrolysis process is followed by an increase in the VFA concentration (end product of acidogenic stage) which cause a

decrease in the pH and solubilize the inorganic ions such as SO_4^{2-}, Ca^{2+}, Mg and Na^+. The highest COD and ammonia concentrations and the lowest pH values are observed in this phase (Anderottola, 1992).

- Phase IV (Figure 2.2). It starts with a low methane generation rate. The pH of leachate is increased as a result of the VFA conversion into methane and CO_2. Based on this, the concentration of inorganic ions decreases in the leachate. The leachate produced in this phase is described by low values of COD and high pH (6.8 - 8).
- Phase V (Figure 2.2). During this phase, there is no biological activity since the nutrients and available substrates are removed. There is no major difference in the leachate concentration from the previous phase.

Table 2.4 summarizes the landfill leachate concentration in different phases of the stabilization process (Reinhart et al., 1996).

Table 2.4: Composition of leachate from landfills

Parameter	Phase II	Phase III	Phase IV	Phase V
	Transition	Acid formation	Methane fermentation	Final maturation
BOD (mg/l)	100-1000	1000 – 57700	600 – 3400	4 – 120
COD (mg/l)	480- 18000	18000 – 71000	580 – 9760	31 – 900
VFA (mg/l) as Acetic Acid	100 - 3000	3000 – 18800	250 – 4000	0
BOD/COD	0.23 - 0.87	0.4 – 0.8	0.17 – 0.64	0.02 – 0.13
Ammonia (mg/l N)	120 -125	2 – 1030	6 – 430	6 – 430
pH	6.7	4.7 – 7.7	6.3 – 8.8	7.1 – 8.8

2.2.4 Landfill gas

Landfill gas is a mixture of gases produced during the biodegradation of MSW in the landfill. They are mainly generated in the anaerobic stage. The production of landfill gas from MSW biodegradation has been researched by several authors. This section covers generation, composition and yield of gas produced from this process.

2.2.4.1 Landfill gas generation

The rate and composition of landfill gas vary according to the stabilization stages and composition of the MSW.

Changes in the generation rate and composition of gas can be described by eight-phases (as in the old landfills), as shown in Figure 2.3. In phase I, oxygen is consumed by the composting of organic matter into CO_2. The concentration of nitrogen does not change during this phase (Christensen et al., 1996). In phase II, after the oxygen is consumed, the anaerobic decomposition starts with the production of CO_2 and H_2. The percentage of N_2 is reduced compared to CO_2 and H_2. Phase III begins with the production of methane, while CO_2 and H_2 decrease. In phase IV, methane is stabilized around 50%-60% whereas the CO_2 is oxidized into CH_4. At the end of phase V, the lower rate of methane production causes air diffusion into the upper part of the landfill and reduces the CH_4 percentage. The N_2 appears at the end of this phase. In phase VI, methane produced in the center of the landfill is oxidized to CO_2 as it migrates through the upper part of the landfill. The concentration of N_2 and CO_2 is increased during this phase. Phase VII, methane formation is negligible and CO_2 decreases to a low percentage. The percentage of N_2 is increased and the O_2 starts to appear in the landfill. Phase VIII, the percentage of CO_2 is now negligible and the gases are mainly N_2 and O_2 which diffuse into the landfill.

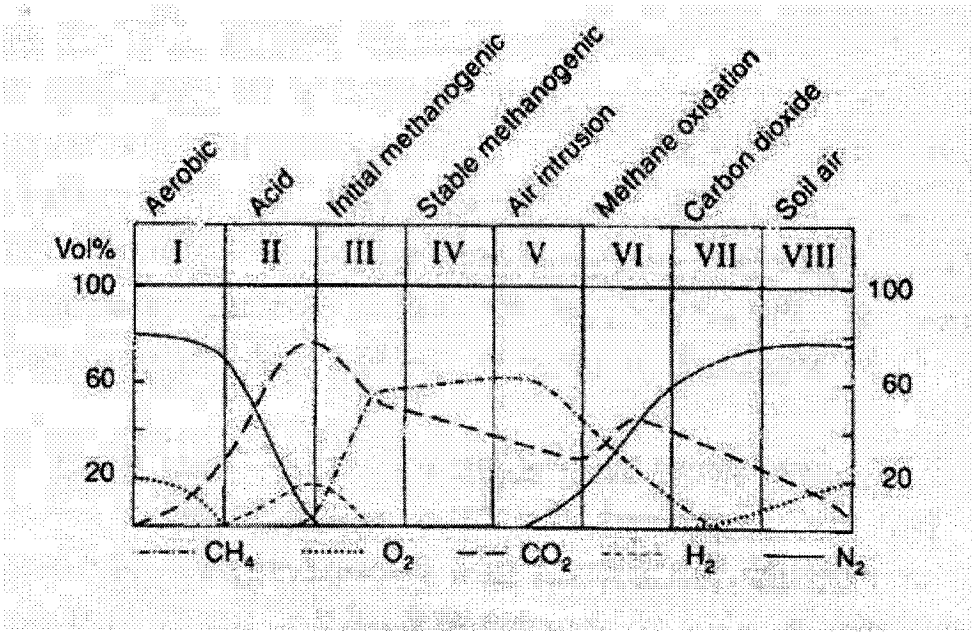


Figure 2.3: Composition of landfill gas (adapted from Christensen et al., 1996).

2.2.4.2 Landfill gas composition

Landfill gases can be classified into three groups: (1) major components which consist of methane and carbon dioxide; (2) minor components which consist of ammonia, hydrogen, hydrogen sulfide, nitrogen, and carbon monoxide; and (3) trace compounds, mainly volatile organic compounds (VOC) (Tchobanouglous et al., 1977; and Dewalle et al., 1978). Table 2.5 shows the composition of major and minor compounds in landfill gases, whereas Table 2.6 shows the concentration of various VOC in landfill gases (Tchobanouglous et al., 1993).

The composition of landfill gas depends on the activity of the bacteria involved, the available substrate and other factors which will be covered in Section 2.2.5.

Table 2.5: Typical composition of landfill gas

Component	Percent (volume basis)
Methane	45 – 65
Carbon dioxide	40 – 60
Nitrogen	2 – 5
Oxygen	0.1 – 1
Hydrogen sulfides	0 – 1
Ammonia	0.1 – 1
Hydrogen	0 – 0.2
Carbon monoxide	0 – 0.2
Trace constituents	0.01 – 0.6

Table 2.6: Typical concentrations of VOCs compounds in landfills gases

	Concentration, ppbV		
Compound	**Median**	**Mean**	**Maximum**
Acetone	0	6,838	240,000
Benzene	932	2,057	39,000
Chlorobenzene	0	82	1,640
Chloroform	0	245	12,000
1,1-Dichloroethane	0	2,801	36,000
Dichloromethane	1,150	25,694	620,000
1,1-Dichloroethene	0	130	4,000
Diethylene chloride	0	2,835	20,000
trans-1, 2-Dichloroethane	0	36	850
Ethylene dichloride	0	59	2,100
Ethyl benzene	0	7,334	87,500
Methyl ethyl ketone	0	3,092	130,000
1, 1, 1-Trichloroethane	0	615	14,500
Trichloroethylene	0	2,079	32,000
Toluene	8,125	34,907	280,000
1, 1, 2, 2-Tetrachloroethane	0	246	16,000
Tetrachloroethylene	260	5,244	180,000
Vinyl chloride	1,150	3,508	32,000
Styrenes	0	1,517	87,000
Vinyl acetate	0	5,663	240,000
Xylenes	0	2,651	38,000

2.2.4.3 Landfill gas yield

Methane yield is defined as the total amount of methane generated per unit weight (dry or wet) of MSW (El-Fadel et al., 1996a). The methane yield is a function of waste composition. Eleazer (1997) found that the methane yield increased as cellulose and hemicelluose content increased. The methane yield was reviewed by El-Fadel et al. (1996a). There are two approaches to estimating this yield: theoretical and experimental.

Theoretical approach. This approach uses the stoichiometric and biodegradability methods to estimate the gas yield. The *stoichiometric* method is based on several assumptions, such as whether or not complete biodegradation of waste has occurred; the biodegradation product only includes CH_4 and CO_2; the balance of substrates and nutrients is available at all times in all places in the landfill, and no portion of the degraded matter is utilized into cell growth (Ham 1979). The following equation is commonly used to estimate the theoretical landfill gas yield:

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right)H_2O \Rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)CO_2 + d\,NH_3 + e\,H_2S \quad [9]$$

Using this method, the estimated yield of the landfill gas is 440 L/kg dry waste with a composition of 53% methane and 46% CO_2 (Ham, 1980). El-Fadel et al. (1997) reported, based on the stoichiometric method, that the estimated methane yield is in the range of 220-270 L/kg dry waste after complete decomposition. Table 2.7 summarizes the estimated methane yield based on this method.

Table 2.7: Methane yield based on the stoichiometric method

Sources	Methane (L/kg dry waste)
Barlaz et al. 1989	373 carbohydrate 274 protein
Ham et al. 1989	270
El-Fadel et al. 1996a	220-270
Peer et al.1993	230-270

In reality, these assumptions are not valid because there are variations in climate conditions, complete decomposition takes a long time, the substrate/nutrient ratio is not always balanced, organic matter in the landfill is converted into biogas, and bacteria cell growth and flushing with leachate occur.

The *biodegradability* method estimates the gas yield based on equation [9] and individual waste components. Waste components can be rapidly or slowly biodegradable (Tchobanouglous et al., 1993). Based on this method, the estimated gas yield is in the range of 120-310 L/kg dry waste and the estimated methane yield is in the range of 60 – 230 L CH_4/kg dry waste. Table 2.8 summarizes the estimated gas and methane yield based on this method.

Table 2.8: Gas and Methane yield based on the biodegradability Method

Source	Gas yield (L/kg dry waste)	Methane (L/kg dry waste)
Ham, 1979	120-310	60-155
Barlaz et al., 1990	120-350	60-175
Ham et al., 1989	100-300	50 - 150
Peer et al., 1993	-	60-230

Experimental approach. In the experimental approach, the landfill gas yield can be obtained from laboratory or field scale studies or anaerobic digestion studies.

Laboratory scale studies. The amount of biogas produced by biodegradation of MSW can be measured in the laboratory. The biodegradation of MSW can be controlled and enhanced by manipulating environmental factors such as pH, temperature, moisture, nutrients, etc. The range of methane yield from lab scale studies varies from no generation to 107 L CH_4/kg dry waste. Table 2.9 summarizes the methane yield from different studies.

Table 2.9: Laboratory scale studies (based on 40% (w/w) initial moisture content)

Source	Methane yield (L /kg dry waste)	Condition
Ham et al., 1989	0.01-30	Run for approximately 1-3 years, 53% CH_4
Barlaz et al., 1989	77-107	Shredded wastes, pH control and leachate recycle at 41°C and moisture of 73% (wt basis)
Leuschner et al., 1982	R1= 0.07 R2 = 0 R3= 35 R4 = 47 R5 = 63 R6 = 22	The experiments were run for 365 days control without leachate recycle. with leachate recycle and anaerobic sludge addition with leachate recycle and buffer addition with leachate recycle, buffer and nutrients addition with leachate recycle, buffer and anaerobic sludge with leachate recycle, buffer, nutrients, and septic tank sludge.
San et al., 2001	R1 = 9 R2 = 35	The experiments were run for 275 days without leachate recycle with leachate recycle.
Sponza et al., 2004	R1 = 28 R2 = 69	The experiments were run for 225 days volume of leachate recycle was 30%(v/v) of MSW volume of leachate recycle was 10%(v/v) of MSW
Sponza et al., 2005	R1 = 23 R2 = 26	The experiments were run for 57 days. All reactors run with leachate recycle. R1 with raw MSW, R2

	R3 = 26	with compacted MSW and R3 with shredded MSW.
Ağdağ et al., 2005	R1 = 27 R2 =33 R3 = 40	The experiments were run for 57 days. All reactors run with leachate recycle. R1 without buffer, R2 with 3 g/l of buffer and R3 with 6 g/l of buffer ($NaHCO_3$).
Chiemchaisri et al., 2002	R1= 39 R2 = 51 R3 = 52	The experiments were run for 240 days and all reactors run with leachate recycle, pH control, and digested sludge but with different frequency of leachate recycle. The frequency was 4, 8 and 15 times per month for R1, R2 and R3, respectively.

Field scale studies. Pilot cells are representative of real landfill conditions because they are built within a landfill and are subject to similar waste composition, climate and field conditions. The methane yield produced from pilot studies is in the range of 40 – 140 L CH_4/ kg dry waste. Table 2.10 summarizes the methane yield from different studies.

Table 2.10: Methane yield in field scale studies

Source	**Methane yield (L/kg dry)**	**Conditions**
Halvadakis et al., 1988	40 (control) 63 (enhancement)	(Mountain view project) Enhanced cell with leachate recycle and pH neutralized.
Laquidara et al., 1986	140	From site for 20 years.

Anaerobic digestion studies. The biodegradation of MSW in anaerobic digestion studies occurs under optimum conditions for methanogenic bacteria. The methane yield based on digestion studies is in the range of 210 - 260 L CH_4/kg of waste (Rees, 1980; Ham, 1979). The reasons for the highest yield in digesters compared to the other experimental studies (lab and field) are seeding with sewage sludge, mixing to provide uniform conditions in terms of substrates and nutrients, and good control of variables such as

temperature, time and moisture content. Table 2.11 summarizes the methane yield of anaerobic digestion studies.

Table 2.11: Methane yield in anaerobic digestion studies.

Source	Methane yield (L/kg wet)
Ham, 1979	210-260
Rees, 1980	230-260
Ham et al., 1989	210-260

Based on these two approaches, it appears that the total amount of methane generated from the biodegradation of MSW is in the range of no generation to 270 L/kg dry waste. The following section will address the factors influencing the amount of methane produced through the biodegradation of MSW.

2.2.5 Factors controlling the biodegradation of MSW in landfills

The biodegradation of MSW in landfills is dependent on a number of factors, including moisture content, pH, oxygen concentration, hydrogen concentration, waste composition (characteristics), the availability of nutrients and biomass, the presence of inhibitors, and temperature. These factors have been studied by several authors (Rees, 1980; Barlaz et al., 1982; Klink et al., 1982; Baldwin et al., 1998 and Kasali et al., 1989) and reviewed by Barlaz et al. (1989); Christensen et al. (1992) ; El-Fadel et al. (1996a); Röhrs et al. (1998) and Warith (2003).

2.2.5.1 Moisture content and movement

Moisture is essential for the activity of all microorganisms in the landfill. The moisture content therefore is one of the most critical factors controlling the biodegradation of MSW.

Many researches have shown that the methane production rate increases by increasing the moisture content of the MSW. Rees (1980) found from existing literature that by increasing the water content from 25% to 60% (wt), the rate of gas production and the percentage of methane in the gas are increased. Baldwin (1994) studied the moisture content in three landfills over 1-6 years and found that wastes with high moisture content are more quickly decomposed. The effects of increased moisture content are: limitation of oxygen diffusion from the atmosphere into the landfill; exchange of substrate, nutrients and microorganisms; dilution of inhibitors and improved distribution of enzymes and microorganisms within the landfill (Klink et al., 1982; Christensen et al., 1996). Furthermore, Klink et al. (1982) concluded that moisture movement through the MSW increased the methane production rate from 25% to 50%, compared to no movement of moisture at the same moisture content levels.

2.2.5.2 pH

The pH of leachate produced from a landfill can have a significant effect on the stabilization of methane production. The fermentative and acidogenic microorganisms have a wider range of pH compared to methanogenic bacteria. The ideal methanogenic bacteria activity occurs in environmental conditions within a pH range of 6.8 to 8.0 (Warith, 2003). Any drop in the pH value below 6.8 will slow down the activity and growth of methanogenic microorganisms. In a well-established methanogenic media, if the methanogenic activity is inhibited by other factors [O_2, H_2, etc.], the conversion of acetic acid to CH_4 and CO_2 decreases and leads to an accumulation of the acids, thereby decreasing the pH which in turn may stop the generation of methane (Christensen et al., 1996).

2.2.5.3 Oxygen concentration

The activity of anaerobic microorganisms is affected by the presence of oxygen. Thus, the absence of oxygen in the landfill is required in order to grow methanogens and degrade the MSW into CH_4 and CO_2.

Christensen et al. (1996) reported that the methanogenic bacteria required very low redox potentials (below -330 mv). In reality, the oxygen that diffuses from the atmosphere into the landfill is consumed by aerobic bacteria in the top layers of the landfill (aerobic zone) (Warith, 2003).

2.2.5.4 Hydrogen concentration

The fermentative and acidogenic bacteria produce hydrogen during the biodegradation of MSW, while the methanogenic bacteria use the hydrogen as a substrate to produce methane. Low partial pressure of hydrogen is required for the acidogenic processes (by hydrogen producing bacteria) and methanogenesis processes.

An increase in the partial pressure of hydrogen causes the generation of propionic and butyric acids with no further conversion, resulting in an accumulation of volatile organic acids which reduce the pH and inhibit the methanogenic bacteria. The conversion of propionic acid requires a hydrogen pressure lower than $9 \cdot 10^{-5}$ atmospheres (Christensen et al., 1989).

2.2.5.5 Nutrients and trace metals

Microorganisms in the landfill require various nutrients for their activity, such as nitrogen and phosphorous, as well as traces of heavy metals like zinc, iron, copper, potassium, calcium, and cobalt. Rees (1980) and Christensen et al. (1996) found from existing

literature that all the necessary nutrients and traces of heavy metals are available in most landfills, but heterogeneous insufficient mixing of the wastes may result in nutrient limited environments. The optimal ratios needed in order to enhance the biodegradation are 100:0.44:0.08 for organic matter expressed as chemical oxygen demand (COD), nitrogen and phosphorous (McCarty, 1964).

2.2.5.6 Inhibitors

There are a number of elements or compounds that can inhibit the biodegradation of MSW (methane production) besides O_2, H_2, pH (acidity) and high concentrations of heavy metals. These inhibitors are carbon dioxide, sulphate, and high concentrations of cations such as sodium, magnesium, and ammonium. The CO_2 acts as an inhibitor by raising the redox potential which has an effect on the acetic acid conversion to methane (Christensen et al., 1996).

Rees (1980) reported that high sulphate concentrations inhibit the methanogenic bacteria for two reasons: reduction of SO_4^{2-} to S^{2-}, which is toxic; and competition for common substrate between methanogenic and sulphate reducing bacteria.

These cations in low concentrations are required for biodegradation, but in high concentrations they inhibit the methanogenic bacteria.

To the author's knowledge, there has been no studies to evaluate the impact of Cl on the biodegradation of MSW.

2.2.5.7 Temperature

Similar to other microbial processes, the biodegradation rate of microorganisms involved in the MSW decomposition is highly affected by temperature. Methane production

increases with an increase in temperature (Dewalle et al., 1978). The optimum temperature for methane production in mesophilic waste decomposition is in the range of 30°C to 40°C, whereas 60°C is the optimum temperature for thermophilic waste decomposition (Ham et al., 1994 and Barlaz et al., 1990).

Hartz et al. (1982) recommended that the optimum temperature for methane generation is in the range of 36°C to 41°C. Ham et al. (1992) concluded that gas production rates at 30°C, 35°C and 40°C are much higher than rates at 20°C and 45°C.

2.2.6 Enhancement methods

The biodegradation of MSW in bioreactor landfills can be enhanced through different methods. In all cases, the purpose is to control and manipulate the influencing factors in a positive manner in order to accelerate the biodegradation of MSW. There are many advantages to enhancing the biodegradation of MSW, including more rapid waste stabilization and increased gas production; lower leachate treatment costs through recirculation to the landfill; reduced length and cost of post closure activities; and greater landfill airspace availability due to increased settlement during the operation rather than the post closure stage, as is the case in conventional landfills (Reinhart et al., 2002).

The technologies used to enhance the biodegradation of MSW are studied by Dewalle et al. (1978), Klink et al. (1982), Stegmann (1983), Laquidara et al. (1986), Pacey (1989), Brummeler et al. (1990), Bae et al. (1998), San et al. (2001), Chan et al. (2002), Chiemchaisri et al. (2002), Warith (2003), and reviewed by Barlaz et al. (1990), Christensen et al. (1992), Stegmann et al. (1996), Warith et al. (1998), Komilis et al. (1999a).

These enhancement methods are leachate recycle, pH buffering, sludge addition, temperature control, reduced waste particle size, improved lift design, daily cover and waste compaction, and pre-treatment of MSW. They will all be discussed in the following sections.

2.2.6.1 Leachate recirculation

Leachate recirculation is the process by which the leachate collected at the base of the landfill is recycled or reintroduced in the landfill in order to control the moisture content. The advantages and impact of leachate recirculation on the biodegradation of MSW were covered by Ham et al. (1982, 1992), Barlaz et al. (1996), Baldwin et al. (1997), San et al. (2001), Reinhart et al. (1996, 2002), Warith et al. (1998, 2002, 2003), and Sponza et al. (2004). The advantages of leachate recirculation lie both in the rapid reduction of the organic content present in the leachate itself which reduces the cost of treatment; and the potential transformation of waste into energy, as it increases the rate of methane production. Leachate recirculation provides optimum conditions for enhancing biodegradation by increasing the moisture content and movement, and by distributing the nutrients throughout the landfill. Both moisture content and moisture movement are necessary settings for bacteria growth and the establishment of methanogenic conditions. They also provide better contact between insoluble substrates, soluble nutrients and microorganisms (Klink et al., 1982).

Ham et al. (1982 and 1994) and Baldwin (1997) studied the effect of moisture content on the biodegradation of MSW and concluded that moisture content has a positive effect on gas production. Dewalle et al. (1978) found that the highest gas production was at 40%-

50% (w/w) moisture content, while the lowest was at 12%. Also, leachate recirculation treats the leachate through the landfill (in situ treatment) because the organic compounds in the leachate are reduced with the recirculation due to the biological activity within the landfill (Sponza et al., 2004).

2.2.6.2 pH buffering

The methanogenic bacteria are sensitive to pH and could be inhibited by acidic conditions. This understanding has led to adding buffer to the leachate prior to recycling it back to the bioreactor landfill. Leachate recirculation with a buffering system to control the pH causes a shorter acidogenic stage compared to leachate recirculation without a buffering system (Komilis et al., 1999a).

In a study conducted by Warith (2002), the reactor with buffered and nutrients amended recycled leachate resulted in the greatest reduction of COD concentration over time. Also, a study by San et al. (2001) found that the highest degree of stabilization occurred in a reactor with a three-time per week recirculation and pH control by addition of buffer. Ağdağ et al. (2005) studied the effect of alkalinity addition to leachate recycle on the biodegradation of MSW in an anaerobic bioreactor. It was observed that lower COD, VFA concentrations and BOD_5/COD ratios were obtained in the bioreactors with alkalinity addition in comparison to the bioreactor (control) without alkalinity addition.

Lab scale experiment results recommend the addition of buffer to leachate recycle, especially in the acid generation phase, to maintain the pH at a neutral level. This helps to establish a methanogenic condition.

2.2.6.3 Sludge addition

The effect of sludge addition on the MSW biodegradation is covered by Leuschner (1982), Pacey (1989) and Warith (2002). They concluded that the addition of sewage sludge has both a positive and a negative effect on the MSW biodegradation and methane generation.

The positive effects of sludge addition occur after the methanogenic bacteria are already established and the landfill environment is optimum (pH neutral) for methanogenic bacteria (Christensen et al., 1992). This positive effect can be attributed to the following factors: 1) sludge can be a source of nutrients and active methanogenic bacteria, and; 2) sludge increases the moisture content.

The negative effect of sludge addition to fresh waste is attributed to the acid accumulation that is associated with it which decreases the pH and inhibits the methanogenic bacteria (Barlaz et al., 1990).

Rees (1980) and Leuschner (1982) found that the anaerobic digested sewage sludge is an excellent source of microbial inoculum, whereas the septic tank sludge is a poor one. Also, Komilis et al. (1999a) concluded that adding anaerobic digested sludge to MSW produces three times more methane than adding primary sludge.

It appears that the addition of anaerobic digested sludge with buffering enhanced the biodegradation and increased methane generation. Buffering controls the pH of the landfill around neutral, allowing the methanogenic bacteria in the anaerobic sludge to acclimatize to the landfill environment faster than without buffer addition.

The addition of old waste or ashes to new waste could improve biodegradation by diluting the acids produced during the acidogenic stage, thereby enhancing the methane formation stage. The percentage of ash should not exceed 10% in weight (Komilis et al., 1999a).

2.2.6.4 Temperature control

The direct effect of temperature on bacteria activity could be manipulated to optimize the biodegradation of MSW in the bioreactor landfill. Thus, it is necessary to realize the temperature constraints on individual microorganisms in order to control the activity of bacteria and enhance waste stabilization.

Dewalle et al. (1978) found that by increasing the temperature from 17°C to 26°C, gas production rose from 0.88 mL/kg·day to 1.07 mL/kg·day. Baldwin et al. (1998) investigated the effect of temperature on a large scale using two different landfills, one located in Florida and the other in Wisconsin. The Florida landfill (30°C) had a more rapid decomposition compared to the Wisconsin landfill (22°C). Kasali et al. (1989) found that by increasing the temperature of MSW with a 60% (w/w) moisture content from 18.7°C to 30°C caused a 2.6 fold increase in the methanogenic rate, while a 7.8 fold increase when the temperature rose from 18.7°C to 40°C.

Based on the experimental work, the optimum temperature for enhancing the MSW biodegradation is in the range of 30°C-40°C.

2.2.6.5 Reduced waste particle size

Shredding or reducing the particle size of MSW has several advantages, such as providing more landfill space and greater MSW stabilization. The arguments for shredding are: 1) it increases homogeneity and distribution of waste within the landfill, 2) it improves the contact surface area of the waste, 3) it promotes better contact between the organic matter and microorganisms (Christensen et al., 1992).

Ham et al. (1982) found that the shredding of waste increases the rate of decomposition and methane production. Some authors (Buirid et al., 1981 and Dewalle et al., 1978) have concluded that refuse with 2.5 to 3.5 cm particle sizes produced 32% more methane than refuse with 1 to 1.5 cm particle sizes in a period of 90 days. This is due to the fact that the smaller particle size increases the rate of hydrolysis and acid formation which in turn decreases the pH and postpones the production of methane.

Based on Ham et al. (1982)'s study, if the negative effect of smaller particle sizes in the initial stage of biodegradation can be controlled (by adding buffer or pre-composting), shredding may enhance the biodegradation process, since the hydrolysis is the rate-limiting step (El-Fadel et al., 1996b; Pareek et al., 1999; Naranjo et al., 2004; Yildiz et al., 2004).

Sponza et al. (2005) reported that the shredding of MSW has a positive effect on the rate of biological degradation in anaerobic bioreactors with leachate recycle. They compared three types of reactors. The first reactor was loaded with raw waste, the second with shredded waste, and the third with compacted waste. At the end of the experiments (57 days later), they found that the reactor with waste shredding had the lowest COD and VFA concentrations and the highest methane percentage.

2.2.6.6 Lift design, daily cover and compaction of waste

The enhancement of waste biodegradation in the landfill is also affected by the lift thickness, daily cover and compaction of waste.

The lift thickness has an adverse effect on the biodegradation of waste. Ham et al. (1982) found that the cell with a 2 m deep lift produced higher leachate concentrations and took a longer time to stabilize than the cell with a 1.2m deep lift. By doubling the lift depth from 1.2 to 2.4 m, the concentration of leachate and stabilization time are doubled as well.

Similarly, the daily cover has a negative effect on the biodegradation of waste because it decreases the initial stage of O_2 diffusion into the waste which in turn diminishes the initial composting phase. If a low permeability soil is used as a daily cover, it could create barriers between the lift and it may impact leachate distribution and landfill gas flow into the collection system. A soil cover more permeable than the waste can direct leachate to the sides. Use of alternative covers that do not create such barriers can reduce these effects. On the other hand, positive effects of daily cover soil may be expected if the soil adds buffer to the landfill (e.g. contain lime) (Christensen et al., 1992).
Ham et al. (1982) found that the cell without cover produced a high leachate concentration, but it was followed by a rapid decrease. It appears that the lack of daily cover enhances the aerobic activity and prevents a long acidogenic stage. The short acidogenic period leads to the rapid establishment of the methanogenic stage.

Likewise, waste compaction has an adverse effect on the biodegradation of waste in the landfill. Ehring et al. (1980) found that cells with low-density waste have shorter periods

of high leachate concentration. This means that there is an enhancement in the acidogenic stage. Dewalle et al. (1978) found that gas production decreased when the density of the waste was increased. Rees et al. (1982) concluded that by increasing the waste density from 0.2 to 0.47 tonne/m^3, there was a decrease in gas production due to acid accumulation, which in turn decreased the pH and inhibited the methanogenic bacteria.

2.2.6.7 Pre-treatment

The objective of the pre-treatment of MSW is to enhance the acidogenic stage and decrease the accumulation of organic acids. This method is based on the stabilization of part of the waste through aerobic processes which will dilute the organic acids and cause a balance between the acidic phase and the methanogenic bacteria. This method was studied by Ham et al. (1982); Stegmann (1983); Beker (1987); and Brummeler et al. (1990) and was reviewed by Komilis et al. (1999b).

Ham et al. (1982), Stegmann (1983) and Baker (1987) found that by placing fresh waste on top of the composted waste layer caused a shorter acidogenic stage and enhanced the methanogenic stage. This is due to the fact that the composted layer acts as an anaerobic filter which has the ability to treat leachate as it passes through. The composted bottom layer can be prepared by the following procedure: a layer (1.5m-2m) of waste is placed without compaction, so that the easy degradable material can be decomposed aerobically with leachate recycle. The leachate concentration and the temperature of the waste can be used as indicators for the progress of the aerobic process. After one year of the placement, the waste layer is compacted and an additional layer of fresh waste can be added on top (Stegmann, 1983). The author suggested that efforts should be made to

reduce the time required for aerobic decomposition of the first layer by injecting air through perforated pipes.

2.2.7 Case studies

Leuschner (1982) studied the effects of different enhancement methods. He used six reactors in his study. Reactor 1 was run as a control with simulated rainfall only. All other reactors were run with leachate recycle and addition of water. Reactor 2 was run with anaerobically digested sewage sludge, while reactor 3 was run with buffer addition. Reactor 4 was run with nitrogen and phosphorous addition and reactors 5 and 6 were run similarly to reactor 4 but with addition of anaerobic digested sewage sludge and septic tank sludge, respectively. The additions were practiced over the first 150 days of operation, and from then until the end of the experiments (365 days), only leachate recycle was added.

The total methane produced was 2.46, 0, 1275, 1642, 2340 and 835 L at standard temperature and pressure (STP) for R1 through R6, respectively. The methane yield was 0.07, 0, 35, 46.86, 65 and 23.19 L/kg dry waste, respectively, based on the assumption that the initial moisture content was 40% w/w of total MSW used in the experiments. The reason why no methane was produced in R2 was that the pH remained below 6 until day 340. He found that using septic tank sludge as a source of inoculum caused high volatile acids in the leachate and decreased the pH.

Brummeler et al. (1990) studied the effect of air injection as a pre-treatment step on the biodegradation of organic fractions of MSW. The study was conducted using two types of reactors both containing 60 kg of organic waste. The first one was operated with air

injection and the second without it. In the first reactor, air was injected for two weeks at a flow rate of 750 L/h. Then, part of the composted waste was mixed with digested sludge in a 6 L reactor at a ratio of 0.04 of seed/substrate total solids (TS).

They found that there was no methane detected for the first 100 days in the non-treated (no air injection) reactor. The reason for it was that high organic acids reduced the pH to 5.5 which inhibited the methanogenic bacteria. In the treated reactor, the methane production rate increased with an increase of volatile solids (VS) degraded during the composting stage. The highest methane production rate was observed at 23.5% VS reduction. The initial composting step therefore can be used to accelerate the biodegradation of MSW in the bioreactor landfill.

Bae et al. (1998) studied the effects of leachate recycling and sludge addition on methane production from MSW in a bioreactor landfill. In this experimental study, the first reactor (R1) operated as a control, the second reactor (R2) operated with recycled leachate only and in the third reactor (R3), the leachate generated was first treated by an anaerobic digester, and then the effluent from the digester was recycled back to R3. The cumulative biogas production from R3 was approximately 15,676 liters in 430 days, which is approximately 10-30 times greater than the other reactors. Also, the composition of methane reached 25%, 45%, and 60% on day 180 in R1, R2 and R3, respectively. The highest CH_4 composition in R3 was due to the addition of active methanogenic bacteria. Similarly, the COD concentration in R3 dropped sharply to below 10,000 mg/l on day 260 days and decreased to 2000 mg/l on day 360 days, whereas the COD concentration

for the other reactors decreased slowly and reached approximately 60,000 mg/l and 50,000 mg/l on day 360 days in R1 and R2, respectively.

The experiments conducted by San et al. (2001) identify the effect of leachate recirculation frequency on the waste degradation in a bioreactor landfill. They used two reactors in their study. The first one was operated with recirculation of leachate and the second one without it (single pass). The reactor with leachate recycle was operated with a recirculation frequency of 1 to 4 times per week.

The COD concentration of the leachate in the single pass reactor decreased due to dilution and washout mechanism.

The total gas produced at the end of the experiment was 269 L of gas in the recycle reactor and 70 L for the single pass reactor.

Chan et al. (2002) studied the effects of leachate recirculation, sewage sludge addition and the addition of marine dredging material on biogas production and MSW biodegradation. The mixture composed of MSW, sewage sludge and marine sediment (75:20:5 fresh weight basis) was placed in a column with a 15 cm diameter and 150 cm length at a constant temperature of 38°C. The experiment was conducted with and without leachate recirculation. The total biogas produced at the end of the experiment was 1139 L in the bioreactor with leachate recirculation and 395 L in the bioreactor without recirculation. The pH of both reactors was in the range of 5.8-6.5 and the COD concentration in the bioreactor with recirculation was lower than the bioreactor without recirculation.

Chiemchaisri et al. (2002) examined the impact of different frequencies of leachate recirculation on the biodegradation of MSW in a bioreactor landfill. A mixture of MSW and digested sludge at a ratio of 5:1 (on dry weight basis) was placed in three anaerobic bioreactors made of PVC with a diameter of 30 cm and a height of 100 cm. However, it is the opinion of this authors that the 5:1 ratio (on dry basis) may be in error as anaerobic digested sludge has a high moisture content and to add the digested sludge at 5:1 ratio on a dry basis would result in a large volume of sludge being added. Reactors 1, 2 and 3 were operated at recirculation frequencies of 15, 8, and 4 times per month for 245 days, respectively, with pH control. The lowest COD concentration was found in reactors 1 and 2. Similarly, the highest biogas production occurred in reactors 1 and 2 with 496 and 493 L, respectively, at the end of the experiment.

Warith (2002) also studied the effect of several enhancement technologies, including moisture increase, nutrient addition and sewage sludge addition on the biodegradation of MSW in a bioreactor landfill. In his experiments, leachate was recycled four times per week for the first 6 months. Three sets of bioreactors were used in this study. The first reactor was used only for control purposes with leachate recirculation. Nutrients and bicarbonate ($NaHCO_3$) were added with recycled leachate to the second reactor. Sewage sludge was added with the recycled leachate to the third reactor at 5% of the total leachate volume. The concentration of BOD and COD started to decline after the third week in all three reactors because of an increase in pH and the onset of the methanogenic stage. The concentration of BOD and COD in the reactor amended with pH control and nutrients reached the minimum value faster than in the other reactors. A higher degree of settlement was achieved in the reactor with sludge addition. The settlements (difference

between the height of MSW layer at the beginning of the experiment and at the end) reached were 50% in the sludge amended reactor, 40% in the nutrient amended reactor and 37% in the control reactor.

In their study, Sponza et al. (2004) compared the effect of leachate recycling at different recirculation rates on the biodegradation of MSW in anaerobic bioreactor landfills. Three Plexiglas reactors were used in this experiment with a diameter of 30 cm and a height of 100cm. The first reactor (R1) operated without recycle (single pass), the second reactor (R2) operated with leachate recirculation at a rate of 9 L/d and the third reactor (R3) operated at 21 L/d. The increased leachate recirculation in R3 had less impact on the COD concentration in comparison to R2. The methane gas production was increased from 10 to 64 L in R2 and from 9 to 50 L in R3 from day 5 to day 50. The lower methane production for R3 in comparison to R2 may have been due to the increased leachate recirculation which caused washout of active methanogenic bacteria. On the other hand, however, the gas produced from the recycled reactors was one and a half times greater than the gas produced from the single pass reactor. Also, the methane content was higher with leachate recycle. The methane content for the single pass reactor was approximately 10%-25% and for R2 and R3 was approximately 40%-60%. The results showed that the 9 L/day recirculation rate accelerated the methane production and waste stabilization faster than the 21 L/day recirculation rate.

One can generally conclude from all these studies that:

- An increase in moisture content and leachate recirculation has a positive effect on the waste stabilization process.

- Smaller size waste particles increase the rate of hydrolysis.
- Too much leachate recycle inhibits the methane production due to the washout of active bacteria.
- Ideal temperature for methane production is in the range of 30°C – 40°C.
- pH should be maintained above 6.8 to enhance methane production.
- Daily cover causes negative effects: it delays the biodegradation of MSW, and it affects the leachate distribution and biogas collection system. However, it has a positive effect on the biodegradation of MSW, if it contains buffer.
- Deeper waste lifts result in higher COD concentrations in the leachate likely due to an increased acidogenic phase.
- Buffering of leachate and the addition of sludge and nutrients both enhance the biodegradation and methane production.
- Pre-treatment (air injection) enhances the acidogenic stage and decreases the accumulation of organic acids in the beginning of the experiment which creates a suitable environment for the methanogenic biomass to take place sooner.

2.3 Saline wastewater treatment

No studies have been conducted to determine the impact of salinity or chloride on the biodegradation of MSW. However, researchers have evaluated the impact of salinity on wastewater treatment and a summary of these studies are presented below.

The high salt content in wastewater reduces the efficiency of conventional treatment processes through the loss of activity by microorganisms. It was found that only 7%-18% of sewage bacteria can grow in wastewater that contains 2.8% to 7% (w/v) (28,000 mg/l to 70,000 mg/l) concentration of salt (Woolard et al., 1994). There are three problems associated with using conventional wastewater treatment processes to treat saline wastewater. First, conventional wastewater processes are sensitive to rapid changes in salt concentration, which causes a reduction in the COD removal efficiency, an increase in the suspended solids in the effluent and a loss of active biomass. Usually, a gradual increase in salt concentration will cause fewer problems, compared to a rapid shift in salt concentration. Second, an increase in salt concentration causes a disruption of the metabolic function of microorganisms and reduces the kinetics of biodegradation. The solution to this problem is a lower F/M (food to microorganism) ratio in order to increase the efficiency of the process. The third problem relates to high suspended solids in the effluent, resulting in low sediment efficiency due to a reduction in the population of protozoa and the build up of filamentous organisms (Kargi et al., 1996, 1998; Woolard et al., 1994; Hamoda et al., 1995). An approximate 30% decrease in BOD removal efficiency is observed when fresh wastewater treated by the activated sludge process was dosed with 3% (w/v) salt concentration (Kargi et al., 1997).

The suitable solution to improve the efficiency of using conventional processes in order to treat saline wastewater lies in using salt tolerant halophilic organisms, marine sediment or a combination of halophilic organisms and activated sludge. Activated sludge with salt tolerant halophilic organisms was successfully used to treat saline wastewater in different processes with high COD removal efficiency at salt concentrations from 3%-5% (w/v) (Woolard et al., 1994; Kargi et al., 1996, 1997, 1998, 2002; Santos et al., 2001).

The biological treatment of saline wastewater by marine sediment was studied by several researchers (Aspe et al., 1997; Kargi et al., 1997; Vidal et al., 1997; Panswad et al., 1998; Gharsallah et al., 2002).

2.3.1 Halophilic organism classification

The halophilic organisms can be classified as non-halophilic, marine, moderately halophilic and extremely halophilic, based on salt requirements for optimum growth and the halophilic microorganism's adaptability to saline environments. Non-halophilic bacteria grow in a medium containing less than 1% (w/v) salt concentration, and marine bacteria grow in 1%-3% (w/v) salt concentration. Moderate halophilic bacteria grow in a medium of 3%-15% and extreme halophilic bacteria grow in 25% (w/v) salt concentration. Most strains of extreme halophilic bacteria grow by anaerobic fermentation and nitrate reduction (Barbara et al, 1984; Woolard et al., 1994; Rosa et al., 2001).

2.3.2 Case studies

This section covers lab scale experiments conducted to assess the impact of salt concentration on microbial activity. Several experiments have been undertaken regarding

the treatment of saline wastewater using halophilic bacteria, marine sediment and activated sludge.

- *Halophilic bacteria*

Woolard et al. (1994) examined the removal of phenol from saline wastewater with a sequencing batch reactor (SBR) using halophilic bacteria. The SBR achieved 95% removal of phenol at 15% salt concentration and showed very stable removal rates during the seven-month period of the study.

Kargi et al. (1996) outlined the effect of salt concentration on the biological treatment of saline wastewater in batch operations in their various studies. Saline wastewater (0-5% w/v) was placed in an aeration tank. The results showed that the increase in salt concentration caused a reduction in the COD removal efficiency. The COD removal efficiency was approximately 85% for the salt free environment and it decreased to approximately 60% at 5% (w/v) salt concentration.

In another experiment, Kargi et al. (1998) used halophilic organisms to treat saline wastewater using a rotating biodisc contactor. Halophilic organisms and activated sludge were used as inoculums in this study at (50/50) volume basis. The results showed that COD removal was 95% at 1% (w/v) salt concentration and that it was reduced to 60% at 10% (w/v) salt concentration after 4 hours of operation.

In a later experiment, Kargi et al. (2002) used halophilic bacteria to enhance the biological treatment of saline wastewater. The experiment was run with both the halophilic bacteria free and halophilic bacteria supplemented activated sludge. The

results exhibited a little difference in COD removal efficiency for both processes at 1% (w/v) salt concentration with 80% and 90% for halophilic bacteria free and halophilic bacteria supplemented activated sludge, respectively. At 9 hours of batch operation and the initial COD concentration at 2300 mg/l, the COD removal was 85% with halophilic bacteria supplemented activated sludge and 58% with halophilic bacteria free sludge at 5% (w/v) salt concentration.

- Marine sediment

Vidal et al. (1997) studied the treatment of saline wastewater by anaerobic filters with marine sediment as anaerobic inoculums without nutrient addition. The results showed that the efficiency of COD removal was 70% with an organic loading rate of 9.5 – 14.3 g/l·d and 3% (w/v) salt concentration.

Panswad et al. (1998) compared the impact of saline wastewater on anaerobic/anoxic/ aerobic treatments with and without acclimated seeds. The results showed that the COD removal efficiency decreased from 97% to 60% as the salt concentration increased from 0 to 30 g/l without seeds, whereas the COD removal dropped from 90% to 71% with acclimated seeds as the salt concentration increased from 0.5 to 3 % (w/v) salt concentration .

From these case studies, it can be concluded that:

- Increased salt concentrations caused a decrease in the efficiency of COD removal.
- Using both halophilic bacteria and activated sludge improved COD removal efficiency.
- Use of acclimated seeds in anaerobic/anoxic/aerobic treatments of saline wastewaters seemed to enhance COD removal efficiency.

2.4 Existing models

This section provides a review of some mathematical models that have been developed to study the biodegradation of solid waste in landfills. Mathematical modeling is an important tool to understanding the steps (hydrolysis, acidogenesis and methanogenesis) involved in the biodegradation process and predicting the behavior of contaminants and biogas production. These models are based on analytical or numerical solutions of equations governing the quality of leachate generation and biogas production during solid waste biodegradation. Several mathematical models have been developed to simulate the landfill stabilization in terms of leachate quality and biogas production.

2.4.1 Landfill leachate models

This section covers the models that were developed to predict leachate quality and quantity. The objectives, formulations and validation of these models are explained below.

The mathematical model of Straub et al. (1982a) was used to predict the movement and concentration of inorganic compounds of leachate in sanitary landfills. The model was based on the theory of unsaturated flow and contaminant transport in porous media. The equations in the model were solved by explicit finite difference methods and the required kinetic parameters were obtained from the soil literature. The model was applied to simulate data reported from an experimental landfill column by Qasim et al. (1970). The authors concluded that the model exhibited good behavior and showed good agreement with the experimental results.

Straub et al. (1982b) also developed a mathematical model for the dissolution, transport and decay of organic compounds in unsaturated sanitary landfills. The model was based on a single well-mixed reactor and a cascade reactor concept and on unsaturated contaminant transport in porous media. The dissolution of solid organic waste into liquid was assumed to follow first order kinetics. Monod kinetics models were used for microbial growth and substrate utilization of both aerobic and anaerobic biomass. The gas produced in the anaerobic stage was estimated according to the mass of COD consumed. The kinetics required were obtained from the aerobic treatment of leachate and municipal wastewater treatment and the anaerobic digestion of organic acids. The model was applied to simulate data obtained from experiments done by Pohland (1975). Straub et al. (1982b) found the simulated COD concentration followed the trend of experimental results. They concluded that the aerobic stage is negligible over the stabilization time of a landfill, and that the leachate recirculation accelerated waste stabilization.

The same unsaturated flow model was used by Korfiatis et al. (1984). They developed a mathematical model to predict unsaturated flow through the solid waste in laboratory columns. The model was based on the theory of unsaturated flow through porous media, and the hydraulic parameters required were obtained from small scale experiments. The model was calibrated and verified with estimated data from laboratory columns. They concluded that the moisture transport through solid waste could be described by unsaturated flow in porous media. Leachate quality and solute transport were not modeled.

Demetracopoulos et al. (1986) expanded the model of Korfiatis et al. (1984) based on Straub et al. (1982b). They developed a mathematical model for the generation and transport of leachate in sanitary landfills. The model was based on the continuous stirred tank reactor (CSTR) in series model and the theory of unsaturated flow in porous media. First order kinetics were applied for the dissolution of solid organic into the leachate, and Monod kinetics were used to simulate the microbial growth and substrate utilization. The parameters required for the model were obtained from the literature. They concluded that the model showed reasonable behavior within the range of values used. The results from the model were not verified with actual data.

Gonullu (1994 a, b) developed an analytical model to predict the organic and inorganic contaminants in leachate from landfills. The models were based on these assumptions: the landfill is a well-mixed reactor; the organic compounds and microorganisms are uniformly distributed; and the initial concentrations of contaminants entering through input flow are ignored. In the model, dissolution, mass transfer, biological decomposition and microbial growth processes are the main factors controlling the leachate concentration. The results of the model showed good agreement with the experimental results of three studies obtained from the literature.

Gau et al. (1998) developed a mathematical model to estimate the leachate quality from MSW landfills combined with incinerated residuals. They considered the effect of adsorption, desorption and biodegradation of easy and difficult organic compounds in the leachate quality. The model was calibrated with anaerobic and semi-anaerobic landfill columns. They concluded that model results were approximately similar to the experimental results.

Katsiri et al. (1999) presented a mathematical model to predict the concentration of organic matter in leachate produced with and without leachate recirculation. First order kinetics was used for the solubilization rate, whereas the Monod kinetics were applied for the biodegradation and microbial rates. The model was based on a single, fully mixed reactor. The kinetics required were obtained from six laboratory columns. The model was calibrated with data obtained from studies published by other researchers. They concluded that the landfill could be depicted as a single, fully mixed reactor due to the very slow rates of reaction, and that solid waste stabilization was accelerated by leachate recirculation.

Lee et al. (2001) developed a mathematical model to predict the contaminant concentration in leachate from landfills. The model was based on the following factors: saturated flow equations for 1D, solubilization of organic matter (hydrolysis step), and microbial growth for aerobic and anaerobic biodegradation. The model was solved by the finite difference method and was applied to emphasize the effect of leachate recirculation and continuous input of clean water without leachate recirculation on the landfill stabilization. The results of the model were compared with two case studies (leachate recycle and single pass) and close agreement was observed. They found from the sensitivity analysis of the model that the landfill stabilization was sensitive to the kinetics parameters (yield coefficient, maximum utilization rate, and anaerobic microbial endogenous decay and half saturation coefficient).

Chanthikul et al. (2004) proposed a mathematical model to simulate the leachate concentration from sanitary landfills. The model was based on the mass balance of the

contaminants in the solid and liquid phases with and without leachate recirculation. The model was solved by fourth order Runge – Kutta methods and was calibrated with two experimental results published by Pohland (1975). The results showed the same profile of the experimental results. They concluded that the model could be used to optimize the recirculation ratio, which enhances the biodegradation rate.

2.4.2 Landfill gas models

El-Fadel et al. (1996b) developed a mathematical model to simulate the biodegradation of solid waste and biogas generation in a sanitary landfill. The model was based on biokinetic equations describing the microbial processes, time dependent transport and generation of gas and heat. The biodegradation process occurred in three stages: hydrolysis, acidogenesis and methanogenesis. They assumed hydrolysis to be the rate limiting step in the biodegradation process and was represented by first order kinetics. Monod kinetics were used to simulate the growth rate of acidogenic and methanogenic biomass. The effect of pH inhibition on the methanogenic growth rate was also included. In El-Fadel et al. (1997b) several runs were performed to assess the model sensitivity to the hydrolysis rate constant, the kinetics constant of acidogenic and methanogenic biomass (μ, k_d, k_s) and initial carbon concentrations (solid, aqueous, acetic acid, acidogenic and methanogenic). They concluded that the hydrolysis rate is the most important parameter in gas generation in landfills. Gas generation showed greater sensitivity to the methanogenic kinetics than to the acidogenic kinetics, and the initial concentrations of acetic acid and methanogenic biomass had a more important impact on gas generation than aqueous and acidogenic biomass.

In El-Fadel et al. (1996c) the model was used to simulate data from the Mountain View controlled landfill. The results of the model showed good agreement with the field data. They concluded that the model could be used to predict the rate and total production of biogases in landfills.

Al-Yousfi et al. (1998) developed a numerical (PITTLEACH) model to predict the leachate quality and quantity and biogas generation from municipal solid waste, for both single pass and leachate recirculation. The model consisted of four phases. In the first phase, the water budget method was used to estimate the net percolation rate of water flow into the waste layer. In the second phase, leachate generation and transport rates were estimated by using the theory of moisture flow through unsaturated porous media. The third step was to simulate the anaerobic process involved in landfill stabilization, including hydrolysis, acid formation and methane fermentation. In the fourth phase, the effect of acetic acids (pH inhibition) on the methanogenic biomass was modeled. The model was calibrated with experiments done by Yari (1986) and Pohland et al. (1992). The model results were close to the experimental results for both scenarios (single pass and leachate recirculation).

Pareek et al. (1999) developed a mathematical model to predict the methane and carbon dioxide production from landfill reactors operated under sulphate reducing and methane producing conditions. The model was based on biochemical processes responsible for the biodegradation of solid waste in landfills. These processes were hydrolysis, acidogenesis, methanogenesis and sulfidogenesis. Hydrolysis was assumed to be the rate limiting step in the process and followed first order reaction, whereas the Monod kinetics were applied

for the growth of acidogenic and methanogenic bacteria. A multiplicative model was applied to estimate the growth rate of the sulfidogenic bacteria. The values of kinetics required were taken from the literature. The model was calibrated with four experiments run for 700 days. The simulated methane production was in good agreement with the measured values in all reactors, but the carbon dioxide production was not so accurate in the sulphate reducing reactors for the first 100 days. They concluded that the moisture factor and initial concentration of biomass and acetic acid were important factors in controlling the microbial growth rates and methane production.

Suk et al. (2000) proposed a numerical model to predict the change in leachate concentration and gas production by microbial activity in landfills. The model included gas and water flows, interphase mass transfer of solids and water phase solutes, microbial growth and death, and aerobic and anaerobic biodegradation. The model was applied to measure gas composition and leachate qualities of the experiments done by Lee (1997). The results of the model matched the experimental data.

Haarstick et al. (2001) developed a mathematical model to simulate the biodegradation of organic wastes (easily and slowly degraded), biogas generation and heat release. The model was based on physical, chemical, thermodynamic and microbial processes occurring in landfills. The biodegradation of organic waste was assumed to follow three biochemical reactions: hydrolysis, acidogenesis and methanogenesis in which Monod kinetics were used for all of them. The specific growth rate was considered to be effected by inhibition terms included substrate limiting, inhibitory substrate, temperature, and pH.

The temperature effect is taken into account in the hydrolysis rate constant, and in the acidogenic and methanogenic bacteria kinetics. The effect of pH on the biodegradation rate is also taken into account by including an inhibition term in the maximum growth rate and expressed as non competitive inhibition.

The kinetics required for the model were obtained from the literature. The model was not calibrated with real data.

IWA task group (2002) developed an anaerobic digestion model (ADM1). The model described the anaerobic biodegradation process in four steps: solubilization, acidogenesis, acetogenesis, and methanogenesis. The solubilization step is divided into disintegration and hydrolysis processes of which the first is a largely non biological process and converts the composite particulate substrate to carbohydrates, protein, and lipids. In the hydrolysis process, the carbohydrates, protein and lipids are converted into amino acids and long chain fatty acids by extracellular enzymes. First order kinetics were used to represent the disintegration and hydrolysis processes; whereas Monod kinetics were used to describe the growth of other groups of biomass. Inhibition of pH (all groups), hydrogen (acetogenic groups), and free ammonia (methanogenic groups) was linked to Monod kinetics (growth rate). The pH inhibition was represented using one of two empirical equations; whereas hydrogen and free ammonia were simulated using a non-competitive equation.

Naranjo et al. (2004) modified the model of Haarstrick et al. (2001) by assuming the hydrolysis followed first order kinetics. The model was calibrated with experiments. They used the model to simulate the effect of temperature and water content on acetate

and methane production. The model showed results similar to the experiments. They concluded that temperature had an impact on the growth and activity of bacteria and that an increase in water content enhanced methane production.

Zacharo et al. (2004) developed a mathematical model to simulate the hydrological and biochemical processes taking place in solid waste landfills. They used a statistical velocity model to represent the water flow through the waste. The waste biodegradation was assumed to follow three steps: hydrolysis, acidogenesis and methanogenesis; and employed a simplified methodology for the rate of biodegradation to reduce the parameter requirements. The model was used to simulate case studies. Sensitivity analysis showed uncertain results. They found the model was sensitive to depth of waste, infiltration rate, waste heterogeneity and biodegradation rate constants. In the end, they concluded that the model could be used as a tool for modeling landfill processes and that further improvements were required to assess the model's performance.

Yadiz et al. (2004) proposed a mathematical model to simulate the landfill leachate behavior, distribution of moisture through the landfill, and methane production. They assumed that landfills consisted of cells and that each cell consisted of several layers. Also, they considered each layer as a completely mixed reactor having uniformly distributed solid wastes, moisture, gases and microorganisms. The model was based on the governing equations that describe leachate production, solubilization of inorganic and organic matter, degradation of soluble organic matter, the growth of acidogenic and methanogenic microorganisms, and their inhibition by acetic acid, and change in pH over time. The solubilization of inorganic solid waste was assumed to have followed zero

order kinetics, whereas the solubilization of organic solid waste was assumed to be a function of the concentration difference in leachate and microbial activity. The growth rate of acidogenic and methanogenic microorganisms were described by the Monod kinetics, and it included an inhibition term for acetic acid. The model was solved by the fourth order Runge-Kutta method and calibrated with real landfill data from the Keele Valley landfill. The values of the kinetics required for the model were determined by using a trial and error procedure with the data obtained from the landfill. These values were then compared with the literature. There was good agreement between the predicted and observed results from the Keele Valley landfill. The authors concluded that the model had the potential to be used during the design of landfills to estimate the quality and quantity of leachate and methane production for different operation conditions.

White et al. (2003, 2004) developed a mathematical model to simulate solid waste biodegradation and gas generation in landfills. The model included biochemical biodegradation of solid waste, and transport of leachate and gas. The biodegradation part was based on the model proposed by Young (1989) and El-Fadel et al. (1996a) and was assumed to occur in three stages: hydrolysis, acidogenesis and methanogenesis. The Monod kinetics were used to simulate the growth rate of biomass in all stages. The moisture content and effect of pH inhibition on the biomass growth rates were included in the model. The required kinetics for the model were obtained from the literature. The model was used to simulate case studies but was not calibrated with real data. White et al. (2003, 2004) concluded that the model could be used for laboratory and field tests to investigate the geotechnical and hydrogeological properties of biodegrading solid waste.

From the review of all of these models it is concluded that:

- Each layer could be assumed as a completely mixed reactor containing uniformly distributed solid waste, moisture, gases and bacteria.
- Those model which describe the biodegradation process in three steps are the best tools to represent this study.
- Hydrolysis is the rate limiting step and could be assumed to follow first order kinetics, and
- Inhibition terms such as substrate limiting, inhibitory substrate, pH and temperature could be included in the Monod kinetics (growth rate of biomass term) to represent the influence of the environment on the biodegradation process.

2.5 Hydrolysis

As mentioned before, the biodegradation of MSW in landfills takes place in two stages, aerobic and anaerobic. There are three steps involved in the anaerobic stage: hydrolysis, acidogenesis and methanogenesis. This section offers a brief description of the hydrolysis process in the biodegradation of MSW and the methods used to estimate its rate constant (k_h).

2.5.1 Biodegradation of MSW

The bacteria involved in the biodegradation cannot consume the complex substrate directly. The complex organic molecules must be reduced in size to pass through the cell membrane (Metcalf et al., 2003). The hydrolysis reactions play two important roles in the biodegradation process of solid waste. First, these reactions solubilize the waste and then they convert the soluble material into desired biodegradable material. Extracellular enzymes are responsible for the solubilization and size reduction of waste and they are produced by fermentative bacteria (Grady et al., 1999).

2.5.2 Hydrolysis of organic matter in the MSW

In terms of chemical composition, solid waste can be divided into three major groups of complex organics: carbohydrates, proteins and lipids.

- Hydrolysis of carbohydrates

Cellulose is used to present the hydrolysis of carbohydrates. The hydrolysis of cellulose is performed by a mixture of cellulolytic enzymes like exo-glucansases, endo-glucansases and cellobiases (Paulostathis et al., 1991).

- Hydrolysis of proteins

Proteins are hydrolyzed by two groups of enzymes, protease and peptidases, into polypeptides and amino acids. The amino acids produced are fermentative to volatile fatty acids, carbon dioxide, hydrogen, ammonia and reduced sulfur (Paulostathis et al., 1991). Heukelekian (1958) stated that the hydrolysis of proteins under anaerobic conditions is slower than the hydrolysis rate of carbohydrates under the same conditions.

- Hydrolysis of lipids

Lipids are hydrolyzed into long chain fatty acids and glycerol by lipases enzymes. The long chain fatty acids are degraded by B-oxidation, whereas the glycerol is degraded via glyceroldehyde phosphate. The products are further utilized into volatile fatty acids, carbon dioxide and hydrogen gas (Paulostathis et al., 1991).

2.5.3 Mathematical description of hydrolysis kinetics

The biodegradation of MSW is a multi-step process. When the process occurs in multi-step reactions, the rate of one step is usually very much slower than the other steps. The slowest step is called the rate limiting step or determining step (Hill, 1977). Hydrolysis is the rate limiting step in the anaerobic biodegradation of MSW. In literature, there are two types of models used to describe the hydrolysis process: first order and surface based kinetics.

2.5.3.1 First order kinetics

First order kinetics are used to explain the biodegradation of complex compounds into soluble smaller compounds with the assumption that hydrolysis is the rate limiting step. There are two methods to estimate the first order hydrolysis rate constant. The first

method is based on the change of solid waste concentration and it is studied by (Borzacconi et al., 1997 and Christo et al., 2000).

$$\frac{dC_{(S)}}{dt} = -\left(k_h\, C_{(S)}\right) \qquad [10]$$

Where,

$C_{(s)}$: solid organic concentration (M/L^3)

k_h : hydrolysis rate constant (T^{-1})

Borzacconi et al. (1997) used two reactors filled with different compositions of waste to determine the rate of hydrolysis. The hydrolysis rate constant was calculated by evaluating the increase of the organic matter concentration (COD) in the soluble phase. This means the rate of soluble organic matter formation was equal to the rate of loss of solid organic matter. The experiment was stopped once methane was produced. They found the hydrolysis rate constant was 0.0016 d^{-1} for the reactor containing higher food waste content, and 0.0008 d^{-1} for the lower food waste content reactor.

The second method is based on assumptions of first order kinetics and no intermediate product (VFA) in the biodegradation process. This means the methanogenic biomass prevents the accumulation of VFA during the biodegradation process. So, this method can only be applied to estimate the hydrolysis constant under methanogenic conditions. In this method, the methane produced is used to calculate the hydrolysis rate constant of the substrate. This method was used by Veeken et al. (1999) and Jokela et al. (2005) to estimate the hydrolysis rate constant.

$$Y = Y_u \cdot (1 - \exp(-k_h \cdot t)) \qquad [11]$$

Where,

Y : cumulative methane at time t (L)

Y_u : maximum methane produced (L)

Veeken et al. (1999) determined the hydrolysis rate constant for six compounds of biowaste (filter paper, grass, orange peelings, straw, bark, leaves and whole wheat bread) using equation (11). They found the hydrolysis rate constant in the range of 0.003 to 0.15 d^{-1} at 35°C.

Jokela et al. (2005) estimated the hydrolysis rate constant for different types of grey waste (newspaper, textiles, diaper and cartons) by using biochemical methane potential (BMP) assays and equation (11). The hydrolysis of the grey waste was in the range of 0.021 to 0.107 d^{-1} at 35°C.

2.5.3.2 Surface based kinetics

This method estimates the hydrolysis rate constant based on the surface area available for the hydrolysis. In this method, it is assumed that enzyme activity is present in excess to hydrolyse complex substrates and the hydrolysis rate constant depends only on the surface area available for the hydrolytic enzymes (Vavilin, 1996).

Sanders et al. (2001) used the surface based method to determine the hydrolysis rate constant. They assumed the particles of the substrate are spherical and are degraded from the outside. The following formula was used:

$$\frac{dM}{dt} = -k_{sbk} A \qquad [12]$$

Where M is the mass (M), t is the time (T), k_{sbk} is the surface based hydrolysis constant and A is the available surface for hydrolysis (L^2). Three substrates containing starch with

different particle size distributions were used in the experiments and the surface based hydrolysis constant was 0.4±0.1 ($M/L^2/T$). It showed that the surface of particulate substrate was the key factor in the hydrolysis process.

2.6 Summary of literature review

- From the bioreactor landfill lab experiments it can be concluded that in order to enhance the biodegradation of MSW, settlement and methane production, pre-treatment (air injection) and leachate recycle with pH control and the addition of anaerobic digested sludge offers the best approach.
- The case studies of saline wastewater treatment showed that the use of halophilic bacteria, marine sediment and activated sludge has a positive impact on the efficiency of conventional processes.
- The majority of model studies assumed that the biodegradation of MSW in landfills followed three stages (hydrolysis, acidogenesis and methanogenesis). The hydrolysis step is assumed to follow first order kinetics and Monod kinetics were used to describe the growth rate of both, the acidogenic and methanogenic biomasses.
- Also, most of the model studies divided the landfill into cells or layers and assumed each layer as a completely mixed reactor.
- The hydrolysis rate constant is often assumed to be the rate limiting step and can be estimated using two different methods, first order kinetics and surface area.
- First order kinetics could be calculated from methane produced in the BMP assays or from the decrease of solid concentration in bioreactors, and
- The surface area method estimated the hydrolysis rate constant based on the surface area available for the hydrolysis.

Chapter 3

Materials and Methods

This chapter covers the experimental work and methods that were used to accomplish the objectives of this study. Two types of experimental work were involved: 1D bioreactors and BMP (biochemical methane potential) assays. The 1D bioreactors consisted of two groups. The first group was designed to study the impact of salinity on the biodegradation of MSW under different operational conditions. The second group was aimed at studying the effect of sludge addition on the performance of bioreactor landfills operating under saline conditions. The BMP assays on the other hand were conducted to estimate the anaerobic hydrolysis rate constant of the biodegradation process at different salt contents. The materials and procedures used in this research are presented and discussed in the following sections.

3.1 Design of the experiment

In order to study the impact of saline water and sludge addition on the biodegradation of MSW in an anaerobic bioreactor landfill, two groups of laboratory scale bioreactor cells were used. The first group of 1D bioreactors consisted of four bioreactors. The first bioreactor (R1) functioned as a control, using tap water (without salt), whereas the second (R2), third (R3) and fourth (R4) bioreactors were run at 0.5%, 1.0% and 3.0% (w/v) salt content, respectively. The second group of 1D bioreactors also consisted of four bioreactors. Bioreactor (R5) was run with sludge and without salt addition. Bioreactor six (R6), seven (R7) and eight (R8) were run with sludge addition and 0.5%, 1.0% and 3.0% (w/v) salt content, respectively. All bioreactors were operated with air

injection (first two weeks), leachate recycle and the pH was controlled at a neutral level through addition of buffer ($NaHCO_3$) to the leachate recycle. The bioreactors were placed in 23 ± 2°C room temperature. Table 3.1 shows the experimental variables and their layout.

In the first group of 1D bioreactor experiments, bioreactor R1 acted as a control to examine the impact of salt concentration on bioreactors R2, R3 and R4. In the second group of 1D bioreactor experiments, bioreactor R5 was used as a control for bioreactors R6, R7 and R8 to examine the effect of salt concentration when sludge is added to enhance the biodegradation of MSW in the presence of salt.

Also, bioreactor R1 was used as a control for bioreactor R5 to examine the impact of sludge addition on the biodegradation of MSW without salt addition. Bioreactors R2, R3 and R4 were used as controls for bioreactors R6, R7 and R8 in order to determine the impact of sludge addition on the biodegradation of MSW in the presence of salt.

Table 3.1: The experimental variables and their layout

Bioreactors	Sludge addition	Salt concentration (w/v)	Air injection during initial aerobic phase	pH control of leachate recycle
R1	-	0%	Yes	Yes
R2	-	0.5%	Yes	Yes
R3	-	1.0%	Yes	Yes
R4	-	3.0%	Yes	Yes
R5	Yes	0%	Yes	Yes
R6	Yes	0.5%	Yes	Yes
R7	Yes	1.0%	Yes	Yes
R8	Yes	3.0%	Yes	Yes

The second type of experiment was the BMP assay. The BMP was designed to estimate the anaerobic hydrolysis of biodegradation in the presence of salt (Jokela et al. 2005). The BMP assays consisted of four flasks (BR1, BR2, BR3 and BR4). The first flask (BR1) was run without salt, whereas the second (BR2), third (BR3) and fourth (BR4) were run at 1.0%, 2.0% and 3.0% (w/v) salt content, respectively.

3.1.1 Randomized complete block design

The experiments were set up to explore the interaction between biodegradation of MSW in the bioreactor landfill with or without sludge addition and salinity levels. The runs were designed as randomized complete block designs as shown in Figure 3.1.

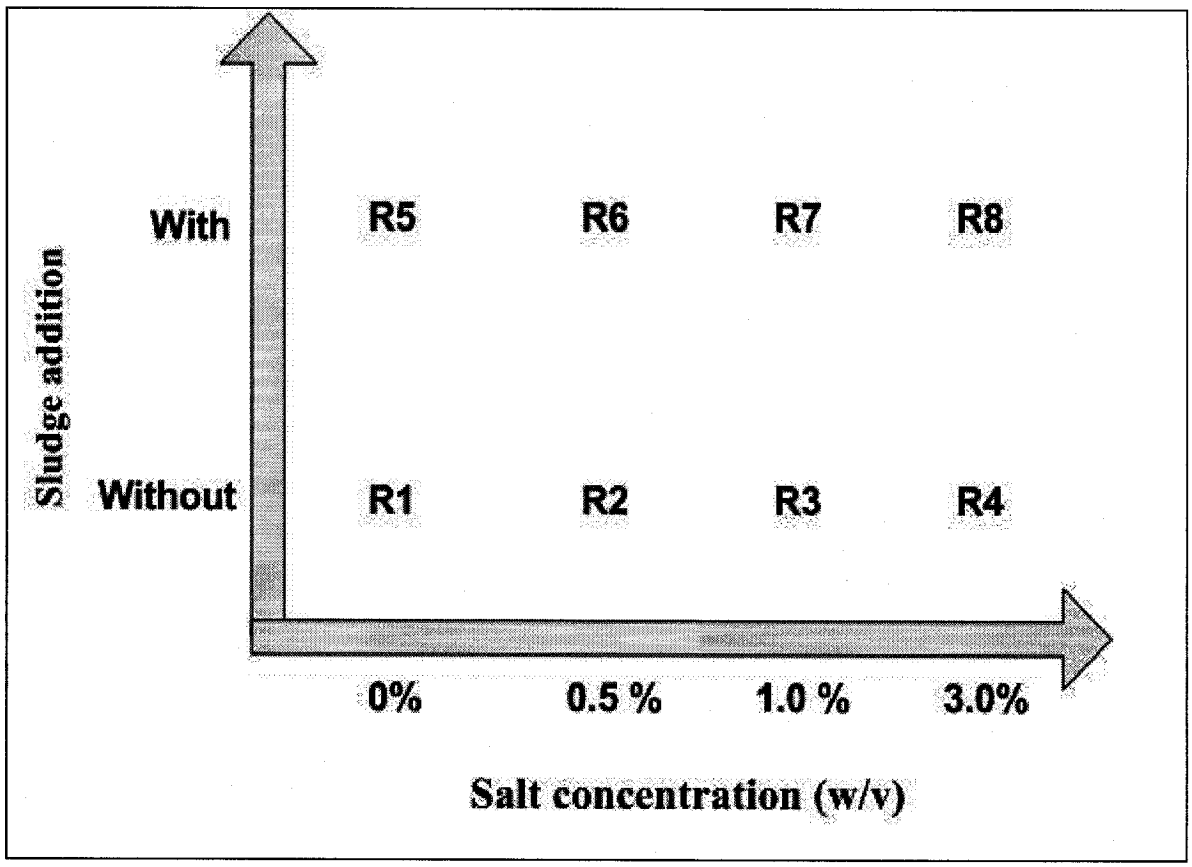


Figure 3.1: The overall design experiment variables.

3.2 Composition of MSW and sludge and 1D column construction

3.2.1 Composition of MSW and sludge

The solid waste used in this study was collected from Carleton University (organic and plastics wastes), Lobe company (shredded paper) and Canadian Tire (textile waste). The composition of MSW used in this study was similar to the composition used in studies carried out by Bae et al. (1998), Katsiri et al. (1999), San et al. (2001), Sponza et al. (2004), Ledakowicz et al. (2004), and Al-Yaqout et al. (2005) and to the waste composition in the UAE.

The solid waste composition based on a weight basis was 60% organic (food), 20% paper, 15% plastics and 5% textile. The wastes were shredded into small pieces to an approximate size of 3 cm to 5 cm. There were two types of sludge used in this research; both obtained from the sewage treatment plant in Ottawa. Aerobic sludge was used in the aerobic stage (first two weeks) and the anaerobic digested sludge was used in the anaerobic stage.

3.2.2 1D bioreactor construction

The 1D bioreactors were designed to simulate the effect of salt concentration on the MSW biodegradation with and without sludge addition. Figure 3.2 shows the configuration of the complete lab scale bioreactor. The bioreactors were made from PVC pipes with 8 mm thickness. Each bioreactor was 30 cm in diameter and 125 cm in height.

At the bottom of the bioreactor, a 7-10 cm thick layer of gravel acted as a drainage layer to collect the leachate at the base of the bioreactor cell. A geotextile covered the gravel layer to prevent migration of fines into the drainage layer. Then the bioreactor was

packed with 1 m of MSW and compacted manually in thin lifts. Table 3.2 shows the density and initial moisture content in the bioreactors.

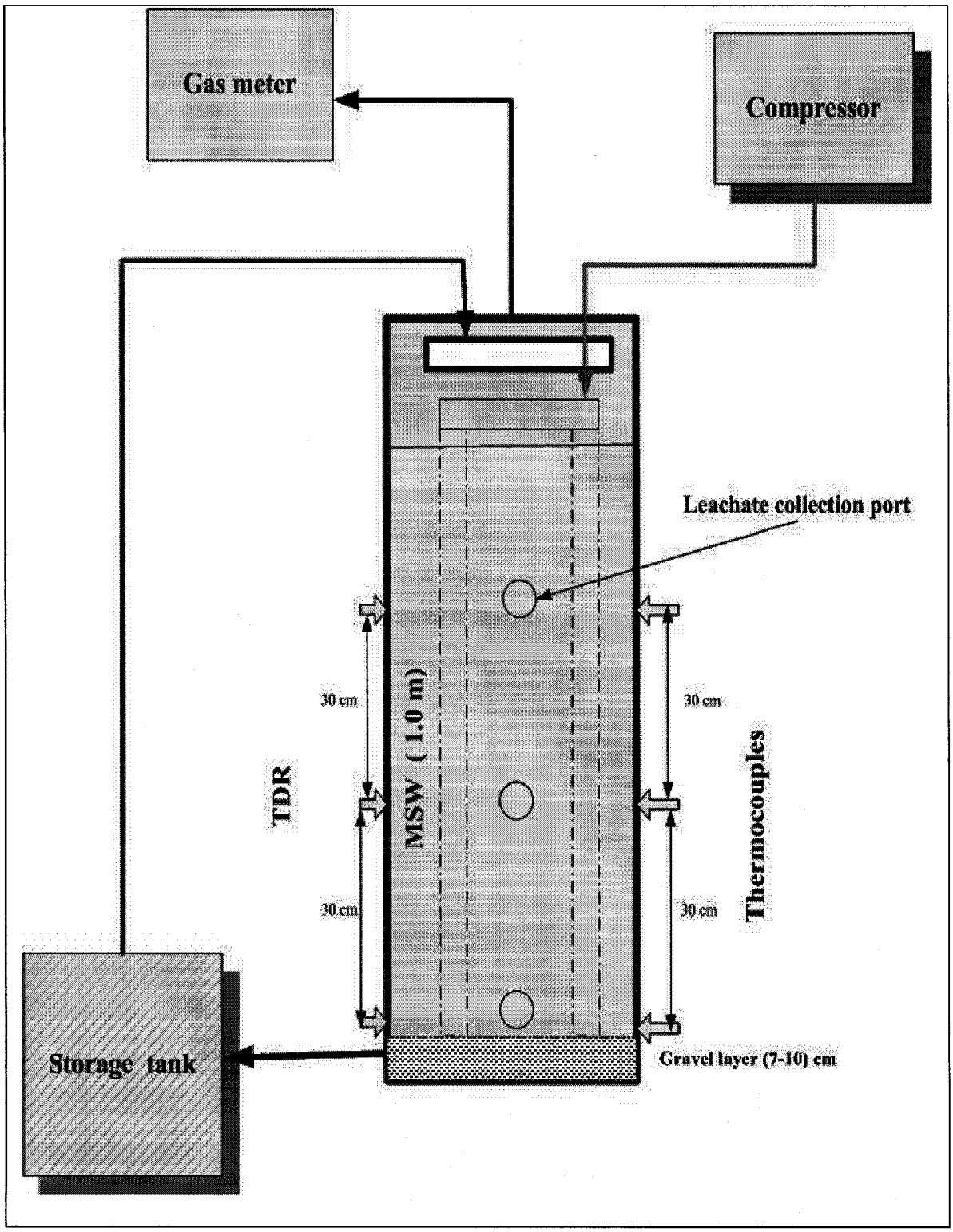


Figure 3.2: Flow diagram of 1D bioreactor landfill.

The bioreactors were operated under aerobic conditions through air injection for the first 16 days of the experiments. For uniform air distribution in the bioreactor, two perforated PVC pipes with a diameter of 1.9 cm were placed in the solid waste and connected to an air compressor. Following the initial 16 days, all bioreactors were sealed with a PVC sheet and operated under anaerobic conditions until the end of the study, approximately 1 year. The PVC sheet was equipped with one vent and two valves. The vent was connected to a gas meter to measure the volume of biogas produced whereas the two valves were used for leachate recycle and air injection.

Table 3.2: Density, initial moisture content and mass of wastes in bioreactors

Parameters	**Density kg/m^3**	**Initial moisture (Wt. basis)**	**Mass of waste kg**
R1	479	39.0%	33.5
R2	490	40.0%	34.3
R3	516	36.1%	36.1
R4	517	44.0%	36.2
R5	502	42.0%	35.1
R6	493	41.8%	34.5
R7	504	43.0%	35.3
R8	517	41.2%	36.2

3.3 Experimental methods and operations

This section covers the operation methods of 1D column bioreactors and BMP assays.

3.3.1 1D column bioreactors

3.3.1.1 Bioreactor filling

The bioreactors were filled with MSW, and the waste was compacted in thin lifts. The height of each lift was in the range of 0.1 to 0.15 m. The average density of the waste was in the range of 479 to 517 kg/m^3. Table 3.2 shows the initial moisture content and density in the bioreactors.

The volume of the waste in the bioreactors was approximately 0.07 m^3 and the mass of the wastes was in the range 33.5 to 36.2 kg.

3.3.1.2 Water addition and leachate recirculation

Once the waste was placed in the bioreactors, water was added into the waste through the leachate recycle valve to increase the moisture content. The bioreactors received a constant quantity of water, 3 L per day, in order to attain field capacity (typically in the range of 45% to 60% by wt.). The total volume of water added to each bioreactor was approximately 7 L before leachate was generated. The addition of water was stopped when the volume of leachate generation reached 7 L. The leachate generated was collected at the bottom of the bioreactor and allowed to gravity drain into a 5 gallon storage container. The leachate was recycled daily in the aerobic stage and three times per week in the anaerobic stage. Once the leachate was drained into the container, the drainage valve was closed to prevent any leakage of biogas.

The volume of leachate recycled was approximately 10% (v/v) of the MSW in bioreactor or 7 L (Chugh et al., 1998), and kept constant during the study.

3.3.1.3 Air requirements

Air was supplied to the 8 bioreactors to maintain aerobic conditions and to satisfy the oxygen demand required by the organic waste decomposition (stoichiometric demand) for 16 days (Brummeler et al., 1990). Anderson (1990) suggested that the suitable aeration rate for the MSW containing moisture of 50 -70% was in the range of 0.6 to 1.8 m^3 air/(d · kg waste). Haug (1993) also provided the general formula – $C_{64}H_{104}O_{37}N$ – for the total organic fraction of MSW. Based on this formula, and assuming the organics were totally degraded, the equation for oxidation of carbon was expressed as:

$$C_{64}H_{104}O_{37}N + 70.75\ O_2 \rightarrow 64\ CO_2 + 50.5\ H_2O + NH_3 \qquad [13]$$

Taking 3 as a safety factor, 16.63 m^3 air kg^{-1} MSW (dry) (25°C and at 1 atm pressure) was supplied. Assuming all the refuse was oxidized in the 16-day aerobic stage, 1.04 m^3 air d^{-1} kg^{-1} MSW (dry) needed to be supplied. Thus, based on the dry weight of the wastes in each bioreactor, approximately 21 m^3 of air per day was injected into each bioreactor.

3.3.1.4 pH control

The leachate pH was adjusted to neutral through the addition of buffer ($NaHCO_3$) before recycling the leachate back to the bioreactor. The addition of buffer was stopped when the pH stabilized around 7.

3.3.1.5 Sludge addition

Two types of sludge were added to the second group of bioreactors (R5 through R8). Waste activated sludge (WAS) was used in the aerobic stage and anaerobic digested sludge (ADS) was used in the anaerobic stage. In the aerobic stage, 5% (v/v) (350 mL) of WAS was added once a week to the leachate recycle, or 800 mL of WAS added during

the aerobic stage. In the anaerobic stage, 5% (v/v) (350 mL) of ADS was added once a week to the leachate recycle until its volume reached 20% of the leachate's volume; that is, 1400 mL of ADS was added for a period of one month.

3.3.1.7 Acclimatized sludge

A 600 mL sample of anaerobic digested sludge was poured into a 2000 mL bottle. The bottle was placed in an incubator at a constant temperature (35°C) and in shaking mode (100 rpm). Initially, the sludge was fed with 60 mL of leachate containing 0.2 % (w/v) salt content and shaken for one day. The following day, the shaker was stopped and 60 mL of this mixture was taken from the bottle using a syringe. After that the bottle was fed again with 60 mL of leachate but this time containing 0.3 % (w/v) salt content and shaken for one day. This procedure was repeated until the salt content reached 2% (w/v). After that the acclimatized sludge was used in the BMP assays as an inoculum.

3.3.1.8 Salt addition

The salt used in this study was sodium chloride (NaCl). The salt concentration in the recycled leachate was maintained at a constant value for each operating condition by adding NaCL to the leachate recycle, as needed.

3.3.2 BMP assays

The BMP was designed to estimate the hydrolysis rate constant of MSW biodegradation operating under saline conditions. One kilogram of MSW (60% organic (food), 20% paper, 15% plastic and 5% textile (w/w)) was used in the BMP assays. The mixture of wastes was shaken with distillated water for 1 day. Then, the supernatant was filtered with a 0.45 μm membrane filter (Veeken et al., 1999 and Jokela et al., 2005). Required nutrients (100:0.44:0.08 for COD: N: P) and buffer ($NaHCO_3$) were added into the

supernatant. A sample of 250 mL from the supernatant was placed in 500 mL serum bottles. ADS acclimatized with supernatant was used as inoculums at a rate of 30% (v/v) or 75 mL for each 250 mL sample. The ratio of volatile solids content of supernatant to volatile solid of inoculum was set to be around 2 to ensure that there was enough inoculum to avoid any accumulation of VFA (Veeken et al. 1999). Then, salt was added to BR2, BR3 and BR4. The headspace of the bottles was flushed with nitrogen gas and they were sealed with rubber septa. A needle was placed in the rubber and connected with a small valve to measure the volume and composition of biogas produced. After sealing, all the bottles were placed in an incubator at a constant temperature (35°C) and shaking mode (100 rpm). The volume and composition of biogas produced were measured at regular intervals.

3.4 Analytical methods

In order to record the progress of biodegradation within the bioreactors, a combination of parameters (solid waste, leachate and biogas) were monitored throughout the experiments.

3.4.1 Solid waste

Solid waste samples were collected from all bioreactors and analyzed at the beginning and at the end of the study for the moisture content and settlement. In addition, temperature was measured in different layers of the solid waste during the first 35 days of the operation.

3.4.1.1 Moisture content

Moisture content was measured according to method 2540 B (APHA, 1992). In this analysis, a sample of 80 – 100 g of wet waste, which had been used in each bioreactor,

was dried at 105°C for 24 hours. The moisture content was expressed as a percentage of weight loss during the drying process divided by the dried weight of the sample.

At the beginning of the study, the moisture content described the initial moisture, and it was analyzed by taking three samples of waste from each bioreactor. At the end of this study, the moisture content was analyzed at different depths (three layers). Then three samples of waste were taken from each of these layers.

3.4.1.2 Temperature

The temperature of the waste during the experiment was measured by inserting thermocouple probes (K-type from OMEG Company) in the bioreactors at 14 cm, 44 cm and 74 cm from the bottom as shown in Figure 3.2. The temperature was recorded in the aerobic stage and in the first 20 days of the anaerobic stage. Later on, the thermocouple probes were removed to prevent any leakage through their wires.

3.4.1.3 Settlement in the bioreactors

Settlement in the bioreactors was estimated by measuring the change in the distance between the top of the bioreactor and the surface of the compacted MSW. This distance was measured at four different points in order to estimate the most accurate height of the MSW settlement. The distance was measured at the beginning (0 day) of bioreactor operations, at the end of the aerobic stage and at the end of the experiments. The settlement that occurred during the aerobic stage was equal to the difference between the distance at day 0 and the distance at the end of the aerobic stage; whereas the total settlement (aerobic and anaerobic stages) was equal to the difference between the distance at day 0 and the distance at the end of the study.

3.4.2 Landfill biogas generation

The volume and composition of biogas produced from the 1D bioreactors and BMP assays during the biodegradation were measured during the experiments.

3.4.2.1 Volume of biogas produced

The volume of biogas produced from the bioreactors and BMP assays was measured using the wet-tip meter and liquid displacement methods, respectively. The wet-tip meter and liquid displacement were calibrated once during the study using a 60 mL syringe. The volume of biogas produced was recorded daily.

3.4.2.2 Biogas concentration

The biogas composition was analyzed with a (SRI 8610 C) gas chromotograph (GC) which had a TCD- HID detector and two columns (6' silica Gel and 3' Molecular sieve). The composition of biogas was determined by injecting 0.5 mL of sampled biogas into a GC in which the carrier gas (helium) was controlled at the flow rate of 32 mL/min. The composition of biogas produced from the bioreactors was analyzed three times per week in the first two months of the anaerobic stage, and from that moment until the end of the study it was analyzed once a week.

The composition of the biogas produced from the BMP assays was analyzed three times per week until it reached 60% (v/v) methane composition and from then on, the biogas was analyzed once a week until the end of the runs. Figure 3.3 shows a sample graph from the GC. The first peak is (N_2 + O_2), the second peak is methane, and the third peak is carbon dioxide.

3.4.2.3 Biochemical methane potential (BMP)

The BMP was used to determine the amount of methane that could be produced from leachate generation (substrate) sampled from the experimental bioreactors. The BMP test was carried out twice during the experiment at the peak leachate concentration (COD), and at one point along the decline of leachate concentration (COD). Two types of inoculums were used in the BMP test. The first inoculum was anaerobic digested sludge; and the second, anaerobic digested sludge acclimatized with salt.

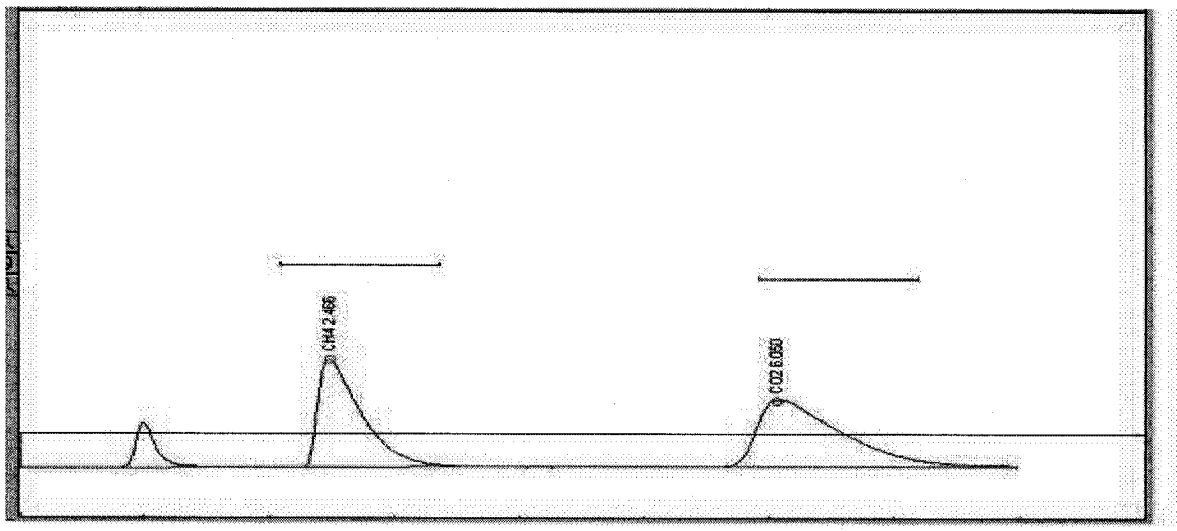


Figure 3.3: Sample of GC result.

3.4.3 Leachate generation

Two hundred milliliter leachate samples were collected from all bioreactors and analyzed in the laboratory three times per week during the aerobic stage; twice per week during the first month of anaerobic stage; once a week from day 40 to day 200 and twice a month from day 200 to the end of the experiments. The leachate parameters, COD, BOD_5, VFA, pH, TVS, TS, NH_3-N, salinity, and leachate profile were measured as indicated in the following subsections.

3.4.3.1 Chemical oxygen demand (COD)

The COD was analyzed according to the 5220 D method (APHA, 1992). This method involves oxidation of organic and inorganic matter using potassium dichromate (digestion solution). The COD was analyzed in duplicate by adding 2.5 mL of diluted leachate to a mixture of digestion solution and sulphuric acid in tubes, and putting the tubes in the oven at 150°C for 2 hours. Then the tubes were removed from the oven and cooled to room temperature. The oxygen consumed in the oxidation was measured using a Perkin–Elmer 2380 spectrophotometer at 600 nm and a calibration curve. The calibration curve was generated twice during the study using a potassium hydrogen phthalate solution.

3.4.3.2 Biochemical oxygen demand (BOD_5)

BOD_5 measured the amount of oxygen consumed for the biodegradation of organic matter during 5 days incubated at 20°C. The BOD_5 test requires a small amount (e.g. 1 mL) of the sample diluted in a 300 mL bottle. A number of dilutions were required to obtain the initial BOD_5 when BOD_5 concentrations were high. The BOD_5 was measured according to method 5210 B (APHA, 1992). The dissolved oxygen (DO) in the samples was measured by a DO Meter (Model 50B, YSI Incorporated Company) and was calibrated three times during the study.

3.4.3.3 Total volatile fatty acids (VFA)

The VFA were analyzed according to the method presented by Anderson et al. (1992). The test was carried out by using 50 mL of leachate as follows: the pH of the sample was measured; the sample was titrated with 0.1 N sulphuric acid through two stages. The first stage was to pH 5.1 and the second stage was from pH 5.1 to 3.5. Then the VFA and bicarbonate were calculated using formulas presented by Anderson et al. (1992).

3.4.3.4 pH

The change in the pH level can be used as an indicator for the progress of the biodegradation process in the bioreactors. It reflects the establishment of the acidogenic and methanogenic stages. The pH of leachate was measured in duplicate using a model 420A pH meter which was calibrated using a buffer solution of pH 4 and 7. The pH was measured immediately after sampling (20 mL of leachate) to avoid any change due to CO_2 stripping.

3.4.3.5 Total solids (TS) and total volatile solids (TVS)

The TS was measured according to method 2540 B (APHA, 1992) by placing 25 mL of leachate in the oven at 105°C for 24 hours. The TS was equal to the weight that remained after placing a sample in the oven.

The TVS was measured according to method 2540 E (APHA, 1992) by placing the TS sample (dried residue) in the furnace at 550°C for 2 hours. The ash was cooled in a desiccator before weighing the sample. The TVS was equal to the weight that is lost in the furnace.

3.4.3.6 Ammonia nitrogen

The dissolved ammonia nitrogen was measured according to standard methods (APHA, 1992) by using an ammonia gas-detecting probe (VWR cat. No. 14002-794). A VWR NH_3 probe and pH meter were used to measured the ammonia nitrogen concentration. First the pH of the sample (50 mL of leachate) was raised to above than 11 by adding 2 mL of 10N NaOH to the sample. Then the ammonia probe was placed in the sample while mixing with a magnetic stirrer and when the reading was stabilized, the mV value was recorded. A calibration curve was prepared once during the study using known

concentrations of ammonia solutions. The mV values were converted into concentrations using a calibration curve.

3.4.3.7 Salinity

Salinity of the leachate was measured according to method 2520 (APHA, 1992) by using Chloride electrode (ORION 9617 BN) and a calibration curve. The calibration curve was prepared five times during the study using known concentrations of chloride standard. First the leachate samples needed to be diluted to fit within the calibration curve (0 to 1000 mg/l Cl). The leachate samples obtained from bioreactors operated at 3% (w/v) salt content were diluted 30 times, and 10 times those obtained from bioreactors operated at 0.5 and 1% (w/v). Then the chloride electrode was placed in a sample (20 mL) of diluted leachate while the sample was being mixed with a magnetic stirrer. When the reading was stabilized, the mV value was recorded. Then the calibration curve was used to convert the mV values into Cl concentrations. Finally, the formula proposed by (APHA, 1992) was used to estimate the salinity concentration in the leachate samples.

3.4.3.8 Leachate concentration profile

To estimate the leachate concentration (COD) at different depths, leachate samples from R1 and R5 were collected from three ports located at 10, 40 and 70 cm from the bottom of the bioreactors using trays, as shown in Figure 3.2. Then the leachate collected on each tray was removed and analyzed for COD. This analysis was repeated three times for R1 and once for R5 during the study.

Chapter 4

Model development

A mathematical model was developed to simulate the biodegradation of the MSW and to predict the leachate strength (aqueous organic and VFA) and the volume of landfill gas (CH_4 and CO_2) produced. The following sections describe the model formulation, assumptions, and derivation, plus the sensitivity analysis performed.

4.1 Model description

The conceptual model describes the biodegradation of solid waste into methane and carbon dioxide as end products, and VFA as an intermediate product. As mentioned in Chapter 2, the biodegradation process occurs over three stages: hydrolysis, acidogenesis and methanogenesis. Figure 4.1 shows the biodegradation pathways incorporated into the model.

4.1.1 Hydrolysis

During the hydrolysis stage, solid waste first solubilizes and converts to aqueous organic acids. According to several researchers (Halvadakis 1983; El-Fadel et al., 1996b; Pareek et al., 1999; Naranjo et al., 2004; Yildiz et al., 2004), hydrolysis is the rate limiting step in the solid waste biodegradation process and is assumed to follow first order kinetics with respect to solid organic concentration:

$$C_s + H_2O \xrightarrow{Enzyme} C_{aq} \qquad [14]$$

Where,
$C_{(S)}$: solid organic carbon (M/ L^3)

$C_{(aq)}$: aqueous organic acids carbon (M/ L^3)

This reaction requires moisture (H_2O) and enzymes produced by fermentative bacteria (hydrolysis bacteria) to occur.

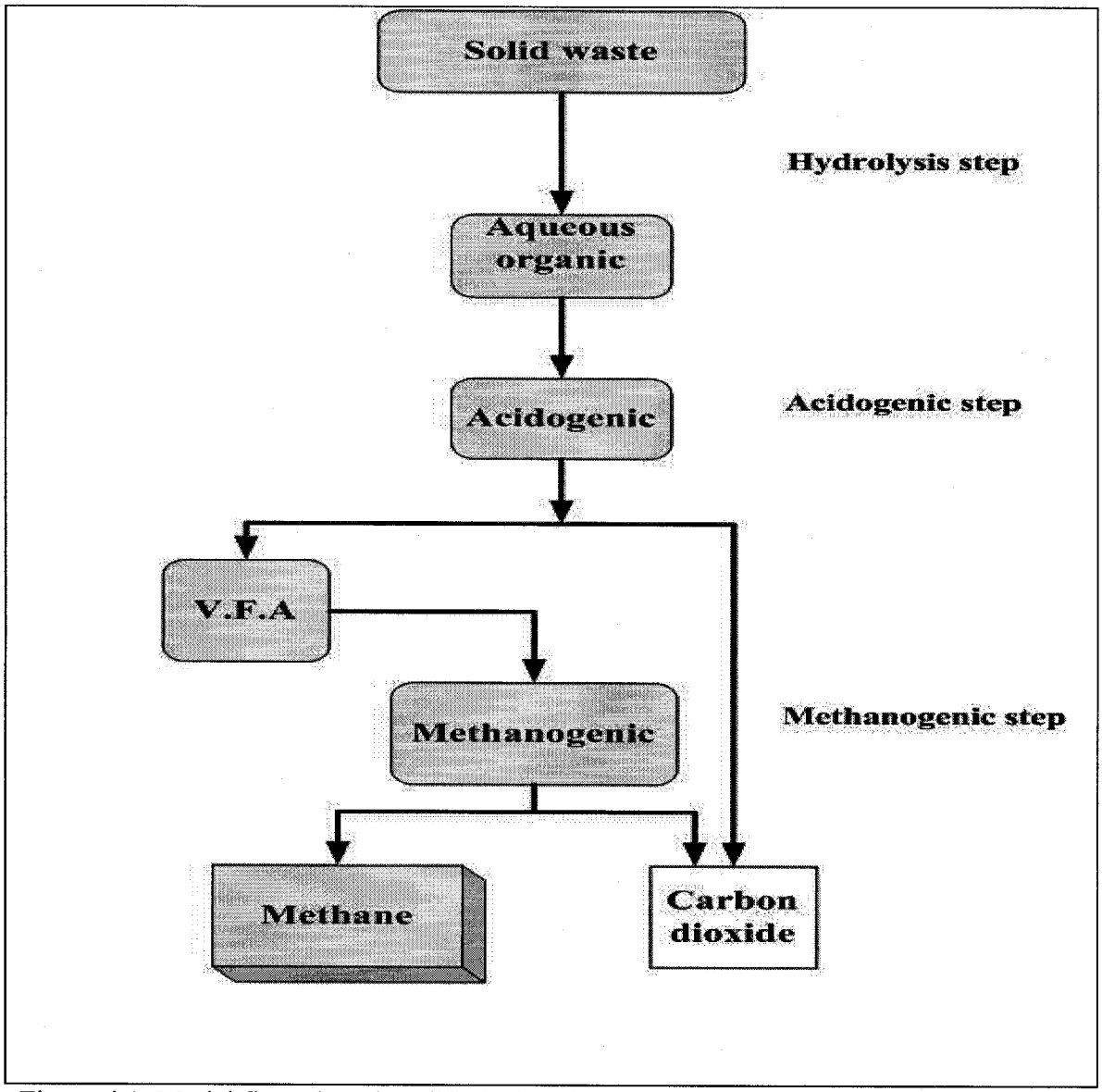


Figure 4.1: Model flow chart (Modified El-Fadel et al. 1996b).

4.1.2 Acidogenesis

In the acidogenic stage, acidogenic bacteria used the end product of the hydrolysis stage (aqueous organic acids) as substrate to produce VFA, carbon dioxide and biomass cells. Monod kinetics were used to describe the growth rate of acidogenic bacteria.

4.1.3 Methanogenesis

In the methanogenic stage, methanogenic bacteria produced methane, carbon dioxide and biomass cells by utilizing the VFA as substrate. Inhibition of methanogenic bacteria by salt content was incorporated into the Monod kinetics and used to describe the growth rate of methanogenic bacteria.

4.2 Model assumptions

There were eight assumptions for the modeling of MSW biodegradation in the bioreactor.

1. The hydrolysis rate constant is the limiting step in the biodegradation of MSW and followed first order kinetics.
2. There is one hydrolysis rate constant for all the solid waste components.
3. There are two types of organisms (acidogenic and methanogenic) involved in the biodegradation of soluble organic matter.
4. Monod kinetics are used to simulate the growth of acidogenic and methanogenic organisms.
5. The inhibition of salt content is applied to the hydrolysis rate constant and methanogenic bacteria because the acidogenic bacteria parameters have less effect on the biogas produced.
6. Acetic acid represents all organic acid generated during the acidogenic stage.
7. The decay of biomass goes to the biodegradable product (VFA or CH_4 and CO_2) at the same ratio as the aqueous phase conversion.
8. Methane generation from hydrogen and carbon dioxide is negligible due to the limitation of hydrogen in the bioreactor landfill and the fact that methane generation from VFA is the dominant process.

4.3 Model development

The mathematical model consists of mass balance equations and sub-models. Both were applied to the acidogenic and methanogenic stages. It is important to note that all concentration are expressed in terms of mass of carbon per unit volume.

4.3.1 Sub-models

The sub-models are substrate, biomass and product models as shown in Figure 4.2.

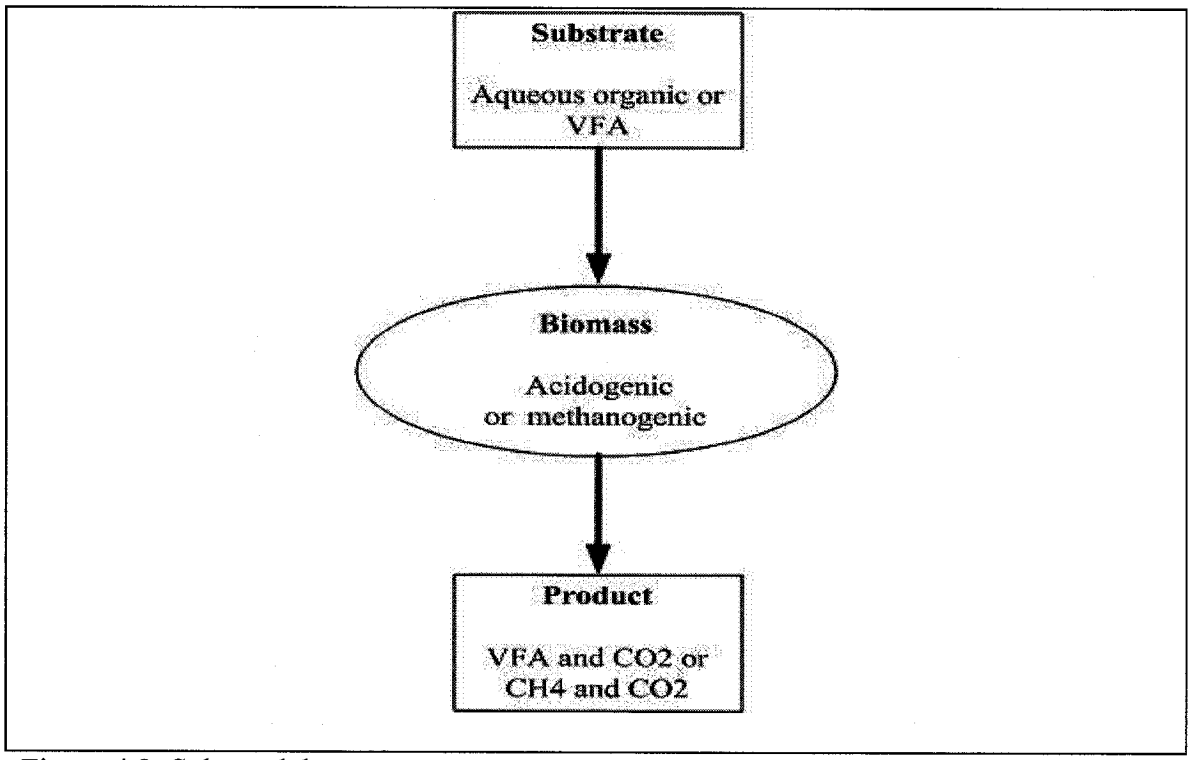


Figure 4.2: Sub-models.

4.3.1.1 Substrate model

The substrate's rate of change in terms of carbon concentration is a function of the biomass growth rate as shown in the following formula:

$$\frac{dC_j}{dt} = -\frac{1}{Y_i}\frac{\mu_i C_j}{K_{Si} + C_j} C_{Xi} \qquad [15]$$

Where,

$\frac{dC_j}{dt}$: change in substrates carbon concentration with time (aqueous organic acids or VFA) ($M/L^3 \cdot T$)

C_j: substrate (aqueous organic acids or VFA) carbon concentration (M/L^3)

C_{xi}: biomass (acidogenic or methanogenic) carbon concentration (M/L^3)

μ_i : maximum specific growth rate constant of biomass (acidogenic or methanogenic) (T^{-1})

K_{Si} : half saturation constant of biomass (acidogenic or methanogenic) (M/L^3)

Y_i: mass of biomass (acidogenic or methanogenic) formed expressed as equivalent carbon mass per mass of (aqueous organic acids or VFA) carbon utilized (M/ M)

The remaining fraction ($1-Y_i$) is converted into biodegradation products; VFA and carbon dioxide for the acidogenic stage; and methane and carbon dioxide for the methanogenic stage. The fraction of carbon converted to each biodegradation product is defined by a fractional formation yield coefficient.

4.3.1.2 Biomass model

The rate of change in biomass carbon concentration is equal to the difference between the growth rate and the decay, as shown in the following formula:

$$\frac{dC_{Xi}}{dt} = \left[\frac{\mu_i C_j}{K_{Si} + C_j} - k_{di} \right] C_{Xi} \qquad [16]$$

Where,

$\frac{dC_{Xi}}{dt}$: change in biomass (acidogenic or methanogenic) carbon concentration with time ($M/L^3 \cdot T$)

k_{di}: decay rate constant of biomass (acidogenic or methanogenic) (T^{-1})

Since salinity is assumed to have an influence on the methanogenic biomass, an inhibition term to simulate the effect of the saline environment was included in the Monod kinetics (growth rate term), which in turn was used to simulate the methanogenic biomass. There are three types of inhibition terms namely competitive, uncompetitive and noncompetitive, as stated in Appendix B (Lehninger, 1975). Since the model will be used to reproduce the 1D bioreactors which operated at neutral pH, the suitable inhibition term is the competitive formulation. The Monod kinetics used to describe the methanogenic biomass is shown in the following formula:

$$\mu = \frac{\mu_M C_j}{K_{SM}\left(1+\left(\frac{I}{K_I}\right)^m\right)+C_j} - k_{dM} \qquad [17]$$

Where,

μ_M : maximum specific growth rate constant of methanogenic biomass (T^{-1})

K_{SM} : half saturation constant of methanogenic biomass (M/L)

k_{dM} : decay rate constant of methanogenic biomass (T^{-1})

I : concentration of salt content % (w/v)

K_I : inhibition constant due to salt content (K_I has same concentration unit as I) at which the rate is 50% of the uninhibited rate (IWA, 2002 and Batstone et al., 2006).

m : inhibition constant due to salt content (dimensionless).

The value of K_I could not be estimated from the results of the 1D bioreactors because these bioreactors operated over a narrow range of salt content (0.5, 1, and 3) (w/v)%. Therefore, the K_I and m were used as empirical fitting parameters and have been estimated through model calibration. They are both presented in Tables 5.34 through 5.36.

4.3.1.3 Product model

The rate of change in the product's carbon concentration is equal to the sum of the fraction ($1\text{-}Y_i$) of the biodegradation of substrate (aqueous organic acids or VFA) that is not converted into biomass and decay of biomass involved in the biodegradation process as is shown in the following formula:

$$\frac{dC_G}{dt} = \left[\left(\frac{1}{Y_i} - 1\right) \frac{\mu_i \, C_S}{K_{Si} + C_S} + k_{di} \right] C_{Xi} \qquad [18]$$

Where,

$\frac{dC_G}{dt}$: change in total carbon concentration of all products with time (VFA and CO_2 or CH_4 and CO_2) (M/ $L^3 \cdot T$)

The change in the individual product carbon concentration are equal to equation [18] multiplied by the corresponding fractional formation yield as detailed in Sections 4.3.2.3 and 4.3.2.5 for the VFA and methane factions, respectively.

4.3.2 Model derivation

As mentioned before, first order kinetics was applied to the hydrolysis of solid carbon wastes. So, the rate of change in solid carbon concentration is described as follows:

$$\frac{dC_S}{dt} = -\left(k_h \, C_S\right) \qquad [19]$$

Where,

$\frac{dC_S}{dt}$: change in solid carbon concentration with time(M/ $L^3 \cdot T$)

k_h: hydrolysis rate constant (T^{-1})

As the hydrolysis products are generated, the organic carbon is eventually converted into one of six forms, including aqueous organic acids, acidogenic biomass, VFA,

methanogenic biomass, methane and carbon dioxide. Mass balance and sub-models were applied to every form of carbon to provide the concentration change at any time.

4.3.2.1 Aqueous organic acids carbon

The aqueous organic acids are the product of the hydrolysis stage and also the substrate for the acidogenic biomass. By applying a carbon mass balance, the rate change of aqueous organic acid is equal to the difference between the generation term (hydrolysis products) and depletion term (acidogenic growth rate). The substrate sub-model is applied to the depletion term. The net rate of aqueous organic carbon change was obtained as follows:

$$\frac{dC_{(aq)}}{dt} = \frac{dC^g}{dt} - \frac{dC^d}{dt} \qquad [20]$$

$$\frac{dC_{(aq)}}{dt} = (k_h\ C_S)\ - \left(\frac{1}{Y_A}\right)\left(\frac{\mu_A\ C_{(aq)}}{K_{SA} + C_{(aq)}}\right) C_{(XA)} \qquad [21]$$

Where,

$\frac{dC^g}{dt}$: generation rate of aqueous organic acids carbon concentration ($M/L^3 \cdot T$)

$\frac{dC^d}{dt}$: depletion rate of aqueous organic acids carbon concentration ($M/L^3 \cdot T$)

$\frac{dC_{(aq)}}{dt}$: change in aqueous organic acids carbon concentration with time ($M/L^3 \cdot T$)

Y_A : mass of acidogenic biomass formed per mass of $C_{(aq)}$ utilized (M/ M)

μ_A : maximum specific growth rate constant of acidogenic biomass (T^{-1})

K_{SA} : half saturation constant of acidogenic biomass (M/ L^3)

k_{dA} : decay rate constant of acidogenic biomass (T^{-1})

C_{XA}: acidogenic biomass carbon (M/ L^3)

4.3.2.2 Acidogenic biomass carbon

As mentioned before, Monod kinetics were used to describe the growth rate of the acidogenic biomass. The change in acidogenic carbon concentration is described by biomass sub-model and is equal to the difference between the growth rate (using aqueous organic acids as substrate) and the decay rate of acidogenic biomass. The net rate of acidogenic carbon concentration change was calculated as follows:

$$\frac{dC_{(XA)}}{dt} = \left(\frac{\mu_A \, C_{(aq)}}{K_{SA} + C_{(aq)}} \right) C_{(XA)} - k_{dA} C_{(XA)} \qquad [22]$$

Where,

$\frac{d\,C_{(XA)}}{dt}$: change in acidogenic biomass carbon concentration (M/ $L^3 \cdot T$)

4.3.2.3 VFA carbon

VFA is generated from the biodegradation of aqueous organic acids and from the decay of the acidogenic biomass. Also, VFA is consumed by the methanogenic biomass which uses it as a substrate. The net rate change in VFA carbon concentration is equal to the difference between the generation and depletion terms. The product sub-model is used to describe the generation term where the biomass sub-model is used to describe the depletion term. The change in the VFA carbon concentration is calculated as:

$$\frac{dC_{(VFA)}}{dt} = Y_{HAC} \left[(1 - Y_A) \left(\frac{1}{Y_A} \right) \left(\frac{\mu_A \, C_{(aq)}}{K_{SA} + C_{(aq)}} \right) + k_{dA} \right] C_{(XA)} - \left[\left(\frac{1}{Y_M} \right) \left(\frac{\mu_M \, C_{(VFA)}}{K_{SM} \left(1 + \left(\frac{I}{K_I} \right)^m \right) + C_{(VFA)}} \right) \right] C_{(XM)} \qquad [23]$$

Where,

$\frac{dC_{(VFA)}}{dt}$: change in VFA carbon concentration (M/ L^3·T)

Y_M : mass of methanogenic biomass formed per mass of $C_{(VFA)}$ utilized (M/ M)

Y_{HAC} : VFA carbon fractional formation yield coefficient (M/M)

$C_{(XM)}$: methanogenic biomass carbon (M/ L^3)

Where Y_{HAC} represents the fraction of the carbon in the biodegradation products that is VFA. The remaining fraction (1-Y_{HAC}) is carbon dioxide.

4.3.2.4 Methanogenic biomass carbon

The methanogenic biomass uses the VFA as a substrate to produce methane, carbon dioxide and biomass cells. The change in methanogenic carbon concentration is described by biomass sub-model and is equal to the difference between the growth rate (using VFA as substrate) and the decay rate of the methanogenic biomass. The net rate of methanogenic carbon concentration change is calculated as follows:

$$\frac{dC_{(XM)}}{dt} = \left(\frac{\mu_M \, C_{(VFA)}}{K_{SM}\left(1+\left(\frac{I}{K_I}\right)^m\right) + C_{(VFA)}} \right) C_{(XM)} - k_{dM} C_{(XM)} \qquad [24]$$

Where,

$\frac{dC_{(XM)}}{dt}$: change in methanogenic biomass carbon concentration (M/L^3·T)

4.3.2.5 Methane carbon

Methane is produced from the biodegradation of VFA and decay of the methanogenic biomass. The product sub-model is applied to describe the methane carbon concentration as follows:

$$\frac{dC_{(CH4)}}{dt} = Y_{CH4}\left[(1-Y_M)\left(\frac{1}{Y_M}\right)\left(\frac{\mu_M\, C_{(VFA)}}{K_{SM}\left(1+\left(\frac{I}{K_I}\right)^m\right)+C_{(VFA)}}\right)+k_{dM}\right]C_{(XM)} \qquad [25]$$

Where,

$\frac{dC_{(CH4)}}{dt}$: change in methane carbon concentration (M/ L^3·T)

Where Y_{CH4} represents the fraction of the VFA and decayed methanogenic biomass that is converted to methane. The remainder ($1-Y_{CH4}$) is converted to carbon dioxide.

4.3.2.6 Carbon dioxide carbon

Carbon dioxide is produced by acidogenic and methanogenic biomasses. Carbon dioxide is generated by the biodegradation of aqueous organic acids carbon and the decay of the acidogenic biomass (first term), and the biodegradation of VFA and the decay of the methanogenic biomass (second term).

$$\frac{dC_{(CO2)}}{dt} = (1-Y_{HAC})\left[(1-Y_A)\left(\frac{1}{Y_A}\right)\left(\frac{\mu_A\, C_{(aq)}}{K_{SA}+C_{(aq)}}\right)+k_{dA}\right]C_{(XA)} + (1-Y_{CH4})\left[(1-Y_M)\left(\frac{1}{Y_M}\right)\left(\frac{\mu_M\, C_{(VFA)}}{K_{SM}\left(1+\left(\frac{I}{K_I}\right)^m\right)+C_{(VFA)}}\right)+k_{dM}\right]C_{(XM)} \qquad [26]$$

Where,

$\frac{dC_{(CO2)}}{dt}$: change in carbon dioxide concentration (M/ L^3·T)

4.3.3 Microbial kinetics

The kinetics parameters required for the model are hydrolysis rate constant, specific growth rate constant, half saturation constant, decay rate constant and yield coefficient of

acidogenesis and methanogenesis. Also the inhibition constants (K_I and m) due to the effect of salt addition in the methanogenic biomass are required.

The hydrolysis rate constant was estimated from the BMP assays at different salt content conditions. The kinetics parameters for the acidogenic and methanogenic biomass and inhibition constants (K_I and m) were estimated by calibrating the model with the data collected from 1D bioreactors. Table 4.1 presents the range of the kinetics parameters reported in the literature.

4.4 Numerical solution of model equations

The set of the model equations was solved numerically for a completely mixed single layer of the MSW using the implicit finite difference method. In the literature, most of the models were solved as a complete mix single layer, which showed good agreement with reality. Likewise, the results of 1D bioreactors showed no statistical difference in the mean moisture content, temperature and concentration profile within each bioreactor, as indicated in Chapter five.

A computer program created in Matlab was developed to implement the solution of model equations. The numerical solution provides the carbon concentration of the solid waste, aqueous acids, acidogenic biomass, VFA, methanogenic biomass, methane, carbon dioxide and accumulative biogases. The flow chart of the model solution is shown in Figure 4.3.

Table 4.1: Values of kinetic parameters

Parameter	Unit	Literature
Hydrolysis		
Hydrolysis rate constant (readily), k_h	d^{-1}	(0.2- 2)[c, e]
Hydrolysis rate constant (slowly), k_h	d^{-1}	(0.00002- 0.1)[c, e, f, g]
Hydrolysis rate constant (food waste) , k_h	d^{-1}	0.1- 0.4[d]
Acidogenesis		
Growth rate, μ_A	d^{-1}	(0.5-30)[a, b, c, e]
Half saturation constant, K_{SA}	kg m^{-3}	(0.03-5) [b, c]
Rate of decay, k_{dA}	d^{-1}	(0.004-0.4)[a, b, c]
Yield, Y_A	kg kg^{-1}	(0.1-0.5)[a, c]
Methanogenesis		
Growth rate, μ_M	d^{-1}	(0.1-0.5)[a, b, c, e]
Half saturation constant, K_{SM}	kg m^{-3}	(0.0003-2.5)[a, b]
Rate of decay, k_{dM}	day^{-1}	(0.005-0.04)[a, b, c, e]
Yield, Y_M	kg kg^{-1}	(0.05-0.82)[a, b, c]
Methane fraction yield, Y_{CH4}	kg kg^{-1}	(0.6-0.7)[a]
VFA formation yield, Y_{HAC}	kg kg^{-1}	0.9[a]

a, El-Fadel et al. 1996.
b, Yildiz et al. 2004.
c, Naranjo et al. 2004.
d, Alvarez et al. 2000.
e, Haarstrick et al. 2001.
f, Borzacconi et al. 1997.
g, Jokela et al. 2005.

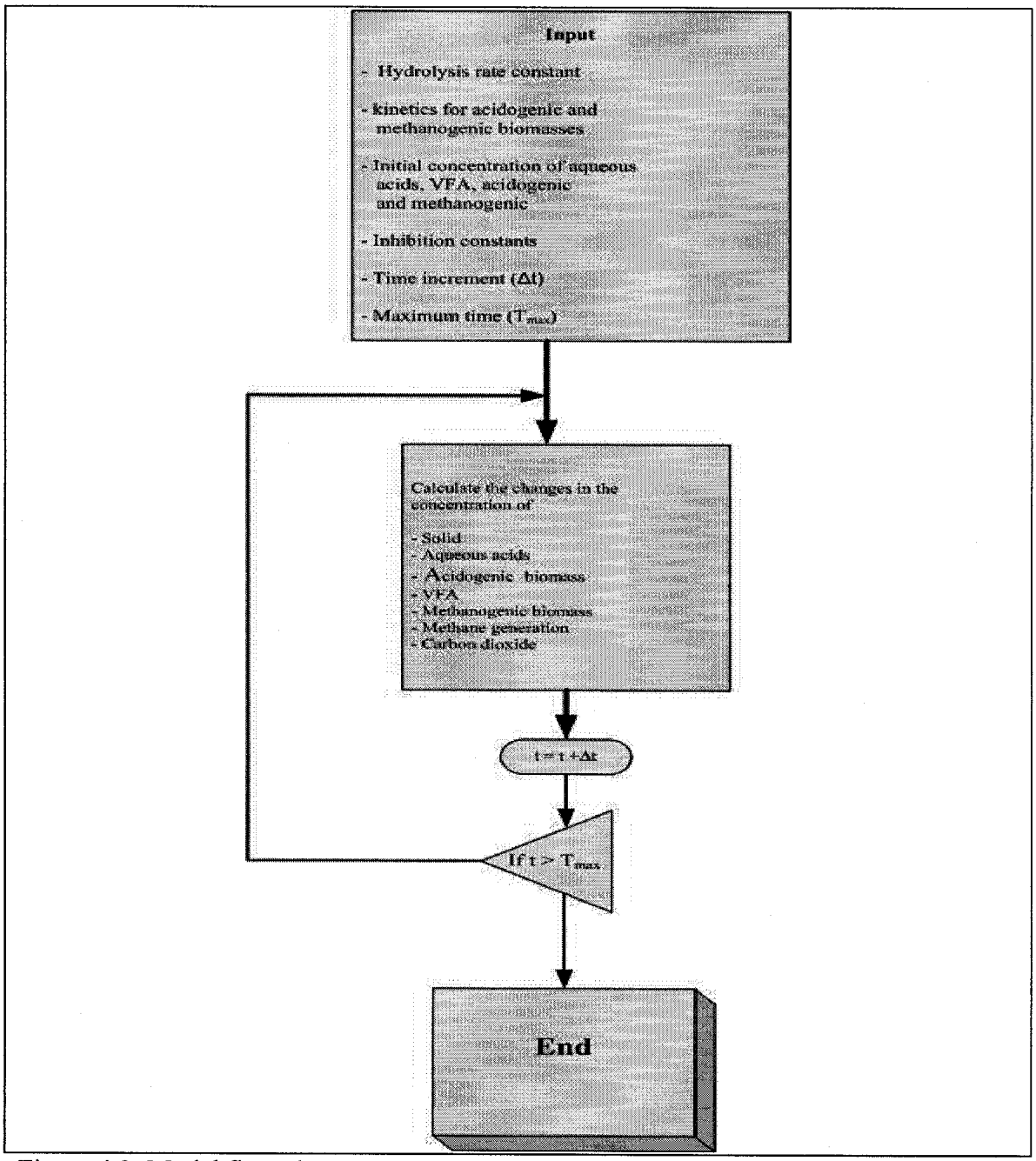


Figure 4.3: Model flow chart.

4.5 Sensitivity analysis

The sensitivity analysis was performed to investigate the performance of the model with respect to changes in model input parameters over a reasonable range. The sensitivity analysis helps to understand the behavior of the system being modeled and evaluates which parameters have significant impact on the model performance.

The input parameters were divided into three groups. Hydrolysis rate constant was the first group, whereas the kinetics (μ, k_d, K_S) of acidogenesis and methanogenesis were within the second group. The third group was the assumed initial concentrations of aqueous acids, VFA, and acidogenic and methanogenic biomasses at the beginning of the simulation. The inhibition constants (K_I and m) are not included in the sensitivity analysis because any changes in these constants produce the same results as increasing the half saturation constant of methanogenic biomass.

The model performance was investigated based on the peak concentration of aqueous acids, VFA and the peak daily methane produced; and the time (T_p) taken to reach each peak. Also, the lag time for methane production was estimated. The lag time ($T_{5\%}$) was estimated in terms of the time required for the accumulative methane mass to reach

5% of the total methane produced in the base condition. A systematic procedure was used to examine the sensitivity of the input parameters in the performance of the model. Only one input parameter was changed while the other parameter values were kept constant at the base value as shown in Table 4.2.

The range of the input parameters was chosen according to the range found in the literature. The results of changing the input parameters were compared to the base scenario and are presented in the following sections.

Table 4.2: Range of input parameters used in the sensitivity analysis

		Base		
Hydrolysis (d^{-1})	0.0007	**0.001**	0.004	0.007
Acidogenic				
μ_A (d^{-1})	2	**3**	6	9
k_{dA} (d^{-1})	0.008	**0.03**	0.06	0.09
K_{SA} (kg /m^3)	0.1	**0.5**	1	1.5
Methanogenic				
μ_M (d^{-1})	0.15	**0.25**	0.35	0.5
k_{dM} (d^{-1})	0.0025	**0.005**	0.0075	0.01
K_{SM} (kg /m^3)	0.1	**0.5**	0.75	1
Initial condition				
$C_{(aq)}$ (kg /m^3)	0.00001	**0.0001**	0.0005	0.001
$C_{(VFA)}$ (kg /m^3)	0.00001	**0.0001**	0.0005	0.001
$C_{(XA)}$ (kg /m^3)	0.00005	**0.0005**	0.0025	0.005
$C_{(XM)}$ (kg /m^3)	0.000005	**0.00005**	0.00025	0.0005

4.5.1 Time increment

Since the model was solved by the finite difference method, it was sensitive to time increments. The model was run at different smaller and smaller time steps until there was no significant change in the model output due to the magnitude of the time step. Figures 4.4 and 4.5 show that there was no difference in the model output at 0.1, 0.5, 0.75 and 1 day time increment steps. The initial total mass was 0.30075 kg carbon/m^3 and the final total mass at the end of the simulation

run (2000 days) was 0.301955, 0.30208, 0.302206, and 0.302332 kg carbon/m^3 for 0.25, 0.5, 0.75, and 1 day time steps, respectively. The percentage increase in the total mass balance with respect to initial mass was 0.4, 0.5, 0.6, and 0.8% for 0.25, 0.5, 0.75, and 1 day time steps, respectively.

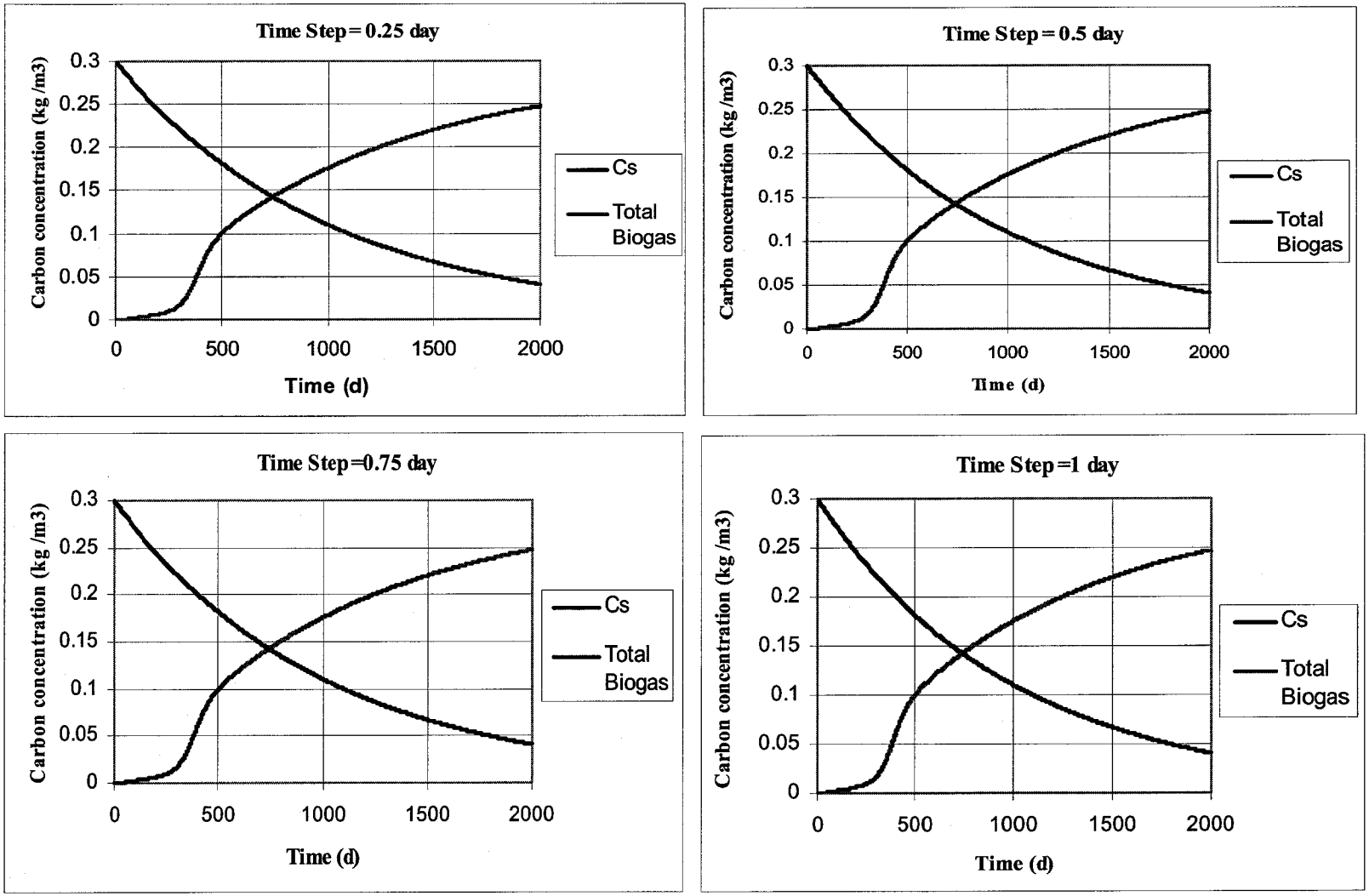


Figure 4.4: Impact of time steps on simulated solid carbon concentration and total biogas produced.

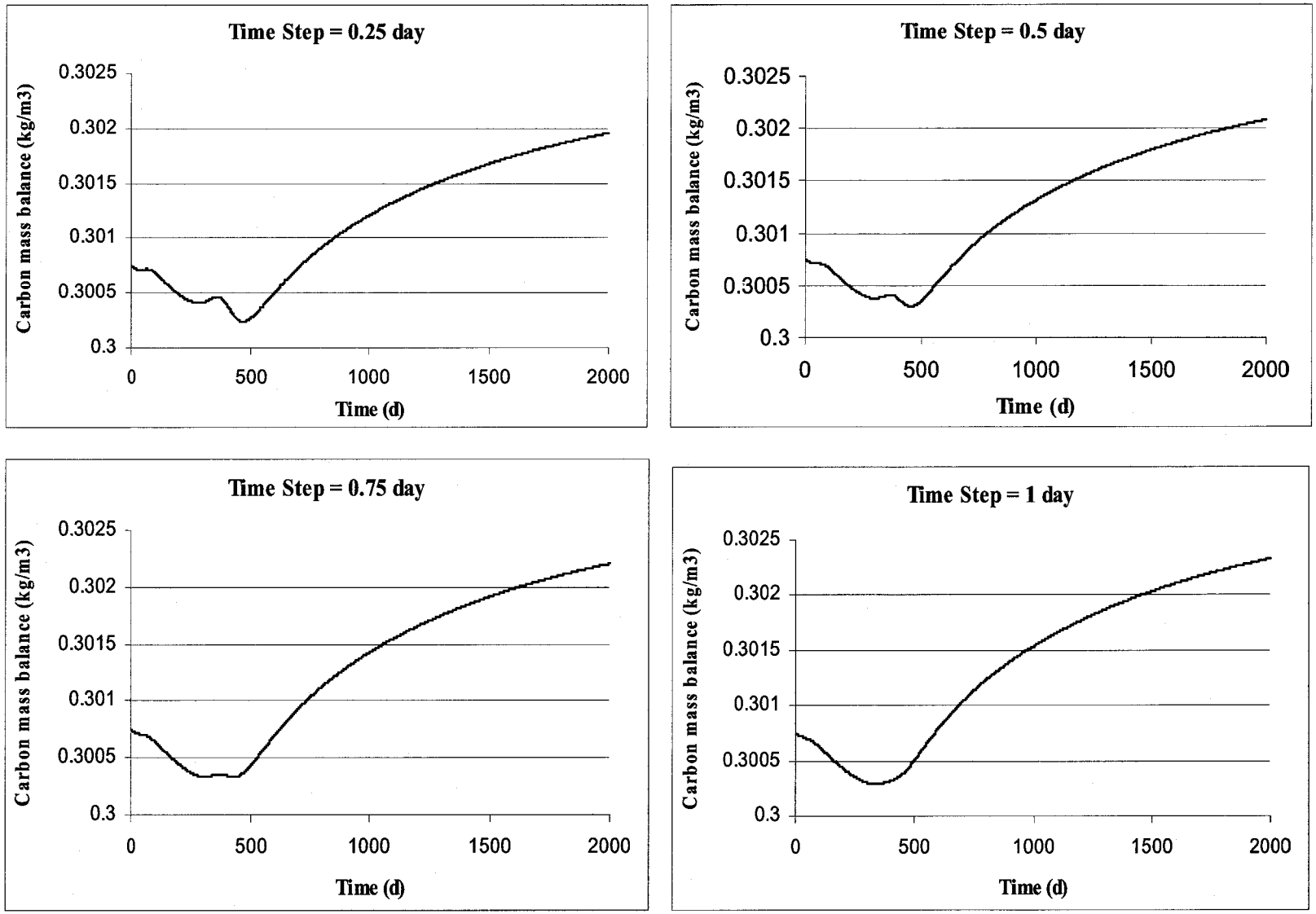


Figure 4.5: Impact of time steps on simulated total mass balance.

The output of the model in terms of overall carbon mass balance, solid carbon and accumulative biogases production showed that the appropriate time increment was 1 day.

4.5.2 Hydrolysis rate constant

The peak VFA, daily methane production and lag time ($T_{5\%}$) were highly sensitive to change in the hydrolysis rate constant as shown in Table 4.3 and Figure 4.6. (Note that certain concentration axis in Figures 4.6 through 4.16 are multiplied by the scientific notation 10^{-x} which appears immediately above the axis).

Table 4.3: Impact of changing the hydrolysis rate constant

Hydrolysis rate constant (d^{-1})		**k_h= 0.0007**	**k_h= 0.001**	**k_h= 0.004**	**k_h= 0.007**
C_{VFA}	Peak (kg/m^3)	0.048	0.0563	0.1067	0.136213
	T_p(d)	360	301	158	123
C_{CH4}	Peak (kg/m^3)	0.000246	0.000341	0.001128	0.001685
	T_p (d)	473	389	210	170
Acc. CH4	$T_{5\%}$ (d)	378	306	150	115

By increasing the hydrolysis rate constant by a factor of 7 from 0.001 to 0.007 d^{-1}, the peak of VFA and daily methane produced increased by a factor of 2.42 and 5, respectively; and the time to reach the peaks was shorten by 178 and 219 days, respectively. Also, the lag time ($T_{5\%}$) was 191 days shorter at k_h=0.007 d^{-1}.

The same results were observed when the hydrolysis rate constant was decreased to 0.0007. The VFA and daily methane produced took a longer time to reach their peaks by 59 and 84 days, respectively, and the lag time ($T_{5\%}$) increased by 72 days.

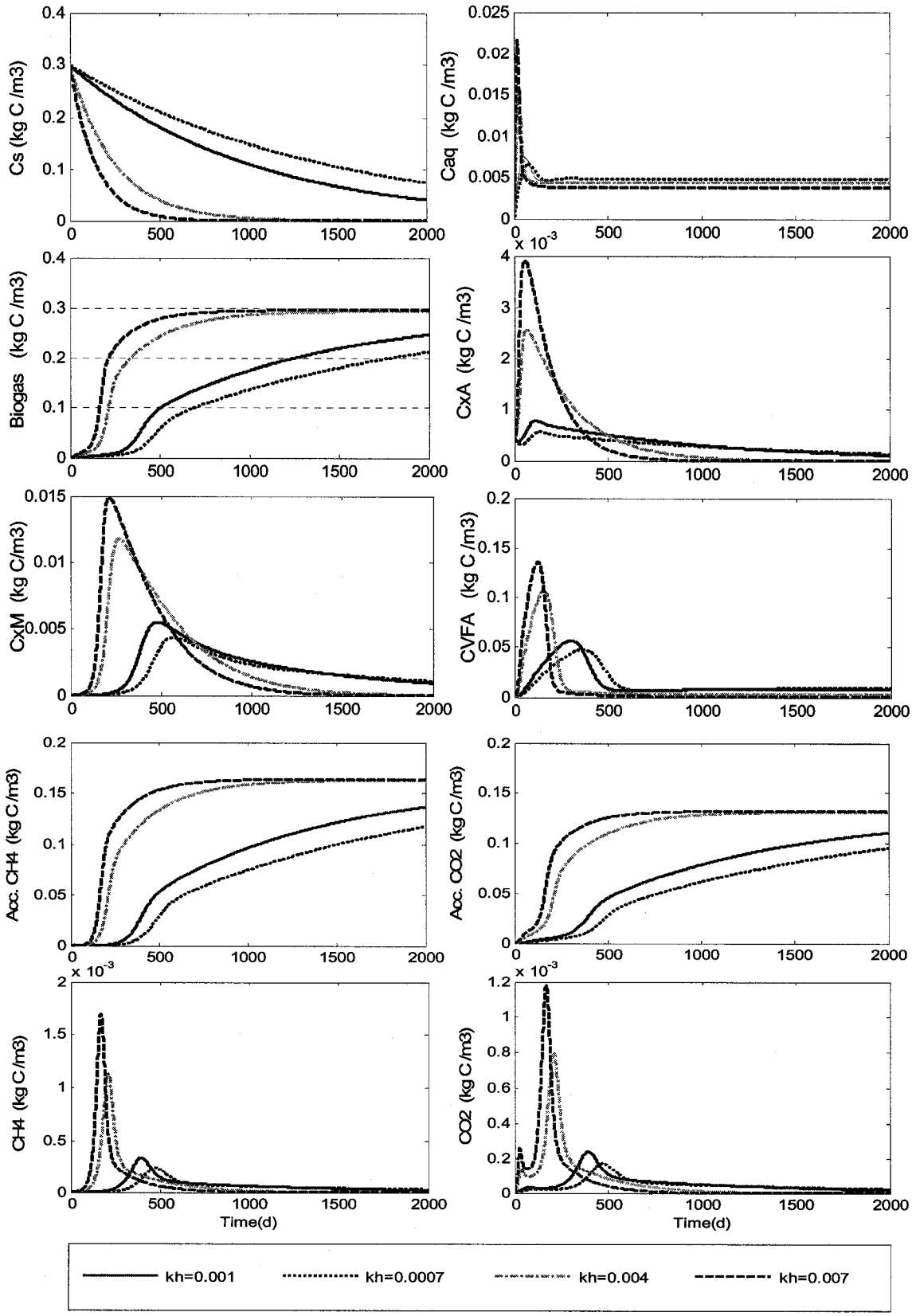


Figure 4.6: Impact of changing the hydrolysis rate constant.

4.5.3 Acidogenic biomass

In general, changing the acidogenic parameters (μ_A, k_{dA}, K_{SA}) had a minor impact on the VFA, and daily methane produced. On the other hand, they had a significant effect on the formation of aqueous organic acids. The reason was that the acidogenic biomass used the aqueous organic acids as a substrate. The results are presented in Tables 4.4 through 4.6 and Figures 4.7 through 4.9.

4.5.3.1 Maximum specific growth rate of acidogenic biomass

Table 4.4 and Figure 4.7 show the effect of changing the maximum specific growth rate of the acidogenic biomass (μ_A). When the maximum specific growth rate of the acidogenic biomass increased by a factor of three, the aqueous organic acids (C_{aq}) were consumed faster and their peak concentration decreased significantly (67%), as well as the time to reach this peak (32 days).

In addition, a minor effect on the peak VFA and daily methane produced was observed

Table 4.4: Impact of changing the maximum growth rate of the acidogenic biomass

Acidogenic growth rate (d^{-1})		**$\mu_A = 2$**	**$\mu_A = 3$**	**$\mu_A = 6$**	**$\mu_A = 9$**
C_{aq}	Peak (kg /m^3)	0.011533	**0.007528**	0.003697	0.002459
	T_p(d)	77	**55**	32	23
C_{VFA}	Peak (kg /m^3)	0.056636	**0.0563**	0.055976	0.055882
	T_p(d)	314	**301**	289	284
C_{CH4}	Peak (kg /m^3)	0.000342	**0.000341**	0.00341	0.00034
	T_p(d)	401	**389**	379	372
Acc. CH_4	$T_{5\%}$(d)	320	**306**	294	290

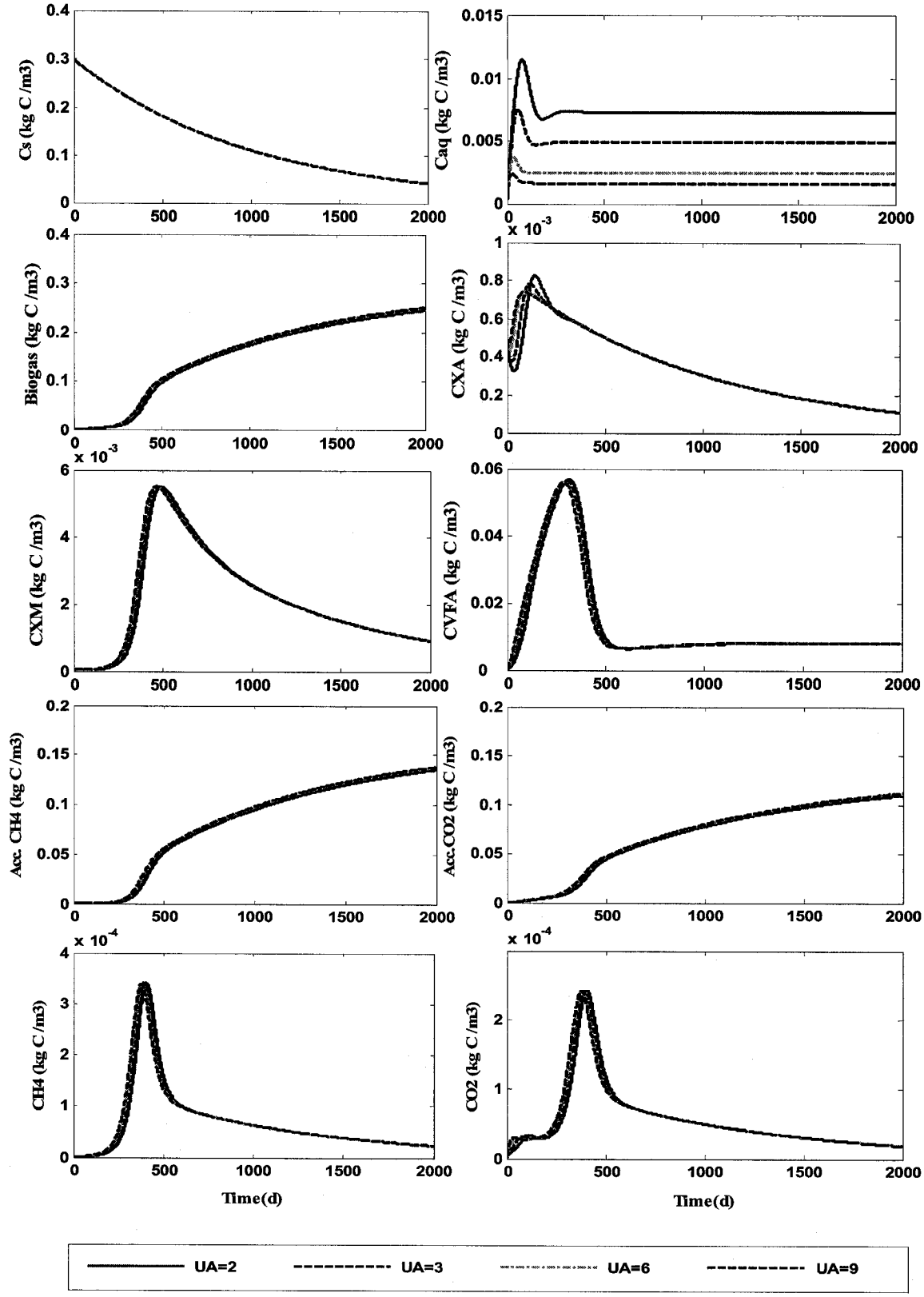


Figure 4.7: Impact of changing the maximum growth rate of the acidogenic biomass.

when the μ_A was increased by a factor of three. The time (T_p) to reach the peak VFA concentration and daily methane production was shortened by 17 days. A consequence of that was observed in the lag time ($T_{5\%}$) of accumulative methane which occurred 16 days earlier.

When the (u_A) decreased to 2 d^{-1}, the (C_{aq}) took longer time to be consumed and its peak concentration increased significantly (53%), as well as the time to reach this peak (22 days). The result of that was an increase in the time to reach the peaks (T_p) of VFA, daily methane production and lag time ($T_{5\%}$) by approximately 15 days.

4.5.3.2 Decay rate of acidogenic biomass

Table 4.5 and Figure 4.8 show the results of changing the decay rate of the acidogenic biomass (k_{dA}). By increasing the k_{dA} by a factor of three, its concentration (C_{XA}) decreased by 43%, the result being that the peak aqueous organic acid concentration (C_{aq})

Table 4.5: Impact of changing the decay rate of acidogenic biomass

Acidogenic decay (d^{-1})		**k_{dA}=0.008**	**k_{dA}=0.03**	**k_{dA}=0.06**	**k_{dA}=0.09**
C_{aq}	Peak (kg /m^3)	0.005017	**0.007528**	0.014342	0.023916
	T_p(d)	35	**55**	86	115
C_{VFA}	Peak (kg /m^3)	0.056278	**0.0563**	0.056481	0.057612
	T_p(d)	292	**301**	324	354
C_{CH4}	Peak (kg /m^3)	0.000343	**0.000341**	0.0034	0.00034
	T_p(d)	380	**389**	412	438
C_{XA}	Peak (kg /m^3)	0.002301	**0.000783**	0.00048	0.00045
Acc. CH_4	$T_{5\%}$ (d)	297	**306**	329	357

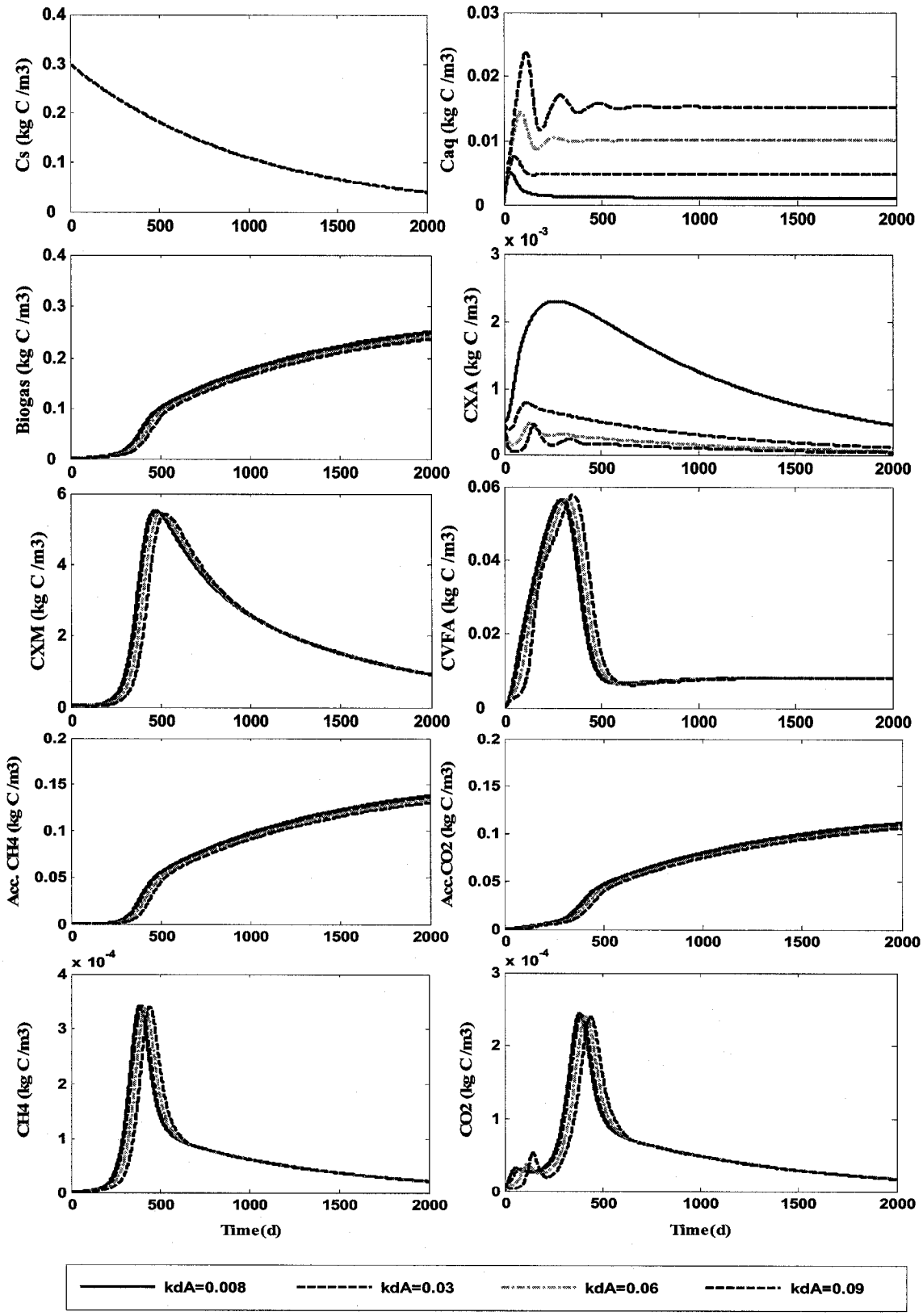


Figure 4.8: Impact of changing the decay rate of acidogenic biomass.

increased by 217% over the base and the time to reach the peak increased as well by 60 days. Minor changes were observed in the peak VFA and daily methane produced. The time to reach their peaks and lag time ($T_{5\%}$) of accumulative methane was delayed by approximately 50 days.

By decreasing the k_{dA} to 0.008 d^{-1}, the acidogenic concentration increased faster, and aqueous organic acids were consumed, thereby decreasing their peaks by 33.5% of the base and shortening their time to reach the peak by 20 days. Consequently, the time required to reach the peaks of VFA and daily methane produced, as well as the lag time ($T_{5\%}$) of accumulative methane, occurred earlier by 9 days.

4.5.3.3 Half saturation constant of acidogenic biomass

Increasing the K_{SA} showed similar results to decreasing the μ_A and increasing the k_{dA} as shown in Table 4.6 and Figure 4.9.

Table 4.6: Impact of changing the half saturation constant of acidogenic biomass

Half saturation constant of acidogenic (kg /m³)		**K_{SA}= 0.1**	**K_{SA} = 0.5**	**K_{SA} = 1**	**K_{SA} = 1.5**
C_{aq}	Peak (kg /m³)	0.001495	**0.007528**	0.015487	0.02377
	T_p(d)	16	**55**	96	134
C_{VFA}	Peak (kg /m³)	0.055814	**0.0563**	0.05703	0.058917
	T_p(d)	282	**301**	324	344
C_{CH4}	Peak (kg /m³)	0.00034	**0.000341**	0.00343	0.000342
	T_p(d)	369	**389**	415	444
C_{XA}	Peak (kg /m³)	0.000735	**0.000783**	0.000864	0.009456
	T_p(d)	82	**111**	162	211
Acc. CH_4	$T_{5\%}$ (d)	289	**306**	333	359

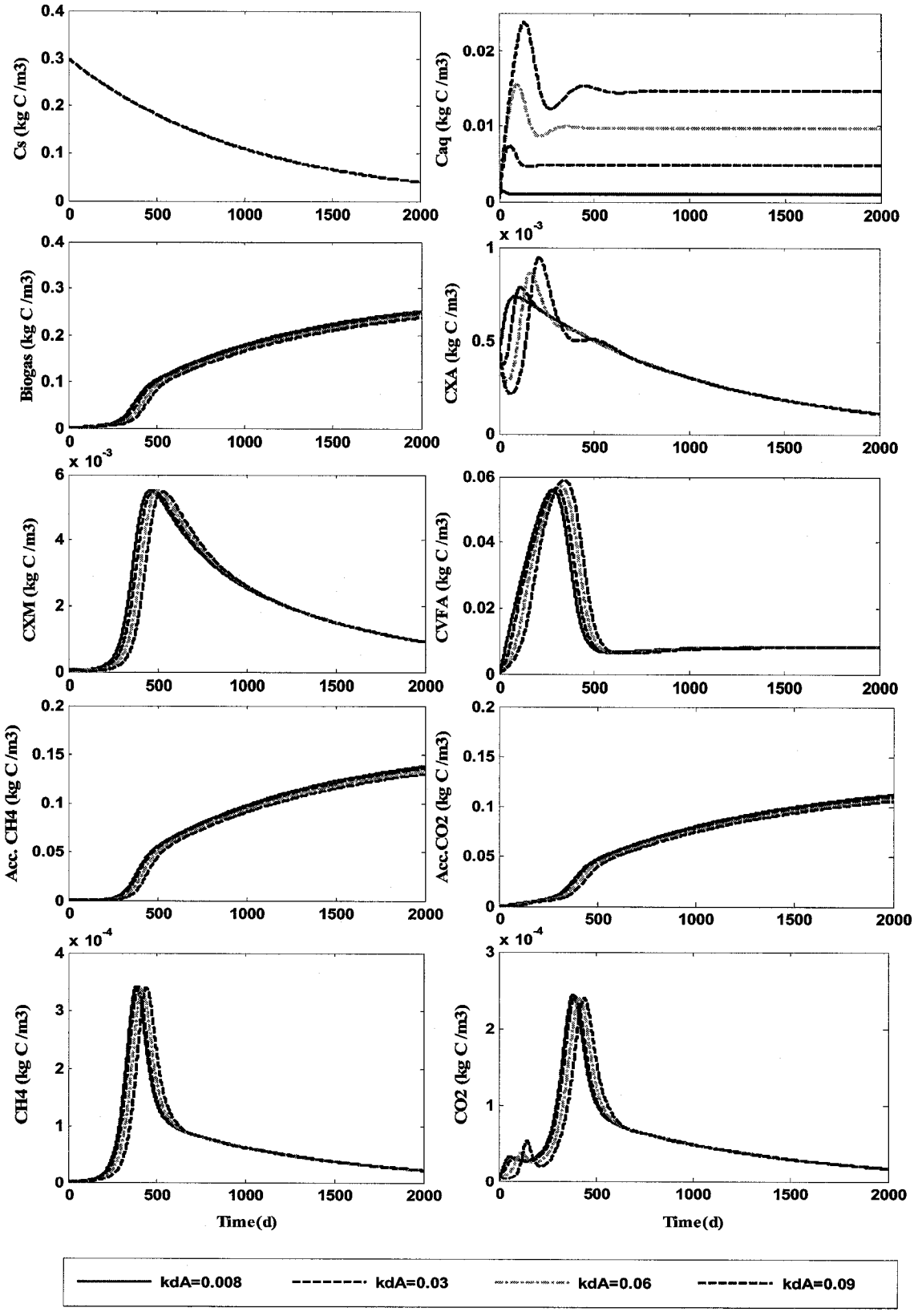


Figure 4.9: Impact of changing the half saturation constant of acidogenic biomass.

There was an increase by 215% in the concentration of aqueous organic acids when the K_{SA} was increased by a factor of three above the base as the concentration of acidogenic biomass was decreased. Also, the time to reach the peak concentration of acidogenic biomass was almost doubled. The K_{SA} had a limited impact on the peaks of VFA and daily methane produced, and just altered the time to reach their peak by 43 and 55 days, respectively.

By decreasing the K_{SA} by a factor of five below the base, the peak of aqueous organic acids concentration decreased by 80% and the time required to reach this peak was shortened by 39 days. The reason for that was that the peak of acidogenic biomass concentration was reached 29 days earlier than the base. The process in terms of $T_{5\%}$ and time required to reach the peaks of VFA and daily methane produced occurred earlier by 17 days.

It is clear from Figures 4.7 through 4.9 that the rate of methane producing as illustrated by the peak rate and $T_{5\%}$, was relatively insensitive to the change in acidogenic parameters.

4.5.4 Methanogenic biomass

Generally speaking, changes in the methanogenic parameters (μ_M, k_{dM}, K_{SM}) had a significant impact on peaks of the VFA and daily methane produced, as well as the time required to reach them.

4.5.4.1 Maximum specific growth rate of methanogenic biomass

Increasing μ_M by a factor of two from the base, caused a decrease in the time required to reach the peak of methanogenic biomass concentration by 132 days as shown in Table

4.7 and Figure 4.10. The consequence of that was a 35% decrease in the peak VFA concentration and the peak concentration occurred 105 days earlier. Furthermore, the peak daily methane production was reached 132 days earlier and the lag time ($T_{5\%}$) of accumulative methane production was reduced by 97 days.

Table 4.7: Impact of changing the maximum growth rate of methanogenic biomass

Methanogenic growth rate (d^{-1})		**$\mu_M = 0.15$**	**$\mu_M = 0.25$**	**$\mu_M = 0.35$**	**$\mu_M = 0.5$**
C_{VFA}	Peak (kg /m^3)	0.07761	**0.0563**	0.045681	0.03677
	T_p (d)	424	**301**	243	196
C_{CH4}	Peak (kg /m^3)	0.000324	**0.000341**	0.000348	0.000353
	T_p (d)	551	**389**	315	257
C_{XM}	Peak (kg /m^3)	0.006191	**0.005508**	0.005023	0.0045279
	T_p (d)	644	**477**	396	345
Acc. CH4	$T_{5\%}$ (d)	420	**306**	253	209

On the other hand, decreasing the μ_M to 0.15 d^{-1} caused a 38% increase in the peak of VFA concentration and the peak concentration was delayed by 123 days because the methanogenic biomass took longer (167 days) to reach maximum concentration. In other words, it took a longer time to consume the VFA. The result of this was a 162-day delay in reaching the peak of daily methane production and an increase of 114 days in the lag time to reach 5% accumulative methane production.

4.5.4.2 Decay rate of methanogenic biomass

As expected, the response to increasing decay rate (k_{dM}) was opposite to the response of increasing the maximum growth rate (μ_M) as shown in Table 4.8 and Figure 4.11.

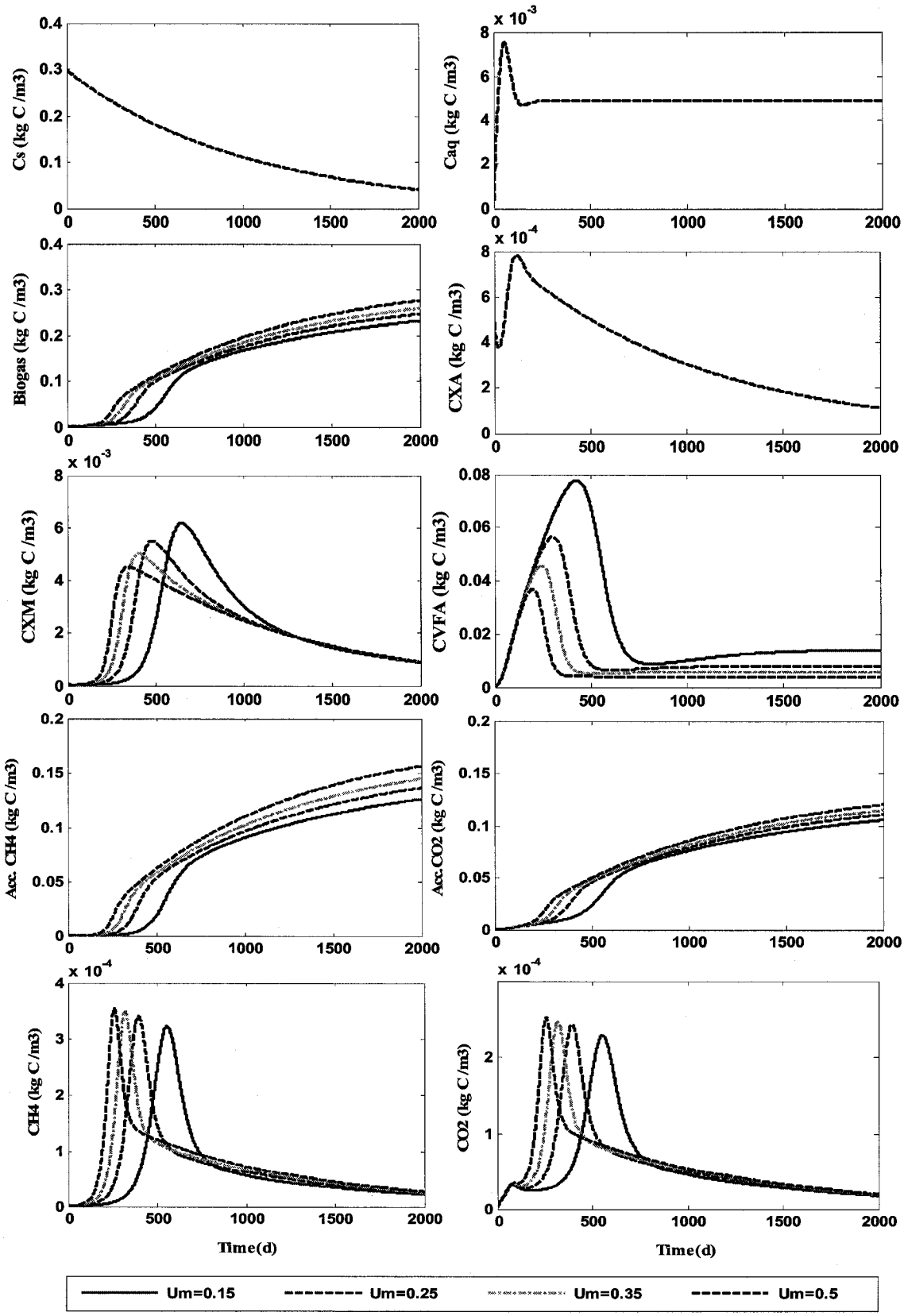


Figure 4.10: Impact of changing the maximum growth rate of methanogenic biomass.

Increasing the k_{dM} by a factor of two above the base caused a 25% decline in the peak methanogenic biomass concentration which allowed VFA to accumulate, thus increasing the peak VFA concentration by 21% and the time to reach this peak by 60 days. This resulted in a 70-day increase in the time to reach the peak of methane production and a 60-day delay in the lag time to reach 5% accumulative methane production.

Table 4.8: Impact of changing the decay rate of methanogenic biomass

Methanogenic decay (d^{-1})		**k_{dM} = 0.0025**	**k_{dM} = 0.005**	**k_{dM} = 0.0075**	**k_{dM} = 0.01**
C_{VFA}	Peak (kg/m^3)	0.051275	**0.0563**	0.06189	0.068072
	T_p (d)	275	**301**	329	361
C_{CH4}	Peak (kg/m^3)	0.00033	**0.000341**	0.000352	0.000366
	T_p (d)	358	**389**	425	459
C_{XM}	Peak (kg/m^3)	0.00693	**0.005508**	0.00469	0.004124
Acc. CH_4	$T_{5\%}$ (d)	282	**306**	334	366

A decrease in the k_{dM} by factor of two caused a 26% increase in the methanogenic biomass concentration, which in turn accelerated the VFA depletion, shortened the time to reach the peak methane production by 31 days and reduced the lag time to reach 5% accumulative methane production by 24 days.

4.5.4.3 Half saturation constant of methanogenic biomass

K_{SM} showed similar results to the k_{dM}, as shown in Table 4.9 and Figure 4.12; that is, increasing the K_{SM} by a factor of two above the base caused a longer time (220 days) for the methanogenic biomass to reach the maximum concentration. Consequently, there was a 49% increase in the peak VFA concentration and the time to reach this peak increased

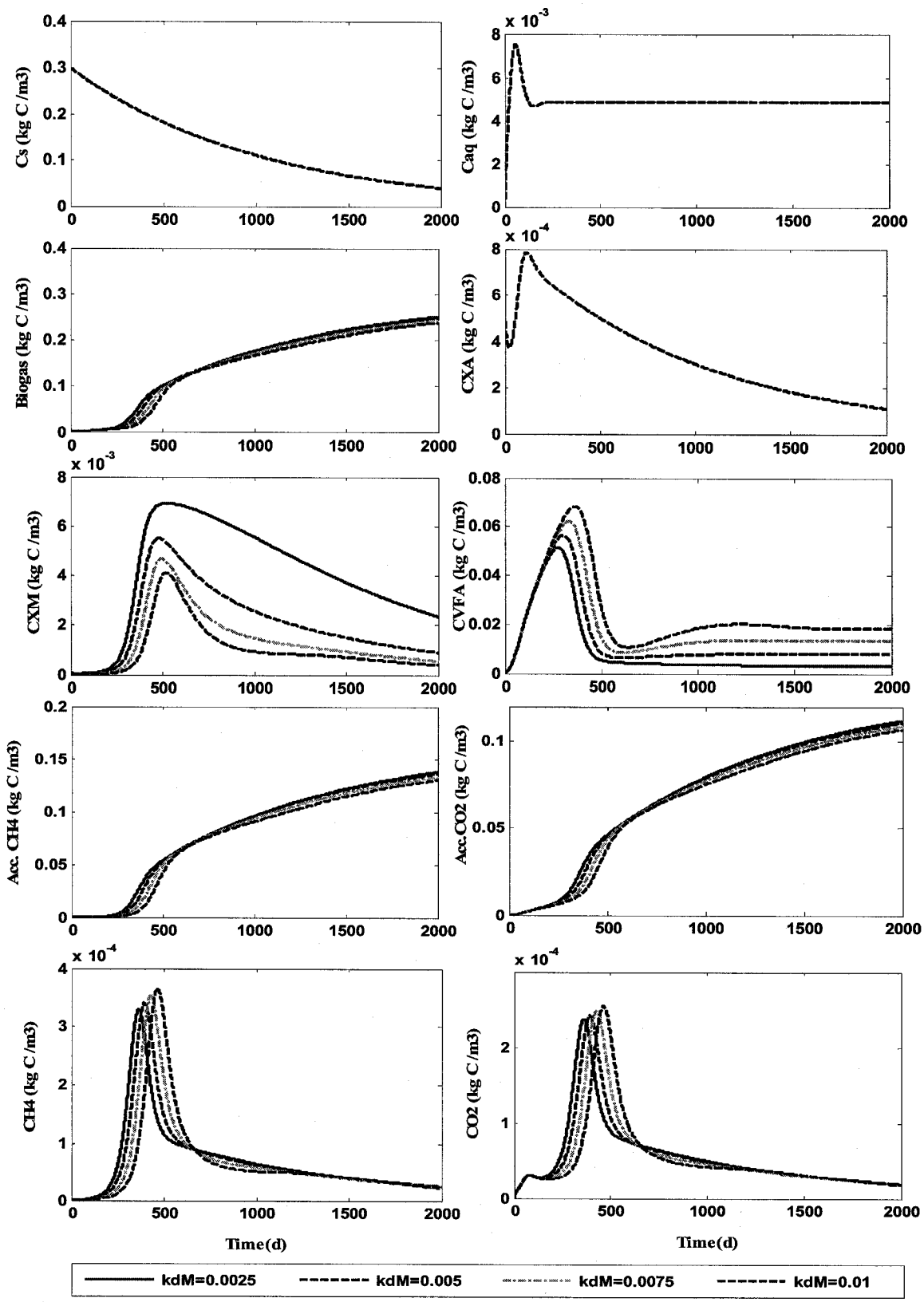


Figure 4.11: Impact of changing the decay rate of methanogenic biomass.

as well by 162 days. A delay in the VFA consumption resulted in an increase in the time to reach the peak of daily methane produced by 208 days and a lag time to reach 5% accumulative methane production by 150 days.

Table 4.9: Impact of changing the half saturation constant of methanogenic biomass

Half saturation of methanogenic (kg /m^3)		**K_{SM} = 0.1**	**K_{SM} = 0. 5**	**K_{SM} = 0.75**	**K_{SM} = 1.0**
C_{VFA}	Peak (kg /m^3)	0.022901	**0.0563**	0.07117	0.084059
	T_p (d)	129	**301**	385	463
C_{CH4}	Peak (kg /m^3)	0.000347	**0.000341**	0.000333	0.000323
	T_p (d)	166	**389**	492	597
C_{XM}	Peak (kg /m^3)	0.003805	**0.005508**	0.00599	0.00627
	T_p (d)	357	**477**	593	697
Acc. CH_4	$T_{5\%}$ (d)	145	**306**	384	456

Decreasing the K_{SM} by a factor of five below the base, caused a decrease in the time required to reach the peak of methanogenic biomass concentration by 120 days. The result of that was a decrease in the peak VFA concentration by 59% and the time required to reach this peak by 172 days; and a decrease in the time required to reach the peak daily methane production and lag time to reach 5% accumulative methane production by 223 and 161 days, respectively.

The biodegradation process, in terms of peaks VFA concentration and daily methane production, time to reach their peaks, and time required to reach 5% accumulative methane production proved to be highly sensitive to any change in the methanogenic parameters as illustrated in Figures 4.10 through 4.12.

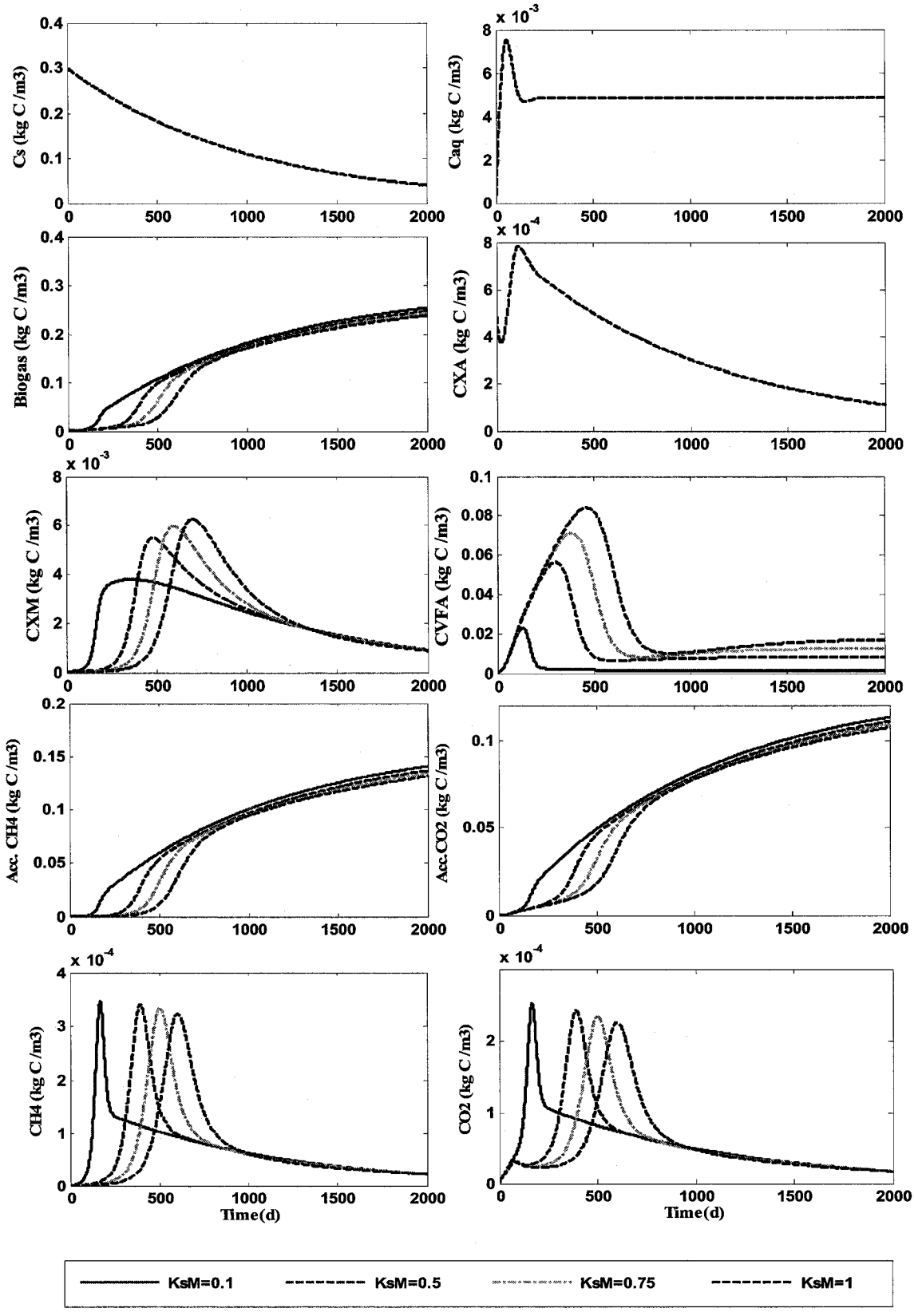


Figure 4.12: Impact of changing half saturation constant of methanogenic biomass.

4.5.5 Initial condition

In general, minor variations were observed by changing the initial concentration of aqueous acids, VFA and acidogenic biomass. However, major variations occurred by changing the initial concentration of methanogenic biomass.

4.5.5.1 Initial aqueous organic acid concentration

Increasing the initial concentration of aqueous organic acids (C_{aq}) by a factor of 10 above the base, caused no significant impact on the peaks of VFA, daily methane produced and the lag time to reach 5% accumulative methane production, as shown in Table 4.10 and Figure 4.13. The process in terms of time required to reach the peak VFA and daily methane production, and lag time to reach 5% accumulative methane production is decreased by approximately 5 days when the C_{aq} increased by a factor of 10.

Also there was no significant impact observed when the C_{aq} decreased by a factor of 10 below the base.

Table 4.10: Impact of changing the initial condition of aqueous organic acids

Aqueous organic acids (kg /m^3)		**C_{aq}=0.00001**	**C_{aq}=0.0001**	**C_{aq}=0.0005**	**C_{aq}=0.001**
C_{VFA}	Peak (kg /m^3)	0.056307	**0.0563**	0.05626	0.05623
	T_p (d)	301	**301**	299	297
C_{CH4}	Peak (kg /m^3)	0.000341	**0.000341**	0.000341	0.000341
	T_p (d)	389	**389**	387	384
C_{XM}	Peak (kg /m^3)	0.005508	**0.005508**	0.005509	0.005513
	T_p (d)	478	**477**	476	473
Acc. CH_4	$T_{5\%}$ (d)	307	**306**	303	302

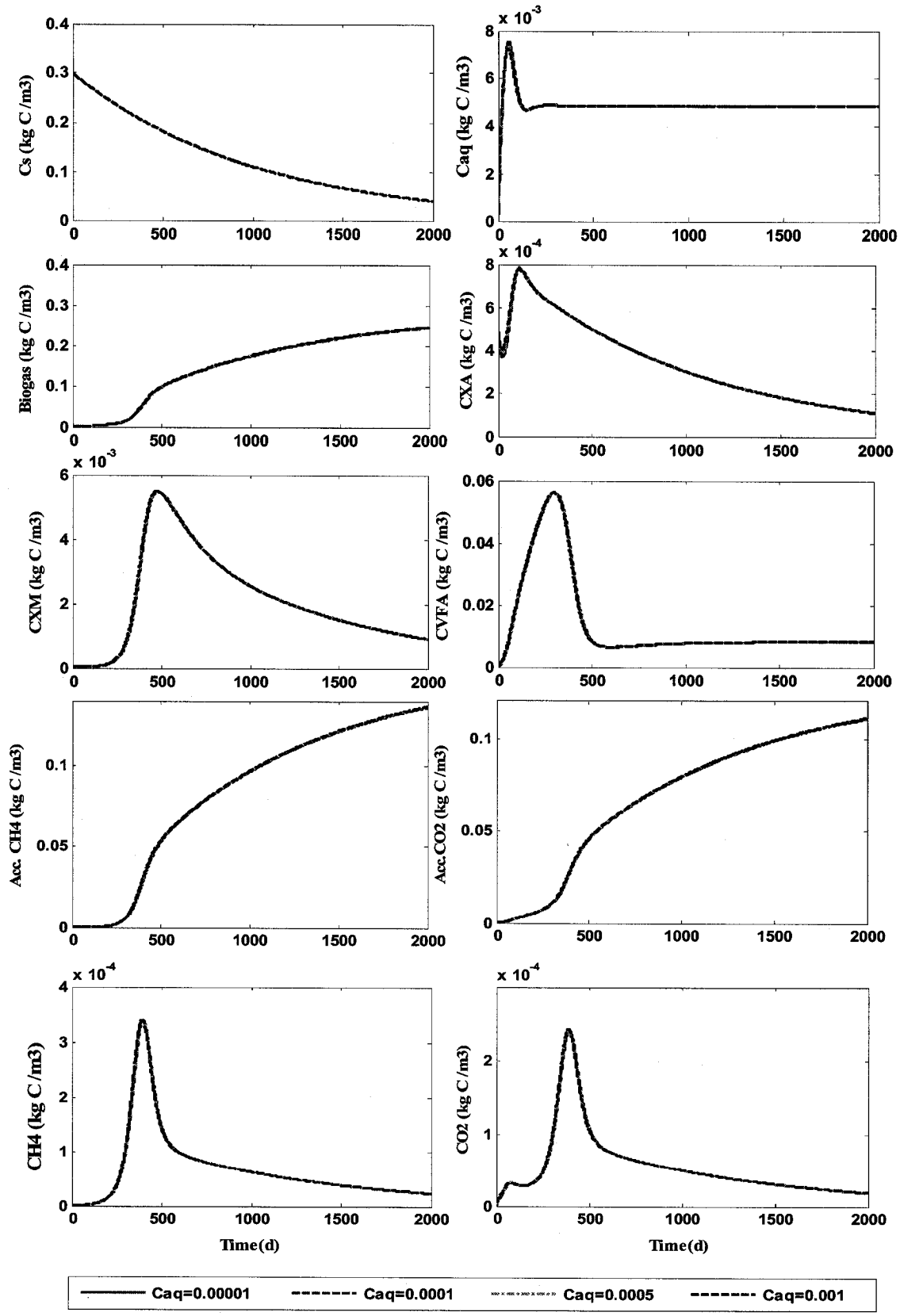


Figure 4.13: Impact of changing the initial condition of aqueous acid.

4.5.5.2 Initial VFA concentration

Increasing the initial concentration of VFA by a factor of 10 showed similar results to the increase in the initial concentration of aqueous organic acids. Table 4.11 and Figure 4.14 show the results of changing the initial concentration of VFA.

Table 4.11: Impact of changing the initial condition of VFA

VFA (kg /m^3)		C_{VFA}=0.00001	C_{VFA}=0.0001	C_{VFA} =0.0005	C_{VFA} =0.001
C_{VFA}	Peak (kg /m^3)	0.056309	**0.0563**	0.05629	0.056213
	T_p (d)	301	**301**	299	296
C_{CH4}	Peak (kg /m^3)	0.000341	**0.000341**	0.000341	0.000341
	T_p (d)	389	**389**	388	384
C_{XM}	Peak (kg /m^3)	0.005507	**0.005508**	0.00551	0.005513
	T_p (d)	478	**477**	476	472
Acc. CH_4	$T_{5\%}$	307	**306**	304	302

4.5.5.3 Initial acidogenic biomass concentration

Increasing the initial acidogenic biomass concentration (C_{XA}) by a factor of 10 above the base caused a 36% decrease in the peak aqueous acid concentration, which in turn decreased the time required to reach the peak VFA, daily methane production and lag time to reach 5% accumulative methane production by 23, 22, and 28 days, respectively. There was no significant difference in the peak VFA and daily methane produced, as shown in Figure 4.15 and Table 4.12.

As expected, the response to decreasing the C_{XA} by a factor of 10 below the base was a 101% increased in the peak C_{aq} .The result of this was an increase in the time required to

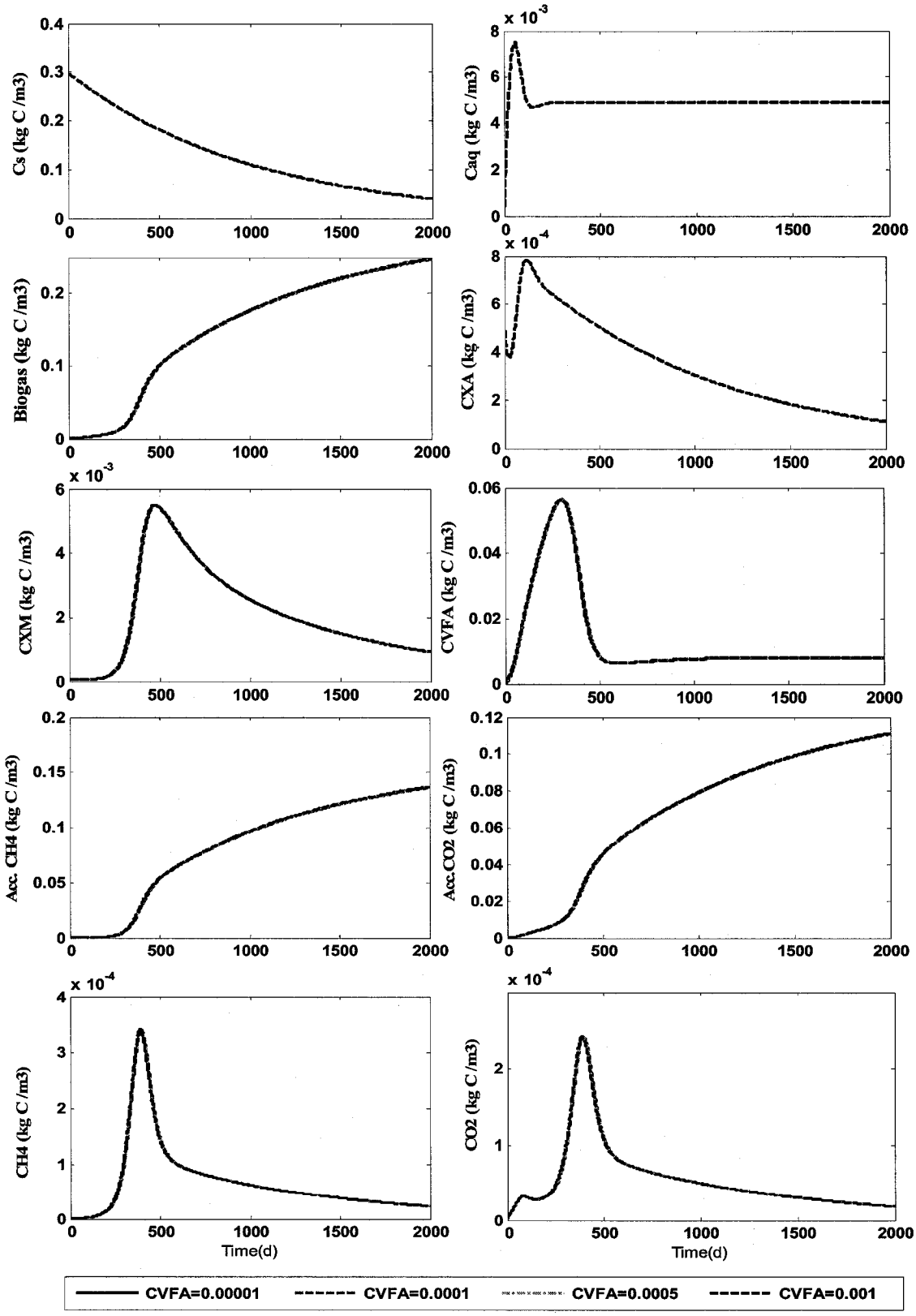


Figure 4.14: Impact of changing the initial condition of VFA.

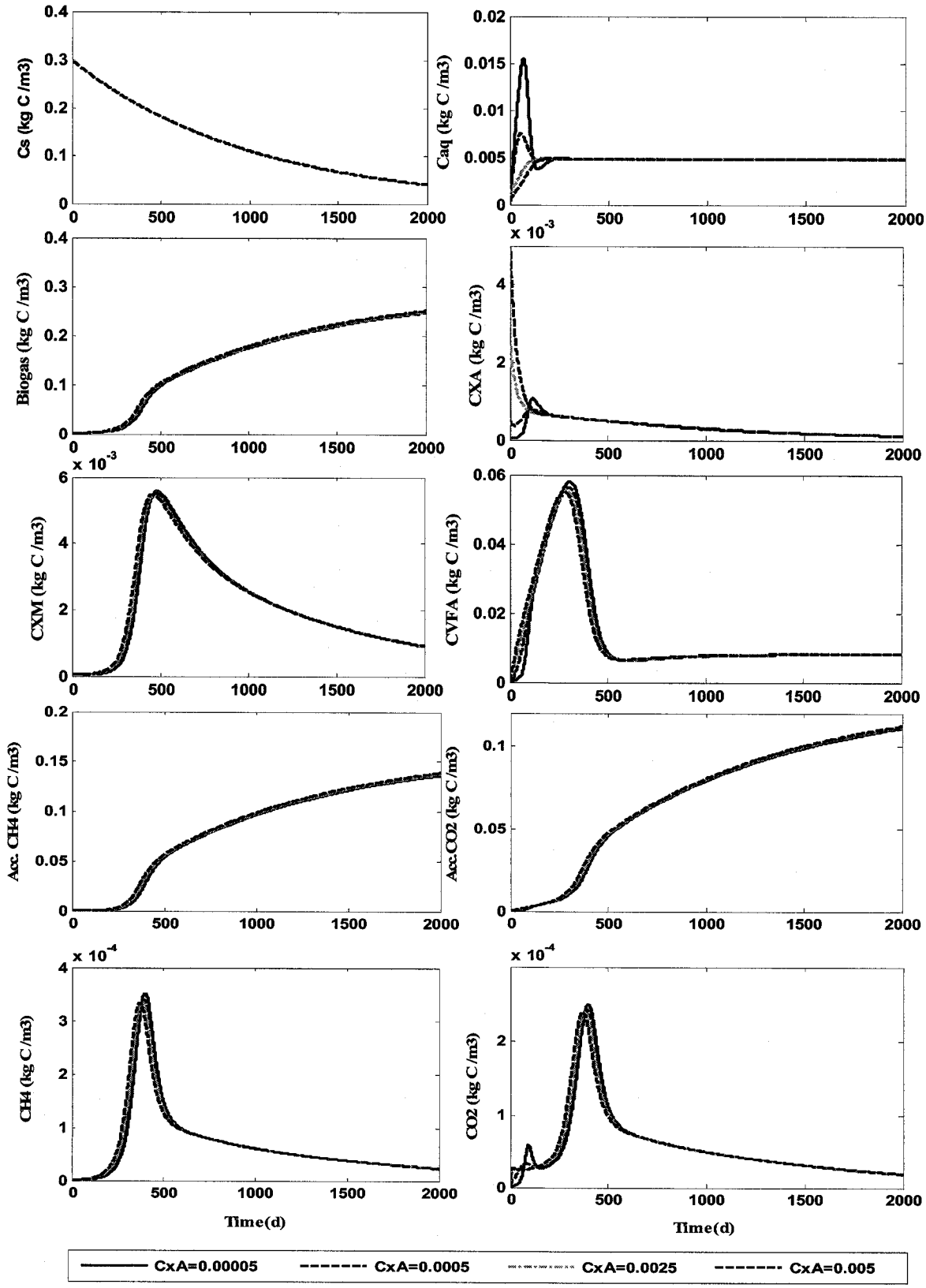


Figure 4.15: Impact of changing the initial condition of acidogenic biomass.

reach the peak VFA and daily methane production, and the lag time to reach 5% accumulative methane production by 7, 7, and 9 days, respectively.

Table 4.12: Impact of changing the initial condition of acidogenic biomass

Acidogenic biomass (kg /m^3)		**C_{XA}= 5E-5**	**C_{XA}= 5E-4**	**C_{XA}= 2.5E-3**	**C_{XA}= 5E-3**
C_{aq}	Peak (kg /m^3)	0.015585	**0.0077528**	0.00493	0.00493
C_{VFA}	Peak (kg /m^3)	0.05784	**0.0563**	0.05536	0.055087
	T_p (d)	308	**301**	290	278
C_{CH4}	Peak (kg /m^3)	0.000352	**0.000341**	0.0003359	0.000336
	T_p (d)	396	**389**	380	367
Acc. CH_4	$T_{5\%}$ (d)	315	**306**	294	278

4.5.5.4 Initial methanogenic biomass concentration

Increasing the initial concentration of the methanogenic biomass (C_{XM}) by a factor of 10 above the base caused 38% reduction in the VFA peak concentration, and the time to reach its peak occurred 78 days earlier, as shown in Figure 4.16 and Table 4.13. The result of this was the peak of daily methane production occurred 79 days earlier and the lag time to reach 5% accumulative methane production was reduced by 107 days.

In addition, by decreasing C_{XM} by a factor of 10, the opposite impact was observed. The VFA were accumulated and their peak concentration and time to reach their peak increased by 30% and 72 days, respectively. Consequently, the peak of daily methane production was delayed by 71 days and the lag time to reach 5% accumulative methane production increased by 84 days.

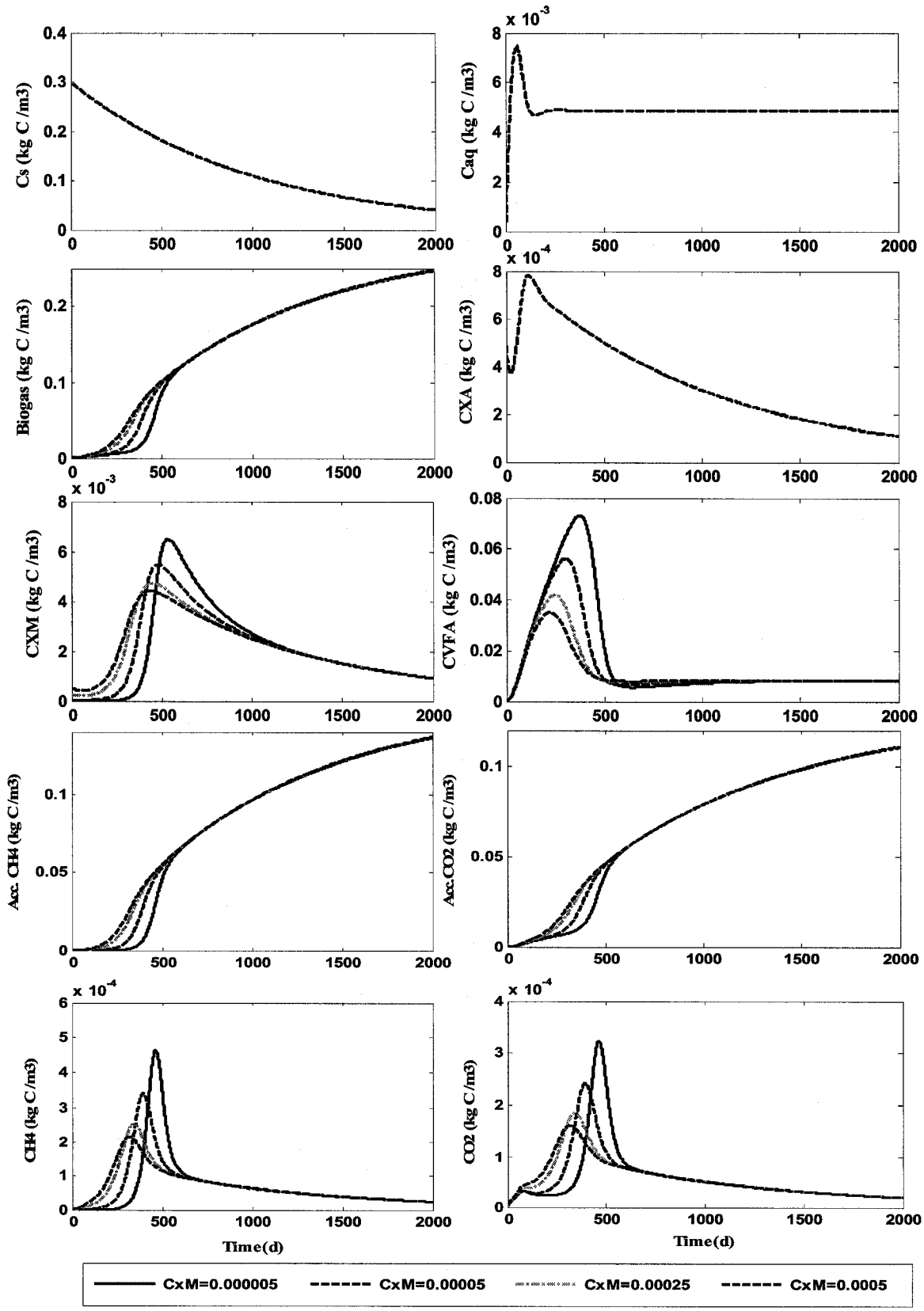


Figure 4.16: Impact of changing the initial condition of methanogenic biomass.

Table 4.13: Impact of changing the initial condition of methanogenic biomass

Methanogenic biomass (kg /m^3)		**C_{XM}= 5E-6**	**C_{XM}= 5E-5**	**C_{XM}= 2.5E-4**	**C_{XM}= 5E-4**
C_{VFA}	Peak (kg /m^3)	0.072945	**0.0563**	0.04188	0.0349315
	T_p (d)	373	**301**	247	223
C_{CH4}	Peak (kg /m^3)	0.000466	**0.000341**	0.0002528	0.000217
	T_p (d)	460	**389**	350	310
C_{XM}	Peak (kg /m^3)	0.006505	**0.005508**	0.004749	0.004439
	T_p (d)	531	**477**	446	432
Acc. CH_4	$T_{5\%}$ (d)	390	**306**	234	199

4.5.6 Summary of sensitivity analysis

- The highly sensitive parameter in the model was the hydrolysis rate constant.
- The model showed more sensitivity to methanogenic parameters (μ_M, k_{dM}, K_{SM}) than to acidogenic parameters (μ_A, k_{dA}, K_{SA}).
- No significant impact was observed when changing the acidogenic biomass parameters on the peaks VFA and daily methane production, only a small variation in the time to reach the peaks.
- The model showed more sensitivity to initial concentration of methanogenic biomass than other initial concentrations (C_{aq}, C_{VFA}, and C_{XA}).
- There were no significant variations occurred when changing the initial concentrations of C_{aq} and C_{VFA} in terms of the values and time to reach the peaks of VFA and daily methane production.
- The initial concentration of C_{XA} causes a significant impact only on the peak of C_{aq} concentration. Also, a slight shift occurred in the time to reach the peak VFA and daily methane production.

Chapter 5

Results and discussion

This chapter provides an overview of the results obtained from two groups of experiments (1D bioreactors and BMP assays) conducted to study the effect of salinity on the performance of MSW bioreactors operated with and without sludge addition and to estimate the hydrolysis rate constant at different salt content. Also, the results of model calibration are included.

It is divided into three sections. The first section covers the results obtained from the 1D bioreactors. The second section presents the result from the BMP assays to determine the hydrolysis rate constant. Finally, the model calibration and parameter estimates are covered in the third section. The complete experimental data discussed in this chapter are presented in Appendix A and the statistical tables are included in Appendix B. All statistical analysis were conducted at 5% significance level.

5.1 1D bioreactors

This section presents the behavior of two groups of 1D bioreactors operated under different saline conditions (0, 0.5, 1, 3) %(w/v), one group without sludge addition (group one, R1-R4) the other group with sludge addition (group two, R5-R8). Three major topics are discussed in this section. First, solid waste results, including initial and final moisture content, temperature profile, and settlements. Second, results of landfill gases, including methane generation and concentration produced from 1D bioreactors and BMP assays. Third, results of leachate quality, including variations in effluent COD, BOD, VFA, pH,

TVS, TS, NH_3-N, salinity, vertical concentration (in terms of COD) profile within the bioreactors, and potential shortcircuiting.

5.1.1 Solid waste

This subsection covers the change in the moisture content, temperature and settlement that occurred during the study.

5.1.1.1 Moisture content

The moisture content of MSW samples were measured before packing them into the bioreactors (initial) and at the end of the study (final). The initial and final moisture content (weight basis) are shown in Table 5.1

Table 5.1: Initial and final moisture content

Moisture content		R1	R2	R3	R4	R5	R6	R7	R8
Mean	Initial	0.39	0.40	0.36	0.44	0.42	0.42	0.43	0.41
	Final	0.63	0.62	0.64	0.61	0.63	0.63	0.63	0.65
	Average[1]	0.41							
	Average[2]	0.63							
P-value	Stages[3]	0.000							

(1) Average initial moisture content.
(2) Average final moisture content.
(3) Comparison between the mean initial and final moisture content ($F_{k-1, n-k} = F_{1, 14}$)*.
*) Where k is the number of groups and n is the number of observations (One way ANOVA). For more details see Appendix B.

The range of initial moisture varied from 0.39 to 0.44. The average initial moisture content was 0.41, whereas the average final moisture content was 0.63. The final moisture content of MSW represents the field capacity.

Table 5.2 shows final moisture content (w/w) in different layers (top, mid and bottom). The average moisture content was 0.60, 0.63 and 0.65 in the top, mid and bottom layers, respectively. The highest moisture content was recorded in the bottom layer which agreed

Table 5.2: Profile of final moisture content

Moisture content		R1	R2	R3	R4	R5	R6	R7	R8
Mean layer	Top (T)	0.59	0.58	0.61	0.57	0.61	0.62	0.62	0.63
	Mid (M)	0.61	0.63	0.64	0.62	0.63	0.63	0.63	0.64
	Bottom (B)	0.67	0.64	0.66	0.63	0.64	0.64	0.64	0.67
	Average	0.63	0.62	0.64	0.61	0.63	0.63	0.63	0.65
	Average of layers	0.60^{T}			0.63^{M}			0.65^{B}	
P-value	Layers[1]	0.07	0.39	0.16	0.59	0.13	0.27	0.39	0.39
	Bioreactors[2]	0.26							

(1) Comparison of the mean final moisture content in all layers within each bioreactor ($F_{2,6}$).
(2) Comparison of the mean final moisture content in all bioreactors ($F_{7,64}$).

with the results presented by Chiemchaisri et al. (2002). They found there was little difference in moisture content in the experiments that they performed with various bioreactors and that moisture content was higher in the bottom part than in the upper part of their bioreactors.

Statistical analysis

The objective of the statistical analysis was to investigate whether there was any significant difference 1) between the mean initial and final moisture contents, 2) in the vertical moisture profile within the bioreactors, and 3) in the mean final moisture content in all bioreactors.

First, the P-value of Stages[3] was less than 0.05 as shown in Table 5.1. That means that there was a significant difference between the mean initial and final moisture contents in the bioreactors.

Second, the P-value of Layers[1] was more than 0.05 in all bioreactors as shown in Table 5.2. This indicates that there was no significant difference in the mean final moisture content in all layers within each bioreactor. In other words, there was no significant difference in the vertical moisture profile in the bioreactors.

Third, the P-value of Bioreactors[2] was more than 0.05 as shown in Table 5.2, meaning that there was no significant difference in the mean of final moisture content in all bioreactors.

5.1.1.2 Temperature profile

Table 5.3 summarizes the temperature profile and statistical analysis. The variations of temperature in all bioreactors are shown in Figures 5.1 and 5.2.

Table 5.3: Temperature profile and statistical analysis

Temperature (°C)		R1	R2	R3	R4	R5	R6	R7	R8
Mean layer	Top (T)	26.09	25.49	25.21	24.59	24.40	24.01	24.35	24.86
	Mid (M)	26.49	25.59	26.19	25.61	24.93	24.70	25.38	25.80
	Bottom (B)	24.88	24.50	24.75	24.44	23.70	23.80	23.56	24.23
	Average	25.81	25.19	25.38	24.88	24.34	24.17	24.43	24.96
	Average of layers	24.88^{T}			25.60^{M}			24.23^{B}	
P-value	Layers[1]	0.38	0.15	0.06	0.28	0.36	0.51	0.10	0.07
	Bioreactors[2]	0.009							

(1) Comparison of the mean temperature in all layers within each bioreactor ($F_{2, 36}$).
(2) Comparison of the mean temperatures in all bioreactors ($F_{7, 304}$).

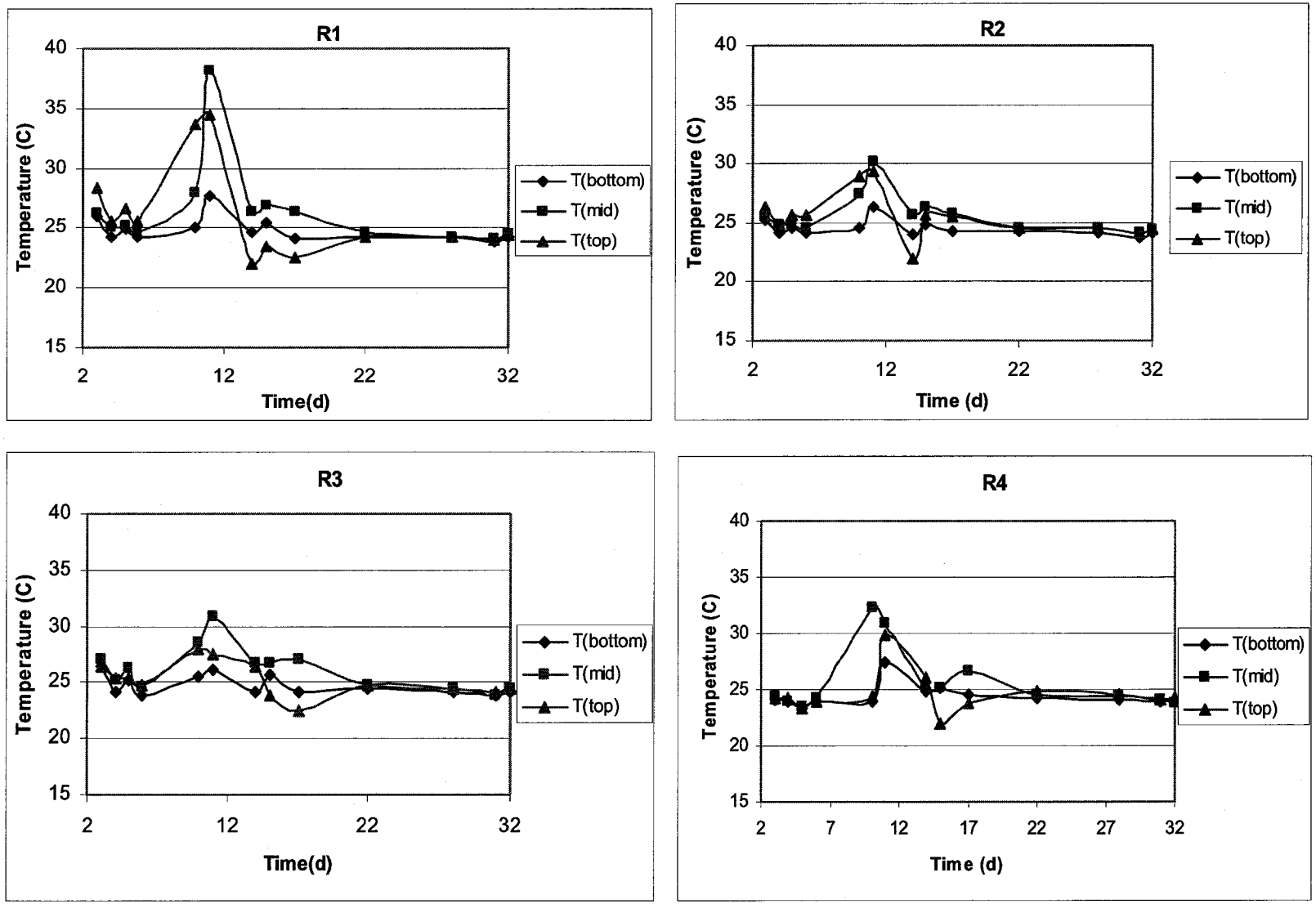


Figure 5.1: Temperature profile in group one.

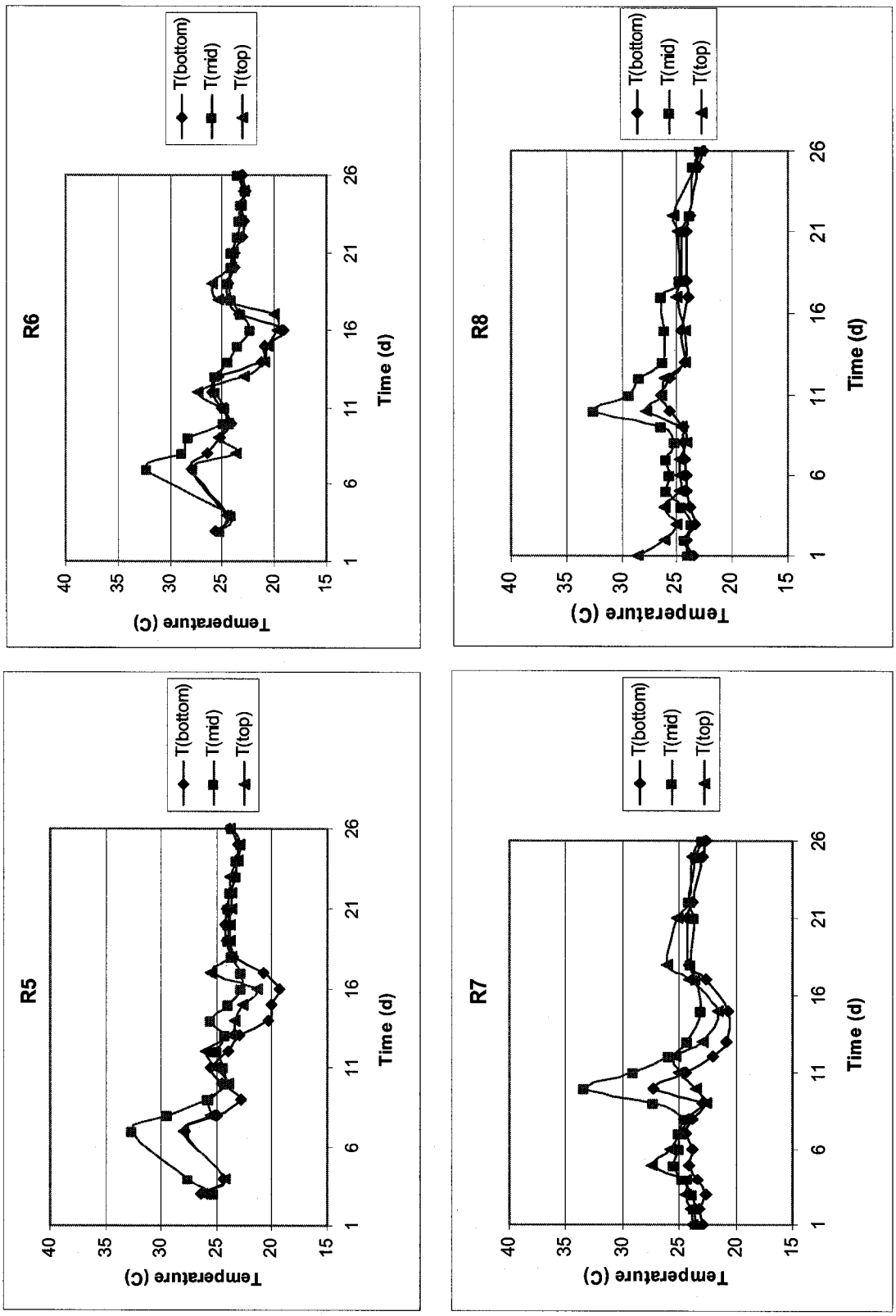


Figure 5.2: Temperature profile in group two.

Generally speaking, in the aerobic stage the temperature increased from approximately 25°C to above 30°C (mid layer) then decreased to lower than 25°C in all layers at the end of this study. This can be used as an indicator for the aerobic biodegradation activity because it constitutes an exothermic reaction. The temperature increased as a result of the high biodegradation rate and then returned to ambient temperature when this rate slowed down. In the last days of the aerobic stage, the temperature of the top layer reached approximately 20°C in R5, R6 and R7 which is attributed to the cooling effect of air and low biodegradation rate.

In the anaerobic stage, the temperature (in all layers) stayed above ambient temperature by 1-2°C. The thermocouples were removed from the bioreactors when the temperature remained 1-2°C above the ambient temperature to prevent any gas leakage through their wires.

There was a small variation in temperature along the vertical profile of the bioreactors. The highest average temperature was recorded in the mid layer (25.6°C), and the lowest in the bottom layer (24.2°C). Those observations coincided with the results obtained from Chiemchaisri et al. (2002). They found that the temperature fluctuated within a range of 26 to 35°C in anaerobic bioreactors, whereas the ambient temperature was 30-32°C, and the temperature at the bottom part of the bioreactors was slightly lower than the upper part.

The low temperature at the bottom layer could be attributed to the cooling effect of leachate at the base of the bioreactors. The leachate was kept in the bioreactor by closing the drainage valve to minimize the shortcircuiting.

Statistical analysis

The purpose of the statistical analysis was to investigate whether there was any significant variation 1) in the temperature along the vertical profile of a bioreactor and, 2) in the mean temperature of all bioreactors.

First, the P-value of Layers[1] was more than 0.05 in all bioreactors as shown in Table 5.3. This indicates that there was no significant difference in the mean temperature of the layers within each bioreactor. In other words, there was no significant variation of temperature along the vertical profile of the bioreactors.

Second, the P-value of Bioreactors[2] was less than 0.05 as shown in Table 5.3. This illustrates that there was a significant difference in the mean temperature of the bioreactors, indicating that the biodegradation rate may have been different from one bioreactor to another.

5.1.1.3 Settlement

Several factors influencing the MSW settlement process include waste composition, density, biodegradation rate and porosity.

Table 5.4 shows the percentage of settlement that took place in the bioreactors with respect to initial height at different stages, plus the statistical analysis. The settlement that occurred in the aerobic stage was 21.4, 21, 17.9, 15.8, 22, 20.7, 18.2, and 16.1%, whereas in the anaerobic stage was 13.8, 13.0, 12.2, 9.3, 19.2, 18.1, 16.4, and 15.0% in R1 through R8, respectively. The total settlement percentages in the bioreactors were 35.2, 33.9, 30.1, 25.1, 41.2, 38.9, 34.5 and 31.0% in R1 through R8, respectively. The average settlement in the aerobic stage was greater than the anaerobic stage. The total settlement

percentage in group two was higher than group one and it decreased by increasing the salt content. Figure 5.3 shows the variation in the average settlement that occurred in the aerobic and anaerobic stages, and the total settlement with salt contents. It was found that sludge addition enhanced the solid waste biodegradation as suggested by the settlements that took place in the aerobic and anaerobic stages.

Table 5.4: Average settlement that occurred in bioreactors

% Average settlement		R1	R2	R3	R4	R5	R6	R7	R8
Stages	Aerobic	21.38	20.98	17.90	15.83	21.98	20.73	18.15	16.08
	Anaerobic	13.79	12.96	12.24	9.26	19.19	18.14	16.38	14.96
	Total	35.17	33.94	30.14	25.08	41.16	38.86	34.53	31.04
	Average	$19.13^{Aerobic}$				$14.61^{Anaerobic}$			
	Average[1]	31.08^{G1}				36.40^{G2}			
P-value	Aerobic	Bioreactors[2]				0.000			
		Groups[3]				0.311			
		Salt content[4]				0.000			
	Anaerobic	Bioreactors[2]				0.000			
		Groups[3]				0.001			
		Salt content[4]				0.009			
	Total	Groups[3]				0.001			
		Salt content[4]				0.001			

(1) Average total settlement in the two groups.
(2) Comparison of the mean settlement in all bioreactors ($F_{7,24}$).
(3) Comparison of the mean settlements of the two groups ($F_{k-1,(n-1).(k-1)} = F_{1,3}$)*.
(4) Comparison of the mean settlement at different salt contents (0, 0.5, 1, 3) %(w/v) ($F_{3,3}$).
*) Where (k-1) is the degree of freedom between the groups, and (n-1) is the degree of freedom between the blocks (Two way ANOVA).

The results of settlement in this study agreed with the results offered by Stessel et al. (1992); Youcai et al. (2002); and Jin et al. (2006). Stessel et al. (1992) found that settlement in bioreactors operated under aerobic conditions was 14.4% of initial height of the waste in a bioreactor run with 10% (v/v) leachate recycle (of waste volume)

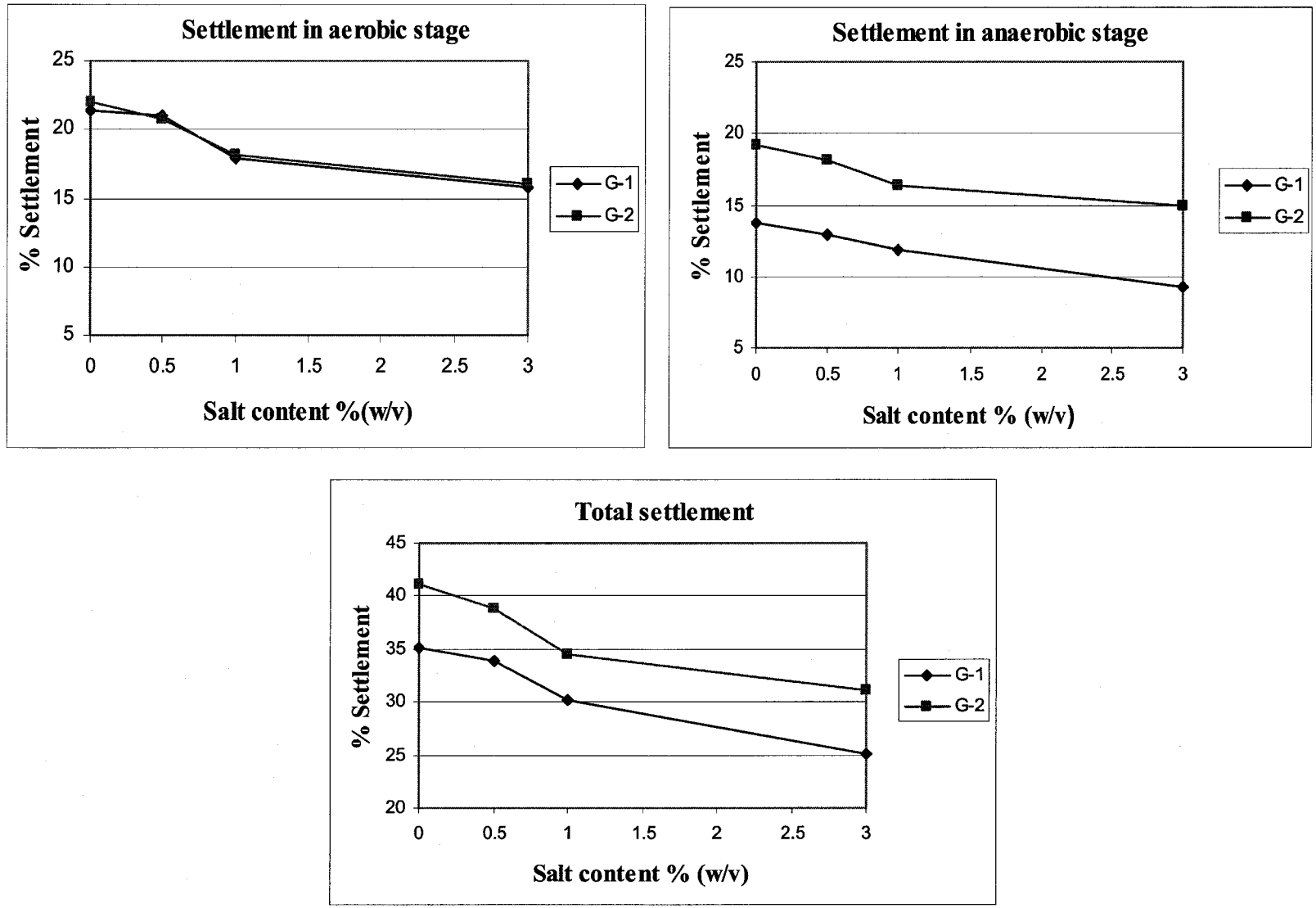


Figure 5.3: Percentage settlement that occurred in the aerobic and anaerobic stages, and total settlement.

and 0.00227 m^3/s air flow during 16 days. Youcai et al. (2002) found the settlement in bioreactors operated under anaerobic conditions was in the range of 2.5 to 22.5% of the initial height of the waste at the end of experiments (300 days). Jin et al. (2006) run experiments in aerobic (18 days) followed by anaerobic conditions for 72 days. They found the settlement in the bioreactor operated with biosolid was 20% of initial height of the waste during the aerobic stage and the total settlement was 25% at the end of the study (100 days).

Statistical analysis

The aim of the statistical analysis was to find if there was any significant difference in the following: 1) the mean settlement of MSW in bioreactors during the aerobic and anaerobic stages, 2) between the mean settlement of the two groups under aerobic and anaerobic conditions and their total settlements, and 3) in the mean settlement at different salt contents under aerobic and anaerobic conditions as well as their total settlement.

First, the P-values of Bioreactors[2] in aerobic and anaerobic were less than 0.05 as shown in Table 5.4. This indicates that there were significant differences in the mean settlement in bioreactors during the aerobic and anaerobic stages. That means there may have been a variation in the biodegradation rate from one bioreactor to another during two stages.

Second, the P-value of Group[3] was more than 0.05 in the aerobic stage and less than 0.05 in the anaerobic stage, suggesting that there was no significant difference between the mean settlements of the two groups in the aerobic stage, but there was a significant difference in the anaerobic stage.

Third, the P-values of Salt Content[4] were less than 0.05 in the aerobic and anaerobic stages, and when considering the total settlements. This indicates that there was a significant difference in the mean of settlements at different salt contents (0, 0.5, 1 and 3) % (w/v) in the aerobic and anaerobic stages and total settlements. Tables 1.3.5, 1.3.6, and 1.3.8 in Appendix B show multiple comparisons of the mean settlement in the aerobic, anaerobic, and total settlement stages, respectively.

The difference was observed in the mean settlement at 1% and 3% salt contents compared to the mean of 0% (w/v) of the aerobic and total settlement stages, whereas, the difference was only significant at 3% when compared to 0% in the anaerobic stage.

5.1.1.4 Summary of solid waste analysis

- There was no statistical difference in the moisture content along the vertical profile of the bioreactors.
- There was no statistical difference in the temperature within the layers of the bioreactors. Temperature is a good indicator of the biodegradation rate in the aerobic stage.
- The total settlement was higher in bioreactors operated with sludge addition and decreased with increasing the salt content. The results of total settlement agreed with the results of methane yield and percentage peak reduction of leachate quality during the aerobic and anaerobic stages. This emphasizes that sludge addition enhances the biodegradation in terms of settlement.
- Statistically, there were significant differences in the mean settlement at different salt contents indicating that the high salt content inhibited the biodegradation of MSW.

5.1.2 Landfill gas

This subsection covers methane production and concentrations produced from the 1D bioreactors and BMP assays. BMP assays were carried out to determine the amount of methane produced from leachate generated in the 1D bioreactors.

5.1.2.1 Methane production

Table 5.5 summarizes the methane yield, total methane produced and time required to reach 10, 50, 70 and 80% of total methane generated in the control (R1). The variation in daily methane production in all bioreactors is shown in Figures 5.4 and 5.5. There was a leakage in R3 and hence no data are reported for R3.

In R1, methane production started on day 20. Daily methane production increased progressively to reach its maximum value of 11.9 L/d on day 58. From that moment on, it gradually declined to 3.1 L/d on day 115. Methane production increased again to 8.1 L/d

Table 5.5: Methane production

	R1	R2	R4	R5	R6	R7	R8
Yield (L/kg dry waste)	70.59	61.66	47.53	84.72	78.73	72.60	59
10%[1]	50	53	120	80	82	98	117
50%[1]	146	214	284	157	172	221	258
70%[1]	199	287	-	210	226	279	313
80%[1]	231	319	-	235	252	295	343
At the end[2]	100%	88%	67%	120%	110%	101%	87%
Average daily CH4 (L)	3.89	3.42	2.60	4.85	4.35	4.11	3.38
Total CH4 (L) produced	1442.6	1269.0	963.6	1724.7	1580.8	1460.9	1256.0

(1) Time (d) to reach 10, 50, 70 and 80% of accumulative methane produced in R1.
(2) Percentage of accumulative methane produced compared to R1 at the end of study.

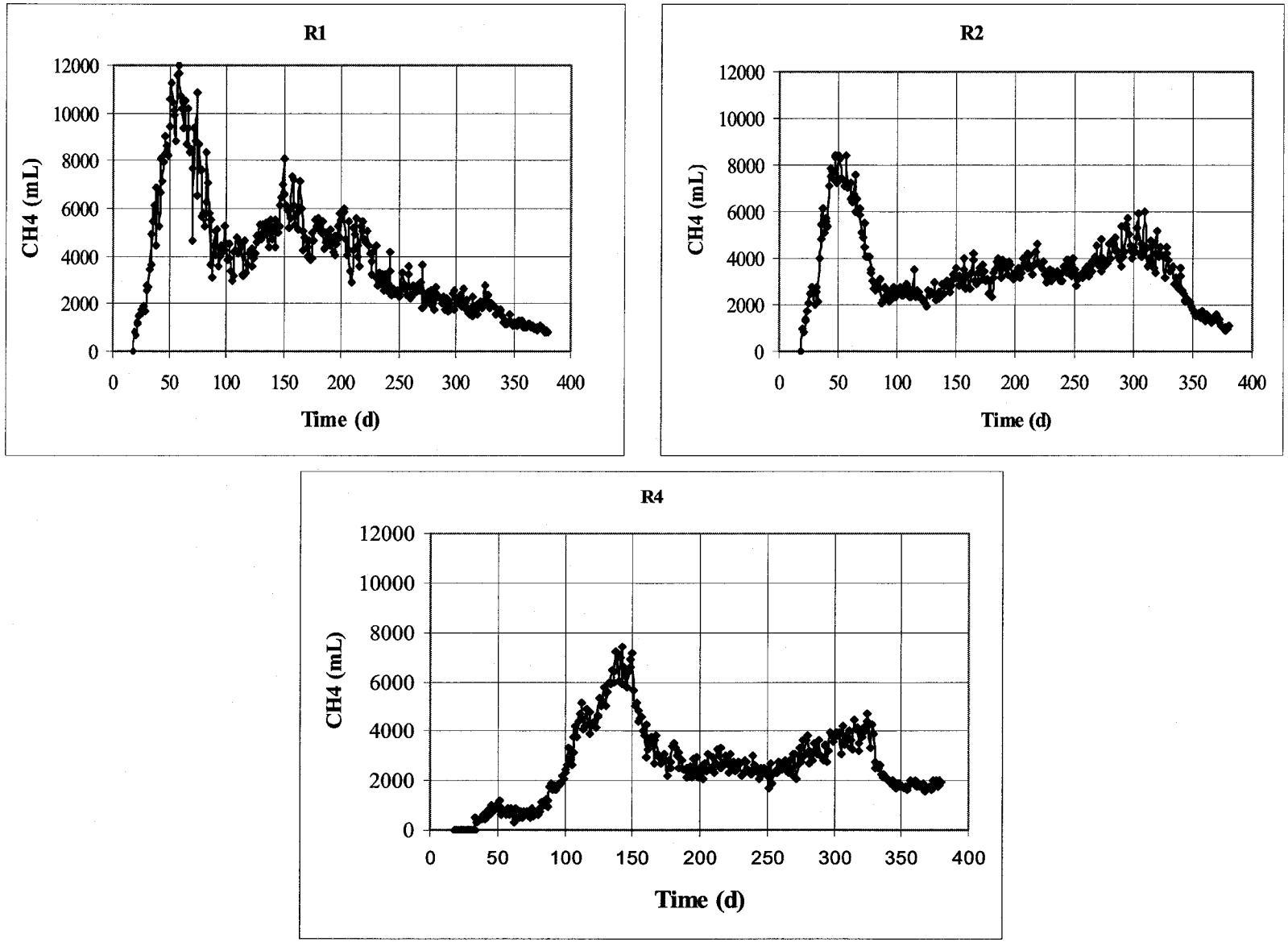


Figure 5.4: Daily methane production in group one.

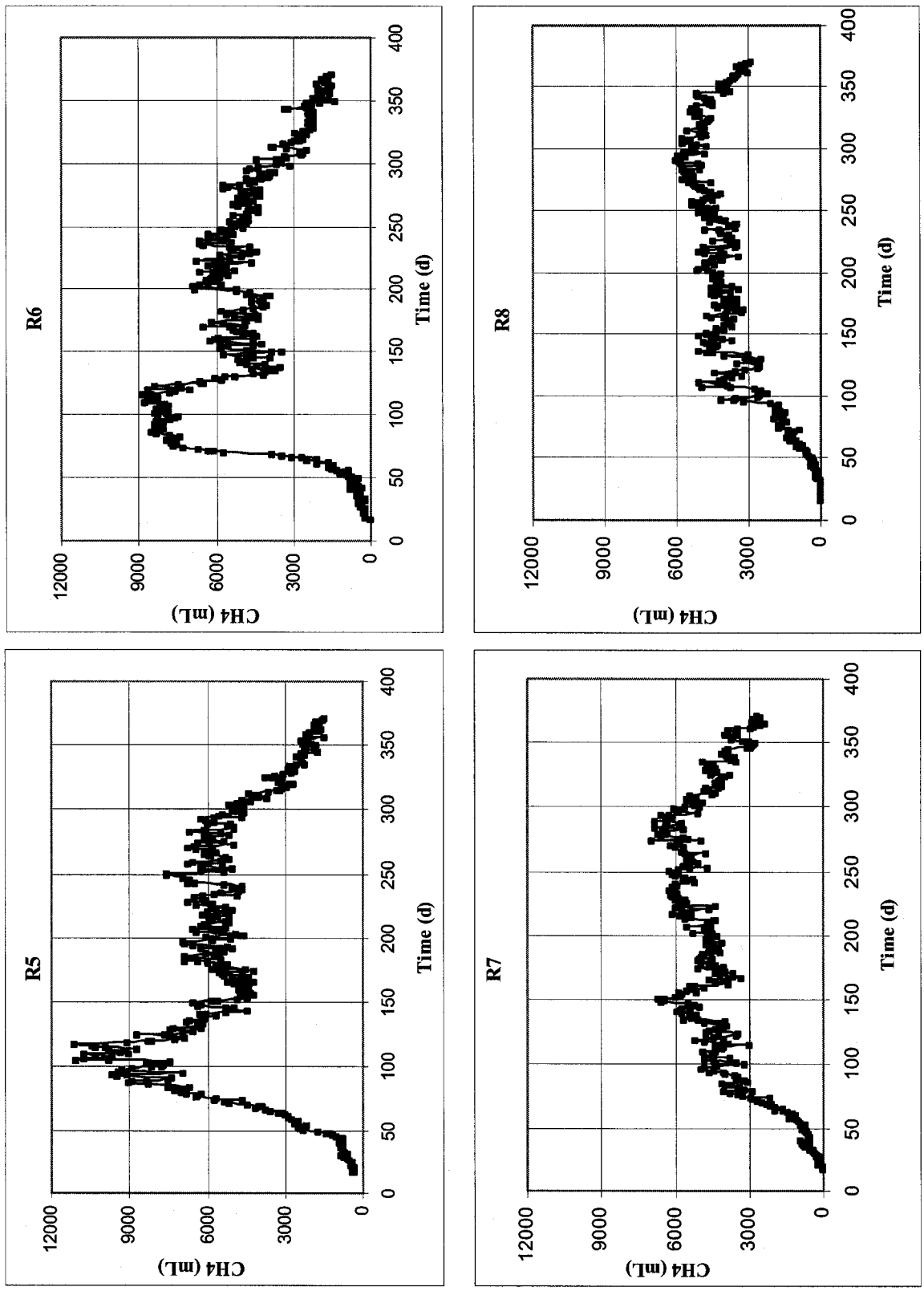


Figure 5.5: Daily methane production in group two.

on day 150, subsequently falling to a level of approximately 0.785 L/d towards the end of the study. The total methane produced in this bioreactor was 1442.6 L and the methane yield was 70.6 L/kg dry waste. The time required to reach 10, 50, 70 and 80% of the total methane produced was 50, 146, 199, and 231 days, respectively.

R2 behaved similarly to R1 at first. Methane production also started on day 20. By day 50, a maximum daily methane production of 8.44 L/d was reached. After this peak, daily production exhibited a slow decline, reaching 2.06 L/d on day 87 and remaining below 3 L/d until day 147. Between days 148 and 250, the daily methane production stayed in the range of 3 - 4.5 L/d. Following day 250, methane production went up to 6 L/d on day 309. Afterwards, it slowly dropped to 1.07 L/d towards the end of the study. The total methane produced in this bioreactor was 1269 L and the methane yield was 61.7 L/kg dry waste. At the end of this study, R2 produced 88% of the total methane produced in R1.

An increase in the lag time of methane production and the time required to reach its first peak was observed in R4 (33 days and 142, respectively), as compared to R1. Following R4 peak methane production of 7.43 L/d, the methane production dropped to 2.18 L/d on day 176. The daily methane production remained constant (2.82 L/d) between days 176 and 278, followed by a second peak on day 325 of 4.7 L/d. Towards the end of this study, this latest value decreased to 1.95 L/d. The quantity of methane produced in this bioreactor was 963.6 L or 67% of the total methane produced in R1. The methane yield was 47.5 L/kg dry waste and the time required to reach 10 and 50% of the total methane produced in control (R1) was 120 and 284 days, respectively. The methane production never reached 70% of R1. As the results of R4 showed, higher concentrations of salt in

the bioreactor increased the lag time of methane production and lowered the amount of daily methane produced.

In R5, methane production took place a bit earlier (day 17). Production was slow and steady for the first 45 days, followed by a significant increase which extended to day 106 when it reached its first peak value of 11.04 L/d. This peak was followed by a sharp drop to 4.2 L/d on day 156. On day 186, methane production rose again to 6.8 L/d, and then remained constant at around 5.88 L/d until day 293, when it started a gradual decline to 1.48 L/d towards the end of the study. The total amount of methane produced by this bioreactor was 1724.7 L, surpassing R1's production by 20%. The methane yield was 84.7 L/ kg dry waste.

Methane production in R6 started on day 19, and then similarly to R5, it increased slowly during the first 50 days, continuing with a dramatic rise until it reached a maximum of 8.85 L/d on day 117. After this increase, the daily methane fell rapidly to 3.46 L/d on day 150. From that moment and until day 250, the average daily methane production was 5.4 L/d, gradually decreasing to 1.5 L/d at the end of this study. The total methane produced was 1580.8 L, which was more than the total methane produced in R1 by 10%. The methane yield was 78.7 L/ kg dry waste.

A small delay in the onset of methane production (day 21) was observed in R7, as compared to R5. Also, like in R5 and R6, daily methane production slowly increased during the first 57 days, followed by a gradual ascent to its first peak of 6.68 L/d on day 151. After this peak, methane production fell to 3.27 L/d on day 168, then rising to its second peak of 6.7 L/d on day 289, only to be followed by a steady and final descent to

2.66 L/d toward the end of this study. The total amount of methane produced in this bioreactor was 1460.9 L, that is, 1% over the total methane produced by R1. The methane yield was 72.6 L/kg dry waste.

Methane production started on day 33 in R8. The daily methane production increased slowly reaching a maximum of 5.06 L/d on day 111. Next, it decreased to 2.5 L/d on day 125, rising again to 5 L/d on day 137. Between days 137 and 250, methane production averaged 4.2 L/d, and then it slightly went up to 5.92 L/d on day 295. From day 295, methane production started its slow decline to 2.88 L/d towards the end of this study. The total methane produced in this bioreactor was 1256 L and it was 87% of the total methane produced in R1. The methane yield was 59 L/kg dry waste. The time required to reach 10, 50, 70 and 80% of the total methane produced in control (R1) was 117, 258, 313, and 343 days, respectively.

The rate of methane production in group two was slow during the first 50 days. The reason being that the addition of anaerobic digested sludge increased the VFA in the bioreactors, which in turn inhibited the methanogenic bacteria by lowering the pH. The addition of anaerobic digested sludge was terminated on day 35. After this day, there was a significant increase in the daily methane production in R5, R6, R7 and R8.

The highest methane yield and average daily methane production were observed in R5. Both parameters were higher in bioreactors operated with anaerobic digested sludge addition (group two) than in bioreactors operated without sludge addition (group one), and they decreased as the salt content increased. The accumulative methane production in bioreactors of group two was higher than in bioreactors of group one as shown in Figure

5.6. This emphasizes that the anaerobic digested sludge enhanced the waste biodegradation, and that the high salt content inhibited it as shown by the average of daily methane production, methane yield, value of the peaks, and total methane produced.

Leuschner et al. (1982) found the methane yield was 35 L/kg dry waste after 365 days from their experiments for a bioreactor operated with leachate recycle and buffer addition, and 63 L/kg dry waste for a bioreactor operated with leachate recycle and addition of buffer, nutrients and anaerobic digested sludge. Ağdağ et al. (2005) found the methane yield was 40 L/kg dry waste after 100 days from their experiments run with leachate recycle and buffer addition. Chiemchaisri et al. (2002) found the methane yield was 51.6 L/kg dry waste after 240 days from their anaerobic bioreactor operated with addition of buffer and anaerobic digested sludge. San et al. (2001) found the total methane produced was 34.4 L/kg dry waste after 275 days from their anaerobic bioreactor operated with leachate recycle.

The methane yield in this study was higher than what was reported in the literature. This could be attributed to the following reasons: higher organic contents, longer operation time, and the effect of injecting air in the first 16 days of operation (aerobic stage). The injection of air enhanced the acidogenic phase, which in turn triggered an earlier methanogenic phase.

Statistical analysis

Table 5.6 shows the results of the statistical analysis performed on the daily methane production and methane yield. It shows the P-values of Bioreactors[1], Group[2], Salt content[3], and Yield[4] were less than 0.05. This indicates the following:

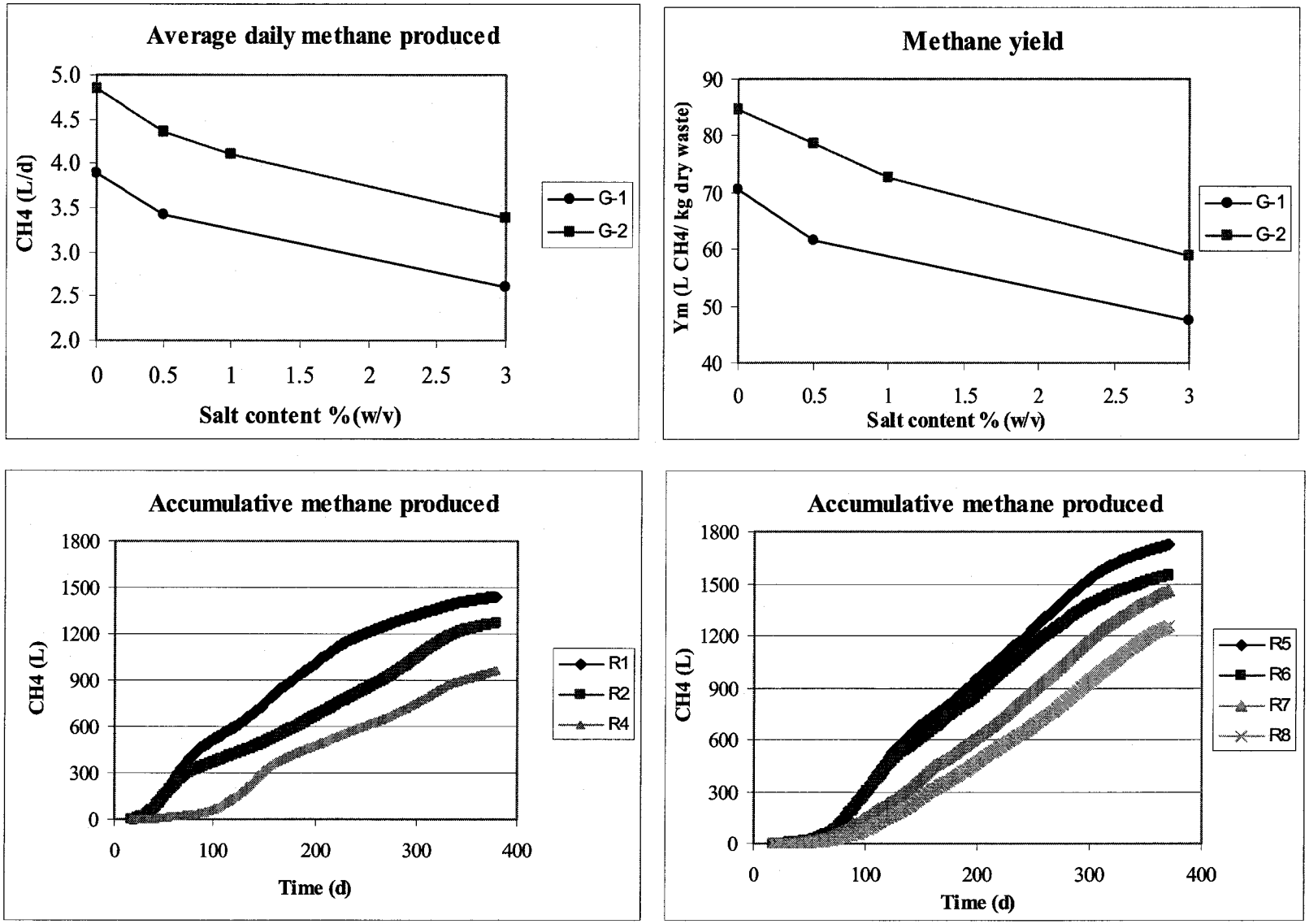


Figure 5.6: Average daily methane production, methane yield and accumulative methane produced.

1) There was a significant difference in the mean daily methane production in all bioreactors (P-value of Bioreactors[1] <0.05). Table 2.1.4 in Appendix B shows multiple comparisons between the mean daily methane production in all bioreactors.

2) A significant variation occurred in the mean daily methane production in the two groups and at different salt contents (P-values of Mean CH4[2] <0.05).

3) Also, a significant difference was observed in the mean methane yield in the two groups and at different salt contents (P-values of Yield[4] < 0.05). The difference was in the mean methane yield at 1% and 3% compared to the mean of 0% (w/v) salt contents, as shown in Table 2.1.6 in Appendix B.

In general, the statistical analysis shows there were significant differences in the mean of daily methane production and methane yield 1) in all bioreactors, 2) between the two groups, and 3) at different salt contents.

Table 5.6: Statistical analysis for daily methane production and methane yield

Methane production					
P-value	Bioreactors[1]	0.000			
	Mean CH4[2]	Groups	0.000	Salt content	0.000
	Yield[3]	Groups	0.001	Salt content	0.002

(1) Comparison of the mean daily methane production in all bioreactors ($F_{6, 2501}$).
(2) Comparison of the mean daily methane production as a function of groups and salt contents ($F^{G}_{1,3}$ and $F^{S}_{3,3}$).
(3) Comparison of the mean methane yield as a function of groups and salt contents ($F^{G}_{1,3}$ and $F^{S}_{3,3}$).

5.1.2.2 Methane concentration

The methane concentration (expressed as a percentage of biogas) in all bioreactors is shown in Figures 5.7 and 5.8. Table 5.7 summarizes the lag time of methane production,

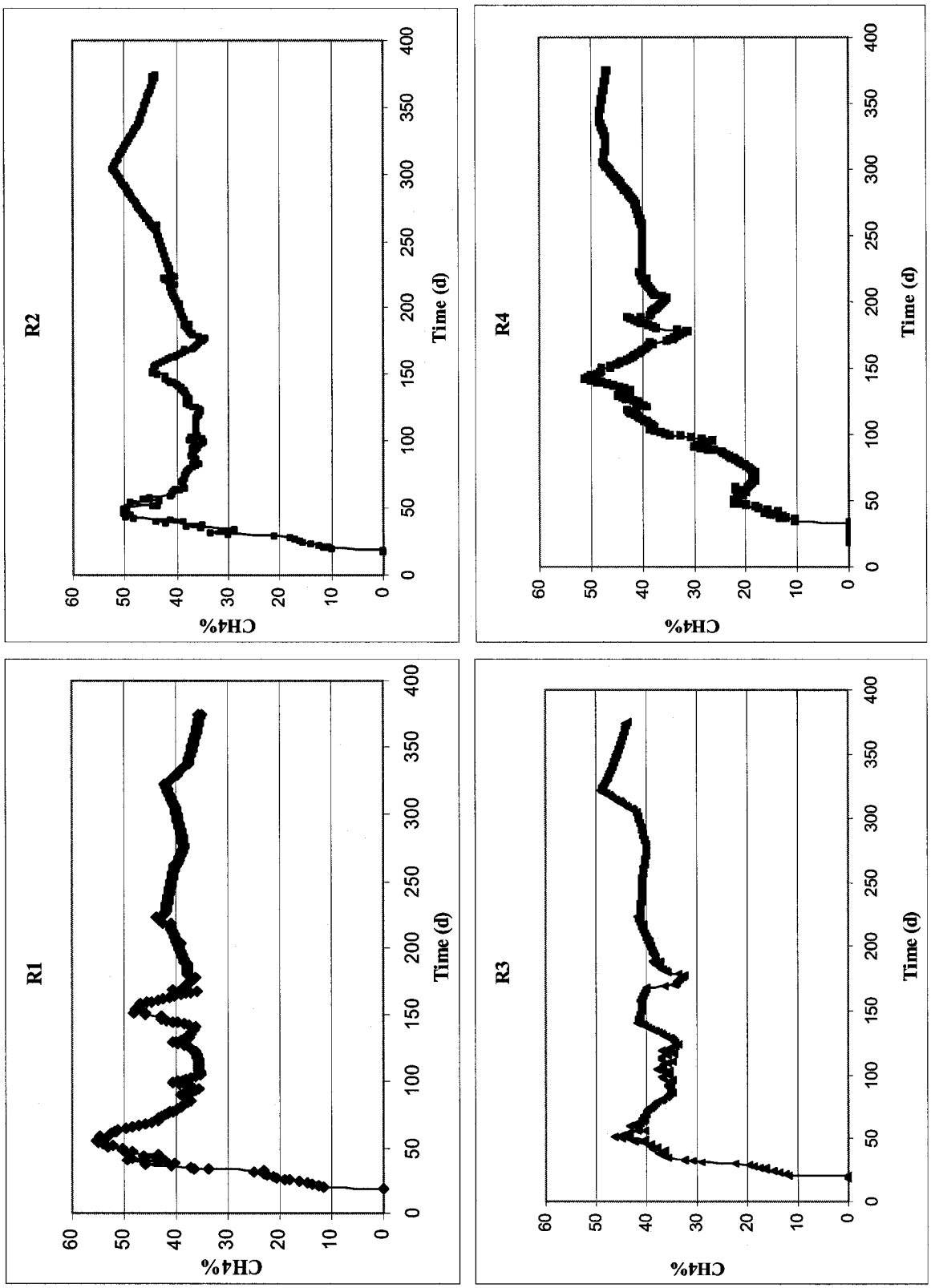


Figure 5.7: Methane composition in group one.

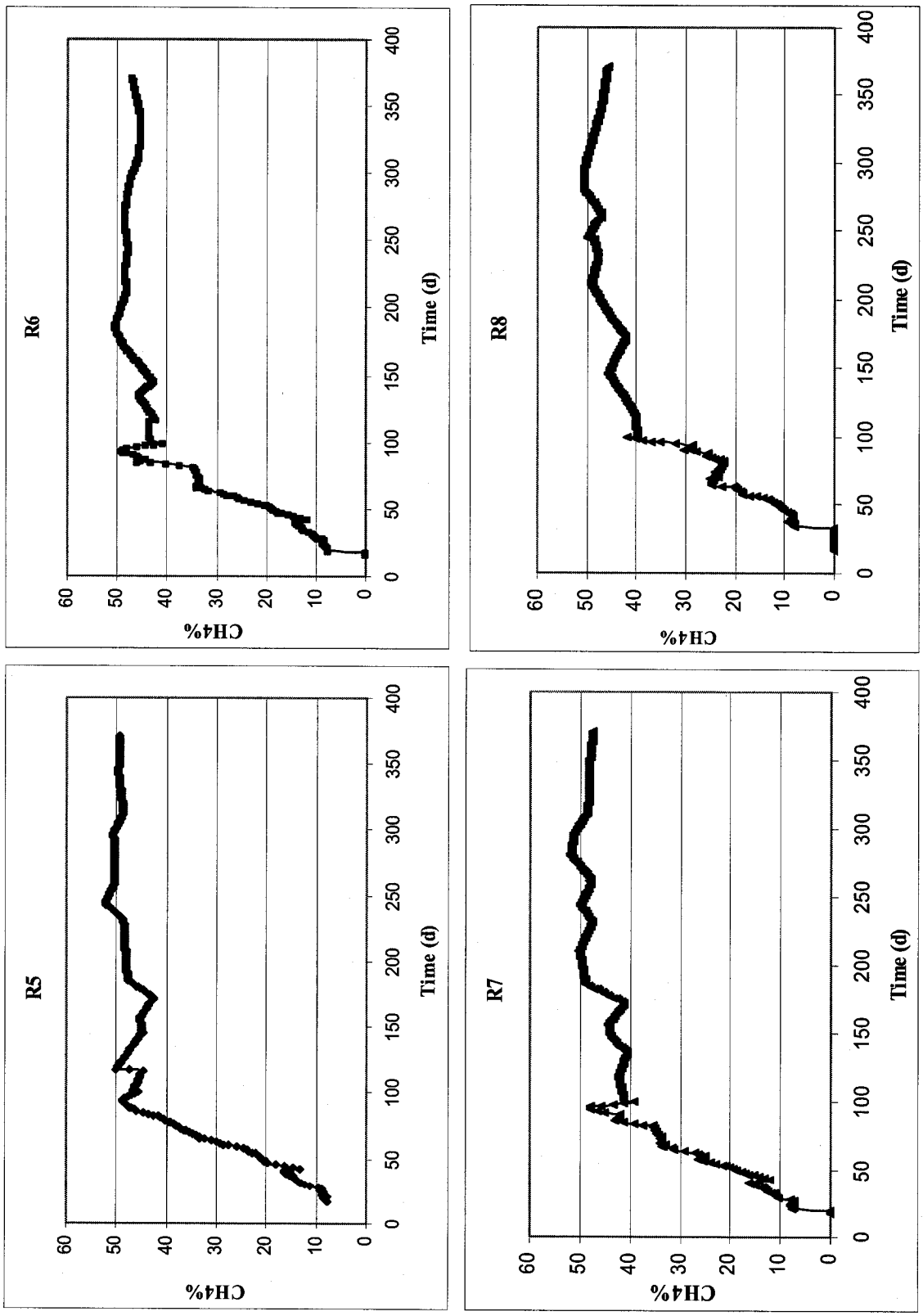


Figure 5.8: Methane composition in group two.

Table 5.7: Methane concentration (expressed as a percentage of the biogas)

% CH4		R1	R2	R3	R4	R5	R6	R7	R8
Lag time (d)		20	20	21	33	17	19	21	33
Time to reach 40%		36	39	47	111	79	84	85	99
Mean		41.4	39.3	39.5	37.0	43.5	41.6	41.9	39.4
P-value	Bioreactors[1]	0.000							
	Group[2]	0.000							
	Salt content[3]	0.000							

(1) Comparison of the mean methane concentration in all bioreactors ($F_{7, 2863}$).
(2) Comparison of the mean methane concentration of the two groups ($F_{2, 2870}$).
(3) Comparison of the mean methane concentration at 0, 0.5, 1 and 3% (w/v) salt contents ($F_{3, 2868}$).

time required to reach 40% of methane concentration in the biogas produced and statistical analysis of methane concentration in all bioreactors. In general, the methane concentration follows the trend of daily methane production.

In R1, methane concentration in the biogas produced initially was 11.7% on day 20, and climbed to 55.2% by day 55. Then it decreased to 35.5% on day 95. Between days 100 and the end of the study, the average methane concentration was 40.2%.

Initially, methane was produced in R2 on day 20 and its concentration in biogas was 10%. Then the methane concentration rose to a maximum of 50.2% on day 50. After that, it declined to 35.2% on day 124. From day 125 and until the end of the study, the average methane concentration was 42.6%.

Methane concentration in the biogas produced in R3 was 11.7% on day 21. Following that point, it reached a maximum of 46.4% on day 52 and then it declined to 34.1% on day 125. From then on, the average methane concentration was 42.2%.

In R4, methane production started on day 33 and its concentration in biogas was 10.7%. Then it increased slowly to reach 51.3% on day 141, followed by a drop to 31.2% on day 178. From that moment, it increased and stayed around 40%. The average of methane concentration from day 180 to the end of the study was 44.6%.

Methane concentration in the biogas produced in R5 was 7.7% on day 17. Subsequently, the methane concentration increased slowly to reach 20% on day 48. Next, it increased dramatically surpassing the 40% value on day 79. It reached its first peak of 48.7% on day 94 and it remained between 42.6 and 52.3% thereafter. From day 100 until the end of the study, the average methane concentration was 48.4%.

In R6, the initial methane concentration in biogas was 7.4% on day 19. Then it rose slowly to reach 20.4% on day 54, climbing further above 40% by day 84. It reached the first peak of 49.2% on day 94 and stayed between 40.8 and 50.4% thereafter. From day 100 until the end of the study, the average methane concentration was 46.6%.

The concentration of methane in the biogas produced from R7 was 7.75% on day 21. Then the methane concentration increased slowly and reached above 20% by day 52. It continued rising sharply to reach above 40% on day 85. The methane concentration reached its first peak of 48% on day 95, remaining between 39 and 52% thereafter. From day 100 until the end of the study, the average methane concentration was 47%.

The initial methane concentration in the biogas produced from R8 was 8.1% on day 33. Then it rose slowly and reached above 40% on day 99. From that point on, the methane concentration remained between 39.7 and 50.7% and the average methane concentration for the same period was 46.7%.

A comparison of the trend in methane concentration between the bioreactors without sludge addition (group one) and with sludge addition (group two) indicates that the bioreactors with sludge addition lagged in terms of the time taken to reach the peak methane concentration, the average methane concentration after the peak was reached were higher in the bioreactors operated with sludge addition. The result was a higher mean methane concentration for R5 through R8 in comparison to R1 through R4 as indicated in Table 5.7.

Statistical analysis

Table 5.7 shows the results of the statistical analysis on methane concentration in all bioreactors. It shows the P-values for Bioreactors[1], Group[2], and Salt content[3], were less than 0.05. This indicates that there were significant differences in the mean methane concentration 1) in all bioreactors, 2) between the two groups, and 3) at different salt contents. Table 2.2.4 in Appendix B shows multiple comparisons between the mean of methane concentration in all bioreactors. It shows that there was no significant difference between the mean of methane concentration in R1 and other reactors, except R4.

5.1.2.3 BMP assays

This part presents the results of BMP assays that were used to determine the amount of methane produced from leachate generated in the 1D bioreactors. Three sets of BMP assays were carried out during the study. In the first set, the leachate used was taken at the growth phase of leachate concentration, whereas, in the second set, the leachate was taken at the decline phase of leachate concentration. The third set of BMP assays was designed to compare the effect of using two types of inoculums on methane production. The two types of inoculums were anaerobic digested sludge (ADS) and acclimatized anaerobic digested sludge (AAD).

- **First set**

In this set, 300 mL of leachate produced from each bioreactor was used as a substrate for the BMP assays with addition of 20% (v/v), or 60 mL of anaerobic digested sludge as an inoculum. The concentrations of leachate (TVS) used were 12270, 10310, 10692, 15360, 15920, 13720, 12204 and 14800 mg/l in R1 through R8, respectively as shown in Table 5.8.

Table 5.8 summarizes the results of the BMP assays, including lag time of methane production, time required to reach the peak of daily methane production, total methane produced, methane yield, and hydrolysis rate constants. The variations in daily methane production, methane concentration and accumulative methane generated are shown in Figures 5.9 and 5.10.

The total methane produced was higher in group two of BMP assays because of their higher leachate concentration (TVS); however, the methane yield was higher for group two and decreased with increasing salt content.

Table 5.8: Results of methane produced from first set of BMP assays

	R1	R2	R3	R4	R5	R6	R7	R8
Salt content %(v/v)	0	0.5	1	3	0	0.5	1	3
Initial TVS (mg/l)	12270	10310	10692	15360	15920	13720	12204	14800
Duration Time (d)	24							
Lag time (d)	0	1	2	10	0	1	1	6
Time to reach peak (d)	10	15	15	20	13	13	14	22
Total CH4 (mL)	1562	1296	1092	242	2052	1678	1364	336
Y_m (mL/g VS $_{added}$)	424	419	340	53	429	408	373	76
k_h (d^{-1})	0.10	0.062	0.063	0.029	0.062	0.058	0.058	0.039

Statistical analysis

Table 5.9 summarizes the results of statistical analysis conducted on daily methane production, lag time of methane production, time to reach the peak daily methane produced, and methane yield.

The P-value of BMP[1] was less than 0.05. This indicates that there was a significant difference in the mean daily methane production of all BMP assays, but no significant difference between the mean daily methane production in the two groups, as suggested by the P-value of Group[2]. The difference was in R4 and R8 compared to R1, as shown in Table 2.3.4 in Appendix B.

The mean lag time of methane production, the mean time required to reach the peak daily methane production, and mean methane yield showed similar statistical results. There was no significant difference between the two groups, but there was a significant

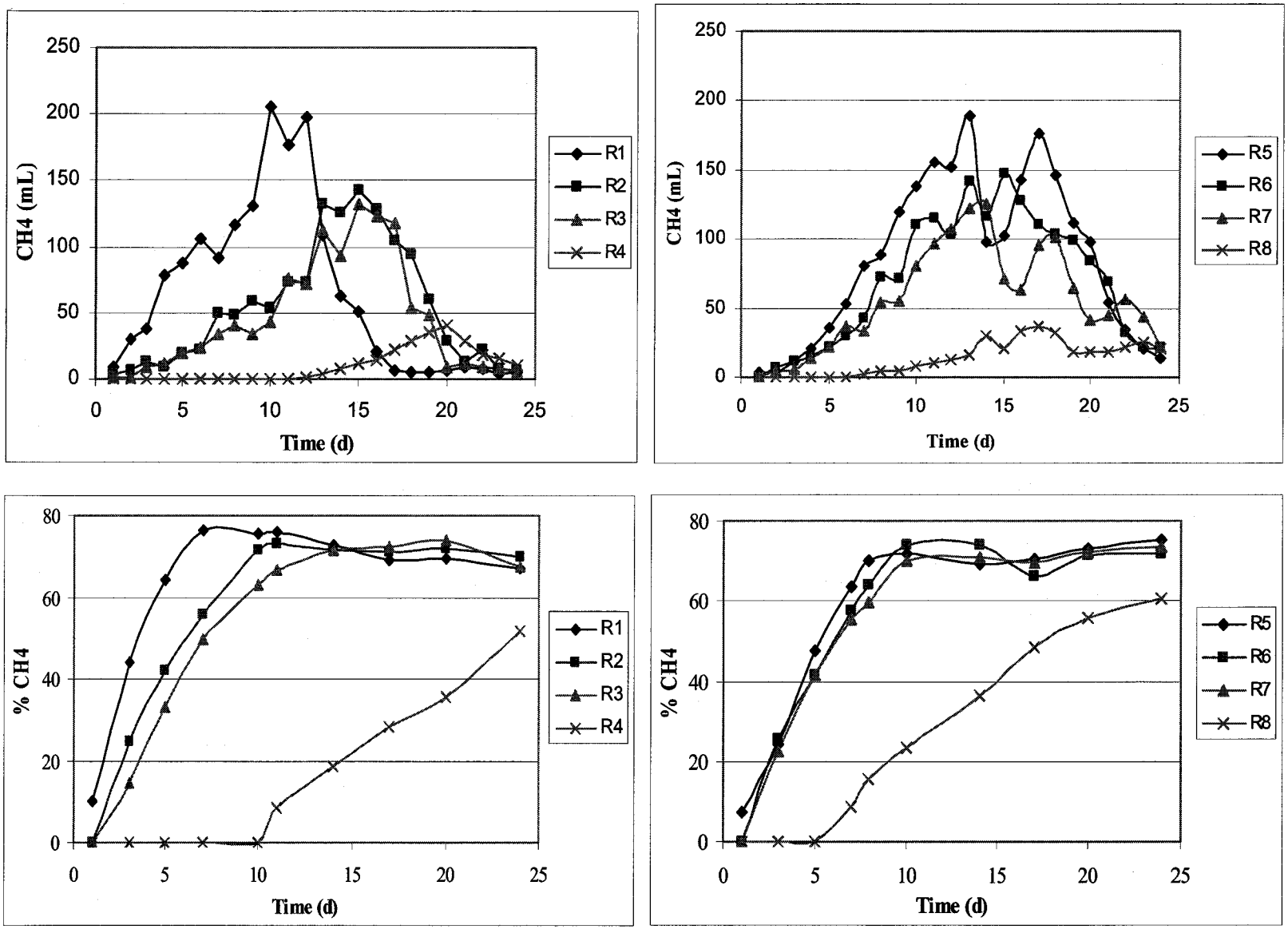


Figure 5.9: Daily methane production and methane concentration in the first set of BMP assays.

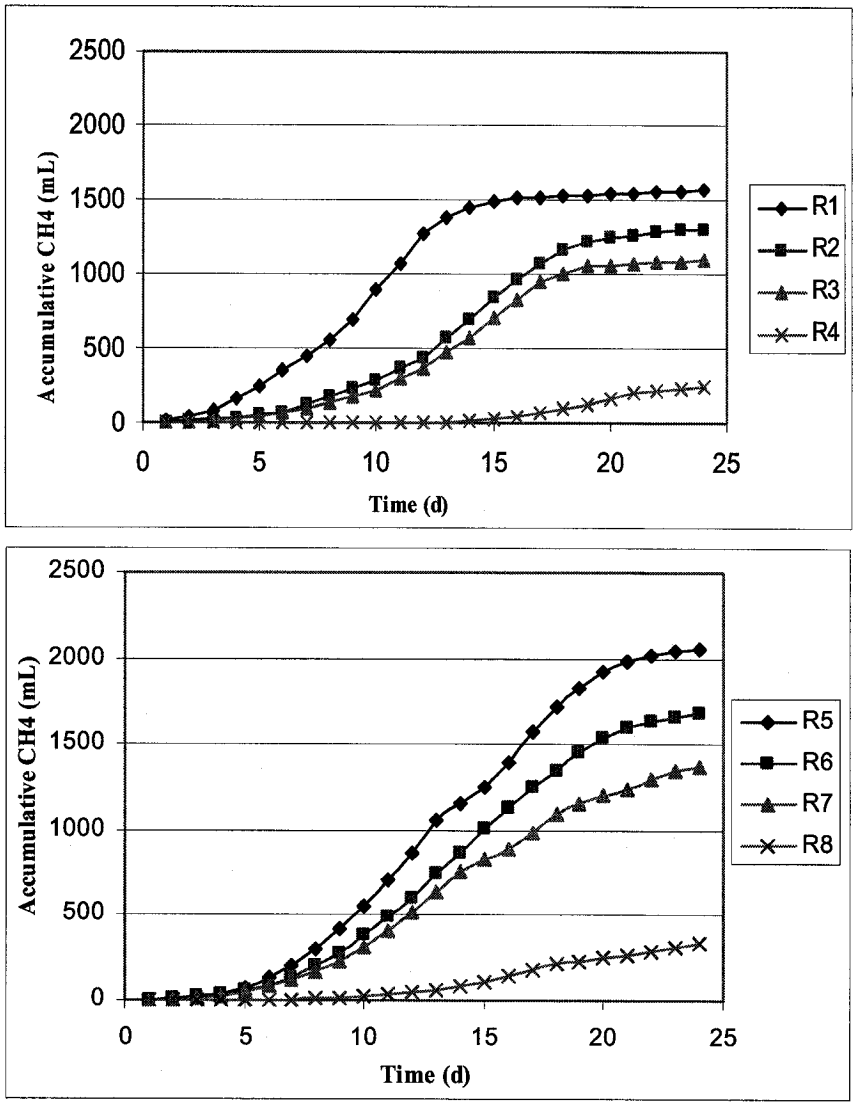


Figure 5.10: Accumulative methane production in the first set of BMP assays.

difference at different salt contents. The difference was at 3% compared to 0% (w/v) salt content in the case of the lag time and the time required to reach the peak daily methane production, whereas it was at 1% and 3% (w/v) in the methane yield, as shown in Tables 2.3.5, 2.3.7, and 2.3.9, respectively in Appendix B.

The results of the statistical analysis emphasize that the high salt content (3%) increased both the lag time and the time required to reach the peak of the daily methane production, and decreased significantly the methane yield compared to lower salt contents.

Table 5.9: Statistical analysis of methane production from the first set of BMP assays

P-value	BMP[1]	0.000			
	Group[2]	0.152			
	Lag time[3]	Groups	0.278	Salt content	0.027
	Peak[4]	Groups	0.703	Salt content	0.037
	Y_m[5]	Groups	0.222	Salt content	0.000

(1) Comparison of the mean daily methane production from all BMP assays ($F_{7, 184}$).
(2) Comparison of the mean daily methane production in the two groups ($F_{1, 190}$).
(3) Comparison of the mean lag time methane production from BMP assays in the two groups and at different salt contents ($F^G_{1, 3}$ and $F^S_{3, 3}$).
(4) Comparison of the mean time to reach the peak daily methane production from BMP assays in the two groups and at different salt contents ($F^G_{1, 3}$ and $F^S_{3, 3}$).
(5) Comparison of the mean methane yield from BMP assays in the two groups and at different salt contents ($F^G_{1, 3}$ and $F^S_{3, 3}$).

- **Second set**

In this set, 250 mL of leachate generated from each bioreactor were taken at the decline phase of leachate concentration and used in the BMP assays. The concentrations of leachate (TVS) were 5170, 8700, 9512, 13333, 10500, 12050, 11886 and 12408 mg/l in R1 through R8, respectively.

Table 5.10 summarizes the results of methane produced from the second set of BMP assays including lag time, time to reach the maximum daily production, total methane produced, stabilization time (time required to reach a low daily methane production rate), and hydrolysis rate constant. Figures 5.11 and 5.12 show the variations in daily methane

production, methane concentration and accumulative methane produced in all BMP assays.

The lag time of methane production increased from 1 day in R1 to 6 days in R4 in group one, and from no lag time in R5 to 5 days in R8 in group two. The lag times of R4 and R8 in this set were shorter than the first set. The reason for that was bioreactors R4 and R8 produced biogas which contained 40% (v/v) methane, meaning that the leachate taken from these bioreactors contained biomass already acclimatized to high salt contents.

Table 5.10: Results of methane produced from the second set of BMP assays

	R1	R2	R3	R4	R5	R6	R7	R8
Salt content %(v/v)	0	0.5	1	3	0	0.5	1	3
Initial TVS (mg/l)	5170	8700	9512	13333	10500	12050	11886	12408
Duration time (d)	24	30	36	69	28	36	46	57
Lag time (d)	1	2	3	6	0	1	2	5
Time to reach peak (d)	10	17	18	52	17	21	25	44
Total CH4 (mL)	685	1161	1252	1522	1427	1573	1543	1551
Stabilization time (d)	22	30	36	69	28	36	43	57
Y_m (mL/g VS $_{added}$)	442	445	439	381	453	435	433	417
k_h (d^{-1})	0.074	0.044	0.04	0.017	0.06	0.035	0.03	0.018

Statistical analysis

Table 5.11 summarizes the statistical analysis for daily methane production, lag time of methane production, time to reach the peak daily methane produced, stabilization time, and methane yield.

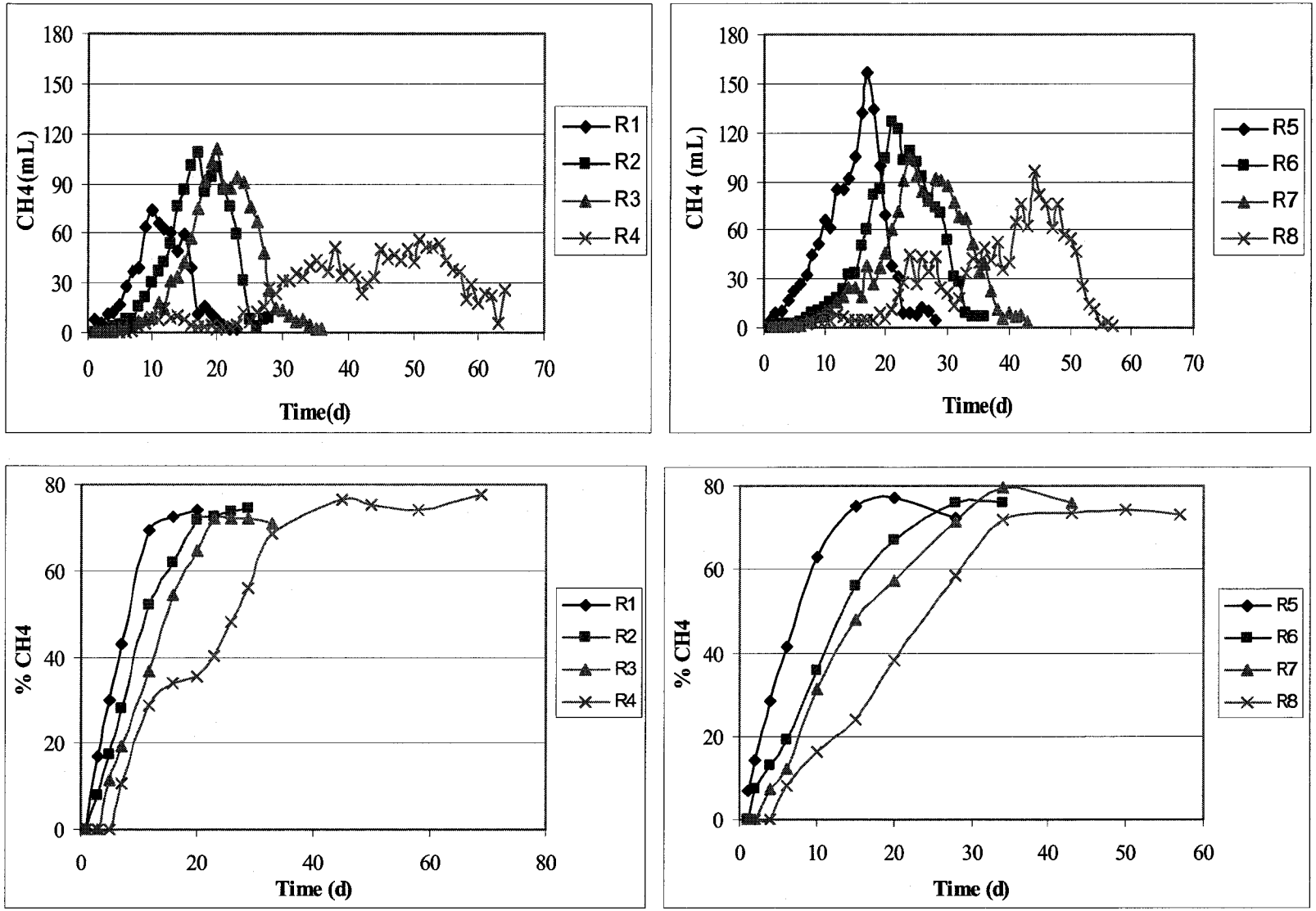
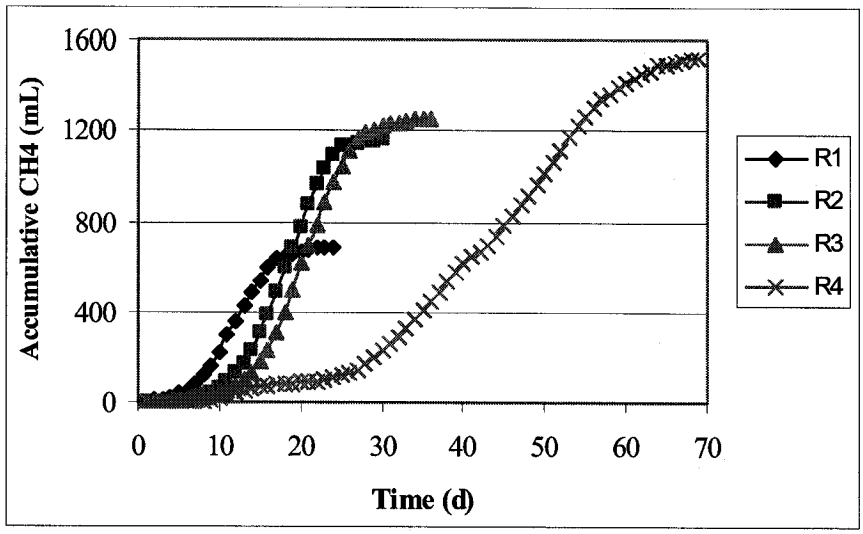


Figure 5.11: Daily methane production and methane concentration in the second set of BMP assays.



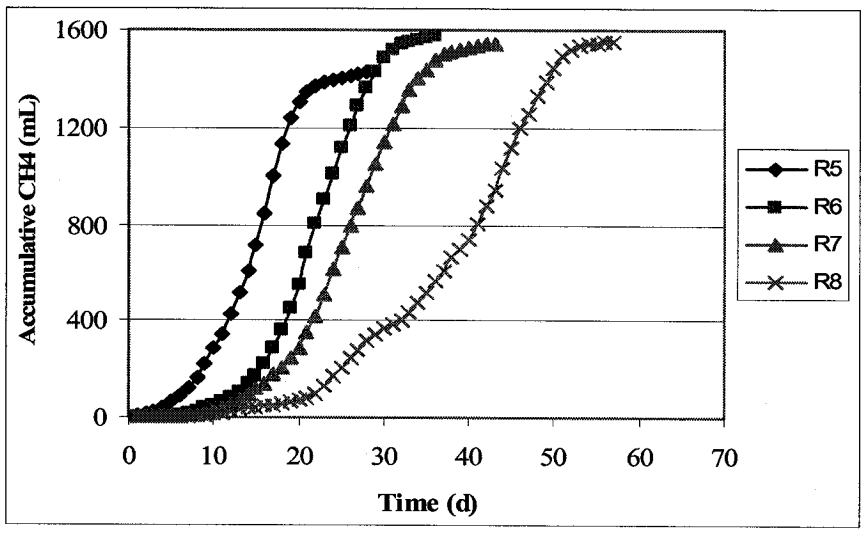


Figure 5.12: Accumulative methane production in second set of BMP assays.

The P-value of BMP[1] and Group[2] were less than 0.05. This indicates that there were significant differences in the mean daily methane production in all BMP assays, and between the mean daily methane produced in the two groups as proposed. The difference was between the mean daily methane production in R5 and both R4 and R8, and between R6 and R4, as shown in Table 2.3.12 in Appendix B.

The mean lag time of methane production, mean time required to reach the peak daily methane production, and mean stabilization time showed similar statistical results. There was no significant difference between the two groups, but there was a significant difference at different salt contents. The difference was observed at 3% compared to 0% (w/v) salt content, as shown in Tables 2.3.15, 2.3.17, and 2.3.19 in Appendix B.

There was no significant different between the mean methane yield in two groups and at different salt contents.

Table 5.11: Statistical analysis of methane production from the second set of BMP assays

P-value	BMP[1]	0.001			
	Group[2]	0.037			
	Lag time[3]	Groups	0.537	Salt content	0.008
	Peak[4]	Groups	0.534	Salt content	0.019
	Stabilization time[5]	Groups	0.762	Salt content	0.032
	Y_m[6]	Groups	0.512	Salt content	0.132

(1) Comparison of the mean daily methane production from all BMP assays ($F_{7,313}$).
(2) Comparison of the mean daily methane production in the two groups ($F_{1,314}$)
(3) Comparison of the mean lag time methane production from BMP assays in the two groups and at different salt contents ($F^G_{1,6}$ and $F^S_{3,4}$).
(4) Comparison of the mean time to reach the peak of daily methane production from BMP assays in the two groups and at different salt contents ($F^G_{1,3}$ and $F^S_{3,3}$).
(5) Comparison of the mean stabilization time for BMP assays in the two groups and at different salt contents ($F^G_{1,3}$ and $F^S_{3,3}$).
(6) Comparison of the mean methane yield from BMP assays in the two groups and at different salt contents ($F^G_{1,3}$ and $F^S_{3,3}$).

➢ **Third set**

The leachate used in this set was taken from R1 (TVS = 9464 mg/l) and run at 0, 1, 2, and 3% (w/v) salt contents with addition of 20% (v/v) or 50 mL of inoculum. Two types of inoculum were used in this set: anaerobic digested sludge (ADS) and acclimatized anaerobic digested sludge (AAD).

Table 5.12 summarizes the results of methane produced from the third set of BMP assays including lag time, time to reach the peak daily methane production, mean and total methane produced, stabilization time, and hydrolysis rate constant. Figures 5.13 and 5.14 show the variation in daily methane production, methane concentration, and accumulative methane produced.

Table 5.12: Results of methane produced from the third set of BMP assays

CH_4 (mL)	N0%	N1%	N2%	N3%	S0%	S1%	S2%	S3%
Salt content %(v/v)	0	1	2	3	0	1	2	3
Initial TVS (mg/l)	9464							
Duration time (d)	40	40	59	64	40	40	58	64
Lag time (d)	0	2	10	14	0	0	2	4
Time to reach peak (d)	14	26	39	52	16	22	37	49
Peak (mL)/d	160	103	96	69	144	100	70	67
Mean CH4 (mL)	33.1	31.1	20.8	18.4	32.5	30.2	22.9	19.2
Total CH4 (mL)	1323	1243	1208	1179	1300	1207	1326	1229
Stabilization time (d)	24	40	54	64	23	38	49	64
k_h (d^{-1})	0.074	0.031	0.019	0.014	0.068	0.041	0.028	0.013

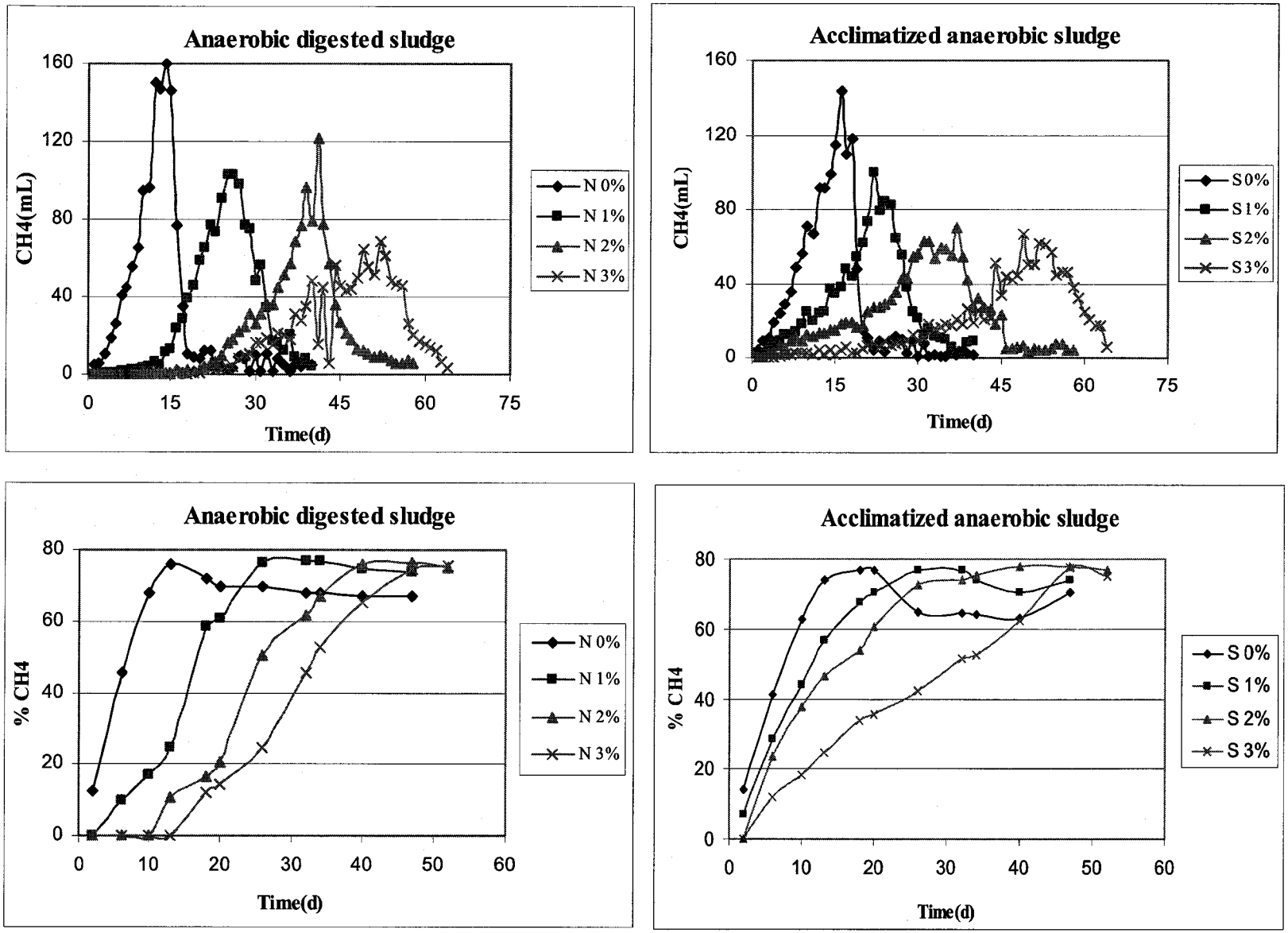


Figure 5.13: Daily methane production and methane concentration in the third set of BMP assays.

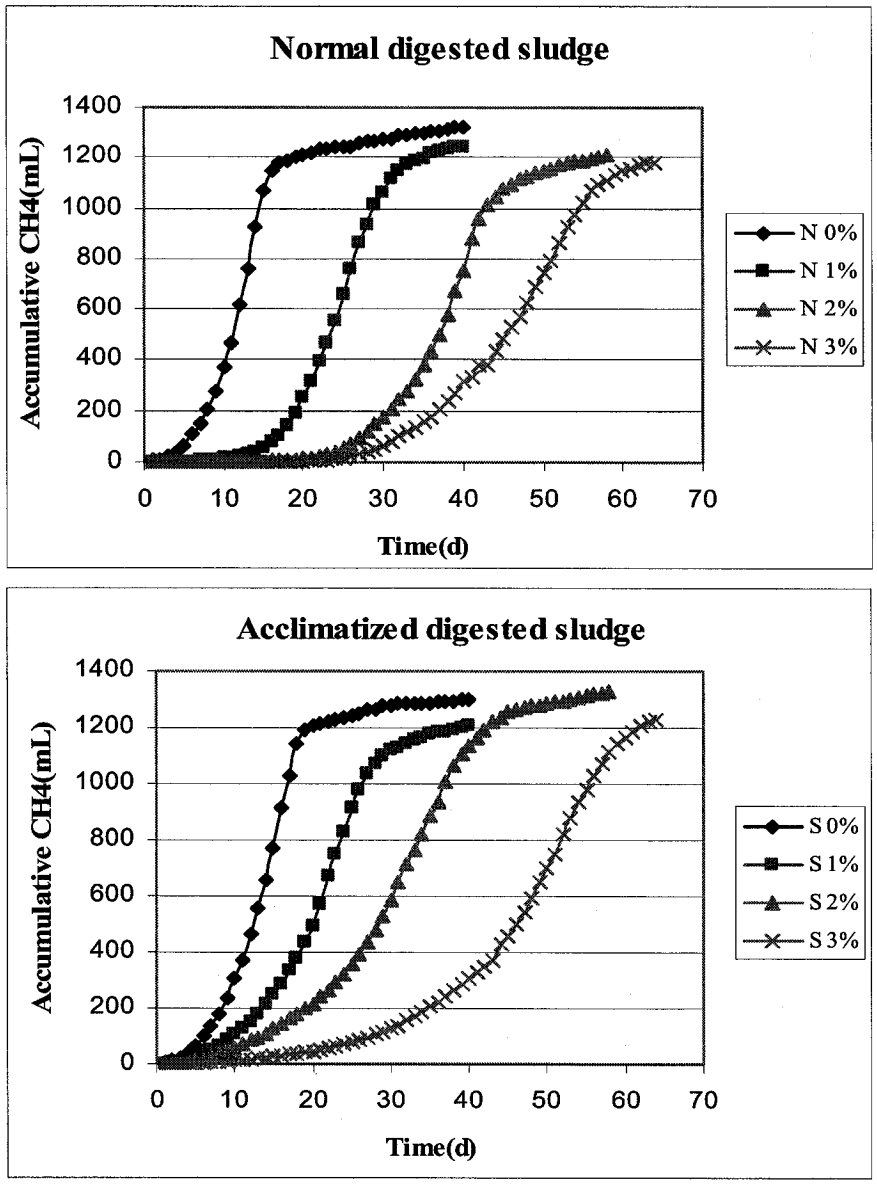


Figure 5.14: Accumulative methane production in third set of BMP assays.

The lag time of methane production increased from no lag time in R1 to 14 days in R4 in the ADS group; and from no lag time in R5 to 4 days in R8 in the AAD group. Also, the time required to reach the peak of methane production was slightly shorter in the AAD group compared to the ADS group. There seems to be limited improvement with AAD. This is supported by the statistical analysis.

Statistical analysis

Table 5.13 summarizes the statistical analysis for mean daily methane production in all BMP assays, lag time of methane production, time to reach the peak of daily methane produced, total methane produced, stabilization time, and average daily methane produced in the two groups and at different salt contents.

The P-value of BMP[1] was less than 0.05. This indicates that there was a significant difference in the mean daily methane production in all BMP assays, but there was no significant difference between the mean daily methane produced in the two groups, as suggested by the P-value of Group[2]. Table 2.3.24 in Appendix B shows multiple comparisons in the mean daily methane produced in all BMP assays.

The P-values for lag time[3] and Total CH_4[5] were more than 0.05, which means that there was no significant difference in the mean lag time and total methane produced in the two groups, and at different salt contents.

The time required to reach the peak daily methane production, stabilization time, and average daily methane production showed similar statistical results. The P-values of Peak[4], Stabilization time[6], and Mean CH_4 production[7] were more than 0.05 in the groups and less than 0.05 in the salt content. This indicates that there was no significant difference between the mean of the two groups, but there was a significant difference in the mean of time required to reach the peak daily methane production, the stabilization time, and the average methane production at different salt contents. Tables 2.3.26, 2.3.29 and 2.3.31 in Appendix B show multiple comparisons in the mean time required to reach

Table 5.13: Statistical analysis of methane production from the third set of BMP assays

P-value	BMP[1]	0.037			
	Group[2]	0.914			
	Lag time[3]	Groups	0.127	Salt content	0.184
	Peak[4]	Groups	0.275	Salt content	0.001
	Total CH_4[5]	Groups	0.501	Salt content	0.324
	Stabilization time[6]	Groups	0.161	Salt content	0.000
	Mean CH_4 production[7]	Groups	0.657	Salt content	0.002

(1) Comparison of the mean daily methane production from all BMP assays ($F_{7, 396}$).
(2) Comparison of the mean daily methane production in the two groups($F_{7, 402}$).
(3) Comparison of the mean lag time of methane production from BMP assays in the two groups and at different salt contents ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).
(4) Comparison of the mean time to reach the peak daily methane production from BMP assays in the two groups and at different salt contents ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).
(5) Comparison of the mean total methane produced from BMP assays in the two groups and at different salt contents ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).
(6) Comparison of the mean stabilization time for BMP assays in the two groups and at different salt contents ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).
(7) Comparison of the mean daily methane production from BMP assays in the two groups and at different salt contents ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).

the peak daily methane production, mean stabilization time, and mean daily methane production, respectively.

Results from statistical analysis suggest that no significant difference was observed when using the two types of inoculum in the BMP assays.

5.1.2.4 Summary of landfill gas analysis

➢ 1D bioreactors

- The saline water inhibited the biodegradation of MSW, as illustrated by the results of methane yield, mean daily methane production and lag time.
- The increase in salt content causes a reduction in the volume of total and daily methane production and methane yield; and an increase in the lag time, the time to reach the peak of daily methane production and the stabilization time.
- The highest methane production was recorded in R5, bioreactor with sludge addition and 0% salt content, and it decreased by increasing the salt content in all bioreactors. Group two, which operated with sludge addition, showed a higher methane yield and total methane production than group one, which operated without sludge addition.
- The addition of anaerobic digested sludge enhanced the biodegradation of MSW operated at different salt conditions, as suggested by the results of methane yield, lag time and mean methane production.
- Statistically speaking, there were significant differences in the mean daily methane production, methane concentration and methane yield 1) between the two groups, 2) in all bioreactors, and 3) at different salt contents (0, 0.5, 1 and 3%) (w/v).

➢ BMP assays

- Results from the BMP assays were consistent with the results from the 1D bioreactors. The increase in salt concentration caused an increase in the lag phase of methane production, and a decrease in the peak and volume of methane production.

- There was a significant difference in the mean of daily methane produced from the BMP assays in all sets.
- There was a significant difference in the mean lag time and the time to reach the peak of daily methane production at different salt contents (0, 0.5, 1 and 3%) (w/v) in the BMP assays of the first and second sets. The difference was observed at 3% (w/v) salt content compared to 0%.
- Statistically, no significant difference was observed when using the two types of inoculums, salt acclimatized anaerobic digested sludge vs. the un-acclimatized anaerobic digested sludge, in the BMP assays, but there was a significant difference in the mean time required to reach the peak daily methane, stabilization time, and average daily methane production at different salt contents (0, 0.5, 1 and 3%) (w/v). The difference was observed at the mean of 3% compared to the mean of 0% (w/v) salt content. This emphasizes that high salt contents inhibited the biodegradation of MSW, as suggested by the results of the BMP assays.

5.1.3 Leachate quality

This part covers the variation in the leachate produced from 1D bioreactors, the results of the concentration profile with depth and the evaluation of potential shortcircuiting. The analysis on the leachate included effluent: COD, BOD, VFA, pH, TVS, TS, NH_3-N, salinity, vertical concentration (in terms of COD) profile within the 1D bioreactors and potential shortcircuiting.

5.1.3.1 Variations in COD

The variation in the COD concentration for all the bioreactors is shown in Figure 5.15. Table 5.14 summarizes the results of COD concentration in all bioreactors, as well as the peak concentration, percentage reduction in peak concentrations and mean COD peak reduction in the two groups during the aerobic and anaerobic stages. The percentage peak reduction is calculated based on the peak and end concentration in aerobic and anaerobic stages.

Generally speaking, the COD concentration in the aerobic stage decreased to its lowest value on day 17 as a result of the onset of air injection on day 2. The average dissolved oxygen in the leachate generated from bioreactors during the aerobic stage was 8.46 mg/l.

The greatest percentage of COD peak reduction occurred in bioreactors operated with sludge addition (group two) and the COD peak reduction decreased as a result of an increase in salt content. The mean COD peak reduction in the aerobic stage was 55.4% in group one and 71.4 % in group two. In addition, the COD peak reduction decreased from 69% in R1 (0%) to 43% in R4 (3%) in group one, and from 80% in R5 (0%) to 57% in R8 (3%) in group two. This indicates that the biodegradation of MSW was inhibited by

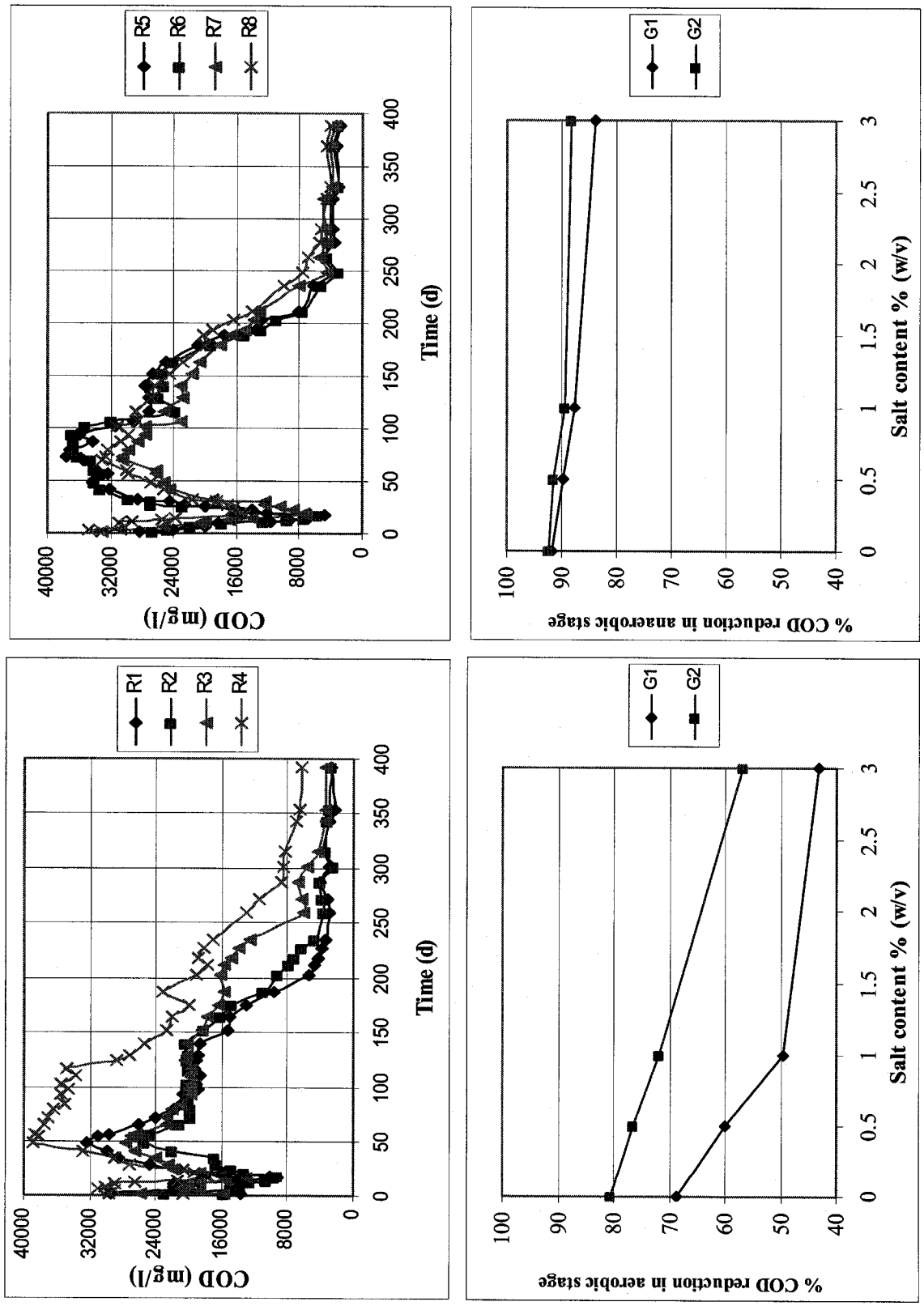


Figure 5.15: COD variation in all bioreactors and percentage COD peak reduction in two stages.

Table 5.14: Results of COD concentration and percentage peak reduction in two stages

COD(mg/l)	R1	R2	R3	R4	R5	R6	R7	R8
First peak	29550	22950	25800	30933	24045	24650	30650	34800
End of aerobic	9267	9133	13000	17600	4700	5800	8550	15050
% Reduction in aerobic[1]	69	60	50	43	80	76	72	57
Second peak	32400	26600	27600	38800	37685	36800	33200	33631
End of anaerobic	2700	2775	3425	6250	2925	3100	3550	4120
% Reduction in anaerobic[2]	92	90	88	84	92	92	89	88
Mean[3]	55.4 G1				71.4 G2			
Mean[4]	88.2 G1				90.2 G2			

(1) Percentage reduction in COD peak concentration during the aerobic stage.
(2) Percentage reduction in COD peak concentration during the anaerobic stage.
(3) Mean COD percentage peak reduction during aerobic stage.
(4) Mean COD percentage peak reduction during anaerobic stage.

the saline condition, as evidenced by the COD percentage peak reduction; and that the sludge addition improved COD peak reduction under a saline environment, as suggested by the COD percentage peak reduction outcome in group two.

Overall, in the anaerobic stage, COD concentrations in all bioreactors increased dramatically at the beginning of this stage, due to the lack of oxygen and transition to the anaerobic phase, allowing the COD concentration to increase as the hydrolysis continued. This increase was followed by a drop in COD concentrations in all bioreactors as a result of an increase in the methanogenic activity and a subsequent rise in the daily methane production (daily methane production played a major role in the COD variation).

In R1, the COD concentration increased from 9267 mg/l on day 17 to 32400 mg/l on day 49 as a result of hydrolysis and acidogenic bacteria. Several significant changes occurred

in the COD concentration after methane production started. When the daily methane production reached more than 2 L/d or 2000 mL/d on day 48, the COD concentration started to fall from 32400 mg/l. Between days 98 and approximately 140, the COD concentration stabilized around 18700 mg/l due to a decline in the daily methane production during the same period. After that, daily methane production rose again and the COD concentration decreased from 18700 mg/l to approximately 2850 mg/l on day 260. From that point on, there was a small change in the COD concentration due to a decline in daily methane production. The COD peak reduction in this bioreactor in the anaerobic stage was 92%.

There was a significant rise in the COD concentration of R2 as it shifted to the anaerobic condition. It increased from 9833 mg/l on day 17 to 26600 mg/l on day 55. Following this increase, the COD concentration fell to 19700 mg/l on day 72 as the daily methane production increased and reached its maximum. Between day 72 and 140, the COD concentration stayed around 19000 mg/l as the daily methane production decreased to its minimum and stabilized around 2.2 L/d. After that, the COD concentration declined to 3350 mg/l on day 260 due to a rise in the daily methane production, which reached its maximum value for the second time. From then on, a small variation was observed in the COD concentration because of the steady decline in daily methane production. The COD peak reduction in R2 was 90%.

The COD concentration of R3 almost followed the same trend of R2 in the first 150 days. From day 150 until day 300, the COD concentration in R3 was higher than R2. At the end of the study, the COD concentration was 3425 mg/l. The COD peak reduction in this bioreactor in the anaerobic stage was 88%.

In R4, the COD concentration increased significantly from 17600 mg/l to 38800 mg/l on day 49. The methane production started on day 33 (50 days from the beginning of the experiment), but the rate was less than 2 L/d in the first 100 days. Consequently, the COD went down slowly, from 38800 mg/l to 34800 mg/l on day 117. Then it dropped rapidly as the daily methane climbed to reach its maximum value. Between days 175 and 228, the COD concentration stabilized around 19000 mg/l as the daily methane reached its minimum value in the same period. Then the COD dropped to 8812 mg/l on day 287 because of the increase in daily methane production. After this, there was no significant change in the COD concentration. The COD peak reduction in R4 during the anaerobic stage was 84%.

The COD concentration in R5 increased sharply from 4700 mg/l on day 17 to 34250 mg/l on day 48. From that moment and until day 73, it increased slowly and reached 37685 mg/l. As the daily methane production increased above 2 L/d, the COD concentration started to decrease, reaching 27112 mg/l on day 129. Between day 129 and 151, it stayed around 26000 mg/l as a result of a decline in the daily methane production. Subsequently, the COD concentration decreased sharply to 3825 on day 249 because the daily methane production increased again. After that, there was no significant variation in the COD concentration. The COD peak reduction in R5 during the anaerobic stage was 92%.

R6 showed similar trend to R5. The COD peak reduction in this bioreactor during the anaerobic stage was 92%.

In R7, the COD concentration initially rose rapidly from 8550 mg/l on day 17 to 24600 mg/l on day 42. After day 42, as methane production started, the rate of increase in COD

concentration slowed down, although this rate was low for the following 50 days. It increased quickly causing a reduction in the COD concentration from 33200 mg/l on day 73 to 4500 mg/l on day 249. From that moment on, there were small variations in the COD concentration. The COD peak reduction in R7 during the anaerobic stage was 89%. R8 showed a similar behavior to R7. The COD peak reduction in the anaerobic stage was 88% in this bioreactor.

In the anaerobic stage, the mean of COD percentage peak reduction of group two (90%) was higher than group one (88%). The percentage of COD peak reduction was reduced by increasing the salt content as shown in Figure 5.15.

Statistical analysis

Table 5.15 shows the statistical analysis for the mean of COD concentration and COD percentage peaks reduction during the aerobic and anaerobic stages. Five observations could be made from the statistical analysis:

- COD concentration

1) The P-value of Bioreactors[1] was less than 0.05. This emphasizes that there was a significant difference in the mean COD concentration in all bioreactors during the experiment. The difference was only in R4 compared to R1 as shown in Table 3.1.5 in Appendix B.

2) The P-value of Group[2] was more than 0.05. This indicates that there was no significant difference between the mean COD concentration in the two groups.

Table 5.15: Statistical analysis for the mean and percentage peak reduction in COD concentration

P-value	Bioreactors[1]	0.000			
	Group[2]	0.116			
	Reduction[3]	Groups	0.006	Salt content	0.016
	Reduction[4]	Groups	0.069	Salt content	0.039

(1) Comparison of the mean COD concentration in all bioreactors ($F_{7, 356}$).
(2) Comparison of the mean COD concentration in the two groups ($F_{1, 362}$).
(3) Comparison of the mean COD percentage peak reduction in the two groups and at different salt contents during the aerobic stage ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).
(4) Comparison of the mean COD percentage peak reduction in the two groups and at different salt contents during the anaerobic stage ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).

- COD percentage peak reduction

3) The P-values of Reduction[3] were less than 0.05. This means there were significant differences in the mean COD percentage peak reduction during aerobic stage 1) between the two groups, and 2) at different salt contents (0, 0.5, 1, and 3) % (w/v). The difference was at 3% compared to 0% (w/v) salt content as shown in Table 3.1.6 in Appendix B.

4) The P-value of Reduction[4] (Groups) was more than 0.05. This means there was no significant difference between the mean COD percentage peak reduction in the two groups during the anaerobic stage.

5) The P-value of Reduction[4] (Salt content) was less than 0.05. This indicates that there was a significant difference in the mean COD percentage peak reduction at different salt contents during the anaerobic stage. The difference was in the mean COD percentage peak reduction at 3% compared to 0% (w/v) salt content as shown in Table 3.1.7 in Appendix B.

5.1.3.2 Variations in BOD

The BOD concentration in the leachate samples showed a similar trend to the COD concentration in all bioreactors. Figure 5.16 shows the BOD concentrations in all bioreactors and BOD percentage peak reduction during the aerobic and anaerobic stages. Table 5.16 summarizes the BOD concentrations in all bioreactors and BOD percentage peak reduction during the aerobic and anaerobic stages.

The highest BOD percentage peak reduction during the aerobic stage was observed in the second group of bioreactors and it decreased by increasing the salt content in both groups, as shown in Figure 5.16. Also, Figure 5.16 shows that the BOD peak reduction decreased from 71% in R1 (0%) to 46% in R4 (3%) in group one, and from 88% in R5 (0%) to 58% in R8 (3%) in group two.

Initially, the BOD concentration increased in all bioreactors at the beginning of the anaerobic stage, as a result of low methanogenic activity which facilitated the accumulation of organic acids from the hydrolysis and acidogenesis steps. BOD peak reductions during this stage were 94, 92, 87, 84, 95, 95, 91 and 89% in R1 through R8, respectively.

The results of BOD percentage peak reduction showed the following:

1) Sludge addition (group two) enhanced the biodegradation of MSW during both stages.
2) Bioreactors operated at high salt content required a longer time to consume the organic matter as suggested by the BOD peak reduction in bioreactors (R4 and R8).

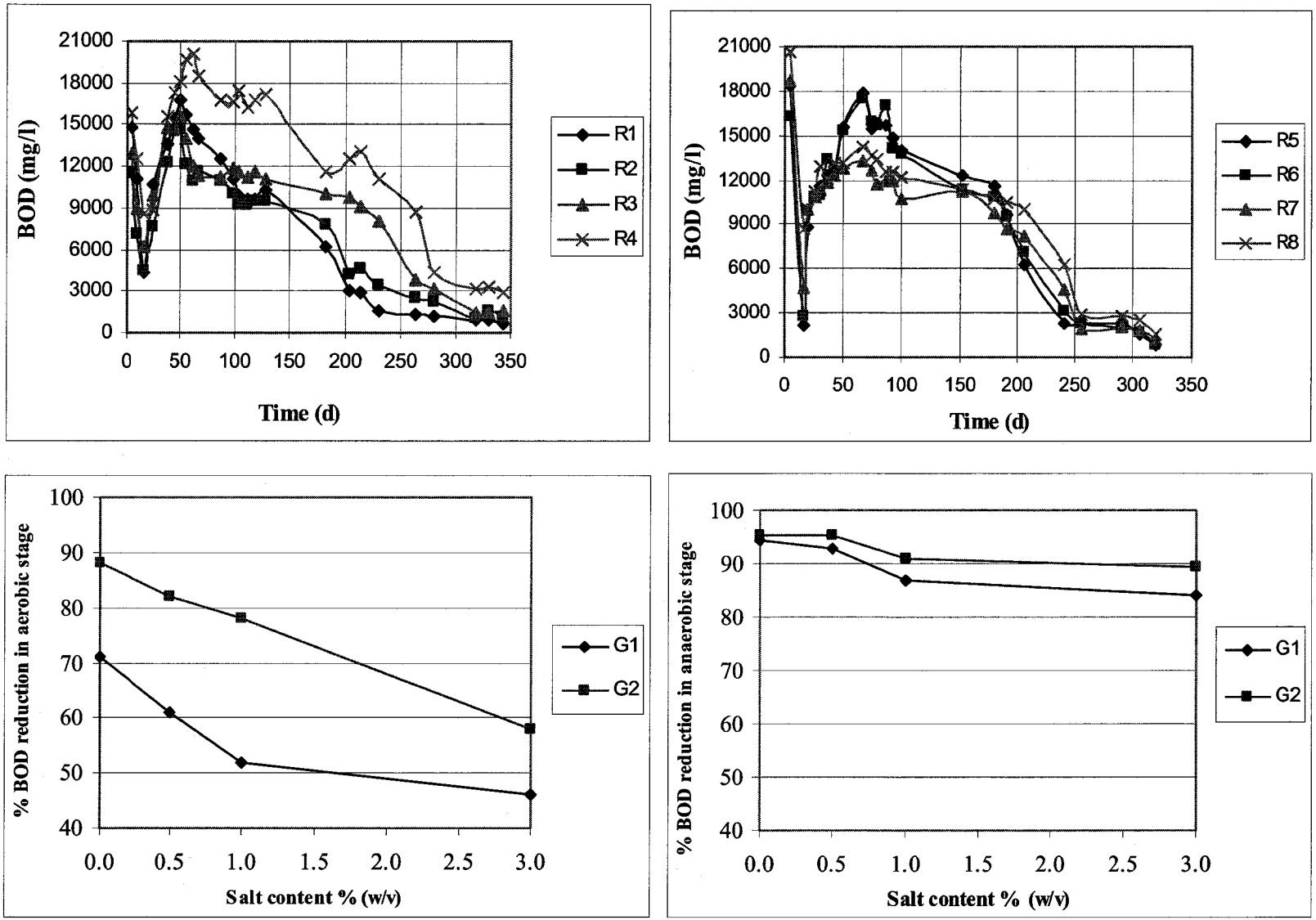


Figure 5.16: BOD variation in all bioreactors and percentage BOD peak reduction in two stages.

Table 5.16: Results of BOD concentration and percentage peak reduction in two stages

BOD(mg/l)	R1	R2	R3	R4	R5	R6	R7	R8
First peak	14805	11498	12926	15880	18363	16269	18697	20664
End of aerobic	4307	4513	6250	8568	2209	2801	4138	8676
% Reduction in aerobic[1]	71	61	52	46	88	83	78	58
Second peak	16800	14640	15600	20100	17820	17440	13270	14270
End of anaerobic[3]	960	1170	2000	3200	810	840	1220	1520
% Reduction in anaerobic[2]	94	92	87	84	95	95	91	89
Mean[4]	57.5 G1				76.8 G2			
Mean[5]	89.3 G1				92.5 G2			

(1) Percentage reduction in BOD peak concentration during the aerobic stage.
(2) Percentage reduction in BOD peak concentration during the anaerobic stage.
(3) BOD concentration on day 319.
(4) Mean BOD percentage peak reduction in two groups during aerobic stage.
(5) Mean BOD percentage peak reduction in two groups during anaerobic stage.

Statistical analysis

Table 5.17 summarizes the statistical analysis for the mean BOD concentration and for BOD percentage peak reduction during the aerobic and anaerobic stages.

- BOD concentration

1) The P-values of Bioreactors[1] were less than 0.05. This indicates that there was a significant difference in the mean BOD concentration in all bioreactors. The difference was only at R4 compared to R1 as shown in Table 3.2.5 in Appendix B.

2) The P-value of Group[2] was more than 0.05. This emphasizes that there was no significant difference between the mean BOD concentration in the two groups.

Table 5.17: Statistical analysis for the mean and percentage peak reduction in BOD concentration

P-value	Bioreactors[1]	0.019			
	Group[2]	0.712			
	Reduction[3]	Groups	0.008	Salt content	0.026
	Reduction[4]	Groups	0.032	Salt content	0.018

(1) Comparison of the mean BOD concentration in all bioreactors ($F_{7, 184}$).
(2) Comparison of the mean BOD concentration in the two groups ($F_{1, 190}$).
(3) Comparison of the mean BOD peak reduction in the two groups and at different salt contents during the aerobic stage ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).
(4) Comparison of mean BOD peak reduction in the two groups and at different salt contents during the anaerobic stage ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).

- BOD percentage peak reduction

3) In the aerobic and anaerobic stages, there were significant differences in the mean BOD percentage peak reduction 1) between the two groups, and 2) at different salt contents (P-values of Reduction[3] and Reduction[4] <0.05). The difference was at 3% compared to 0% (w/v) salt content as shown in Tables 3.2.6 and 3.2.7 in Appendix B.

5.1.3.3 Variations in VFA

The concentration of VFA in the leachate of all bioreactors exhibited a similar trend to the COD concentration. Figure 5.17 shows the variation of VFA concentration over time in all bioreactors and VFA percentage peak reduction at different salt contents during the aerobic and anaerobic stages. Also, Table 5.18 summarizes the results of VFA concentrations in terms of peaks, end of stages and VFA percentage peak reduction in both stages.

In the aerobic stage, the VFA peak reduction during this stage was 65, 59, 51, 41, 80, 78, 71, and 65% in R1 through R8, respectively. The mean of VFA peak reduction in group two (73.5%) was higher than group one (54%).

In the anaerobic stage, the VFA concentration in all bioreactors increased at the beginning of this stage as a result of the accumulation of organic acids from the hydrolysis and acidogenic steps. As mentioned in chapter two, first the organic waste hydrolyzed into aqueous organic acids and then these were consumed by acidogenic bacteria to produce VFA and carbon dioxide. Then the VFA concentration dropped as the daily methane production increased and reached 2 L/d, because the methanogenic bacteria used the VFA as a substrate to produce methane, carbon dioxide and new cells. The mean VFA peak reduction in group two (98.0%) was higher than group one (95.6%).

Two observations could be made from the results of VFA:

1) The highest VFA percentage peak reduction was observed at 0% salt content and decreased by increasing the salt content in both groups.
2) The sludge addition in group two increased the VFA percentage peak reduction in both stages in comparison with group one.

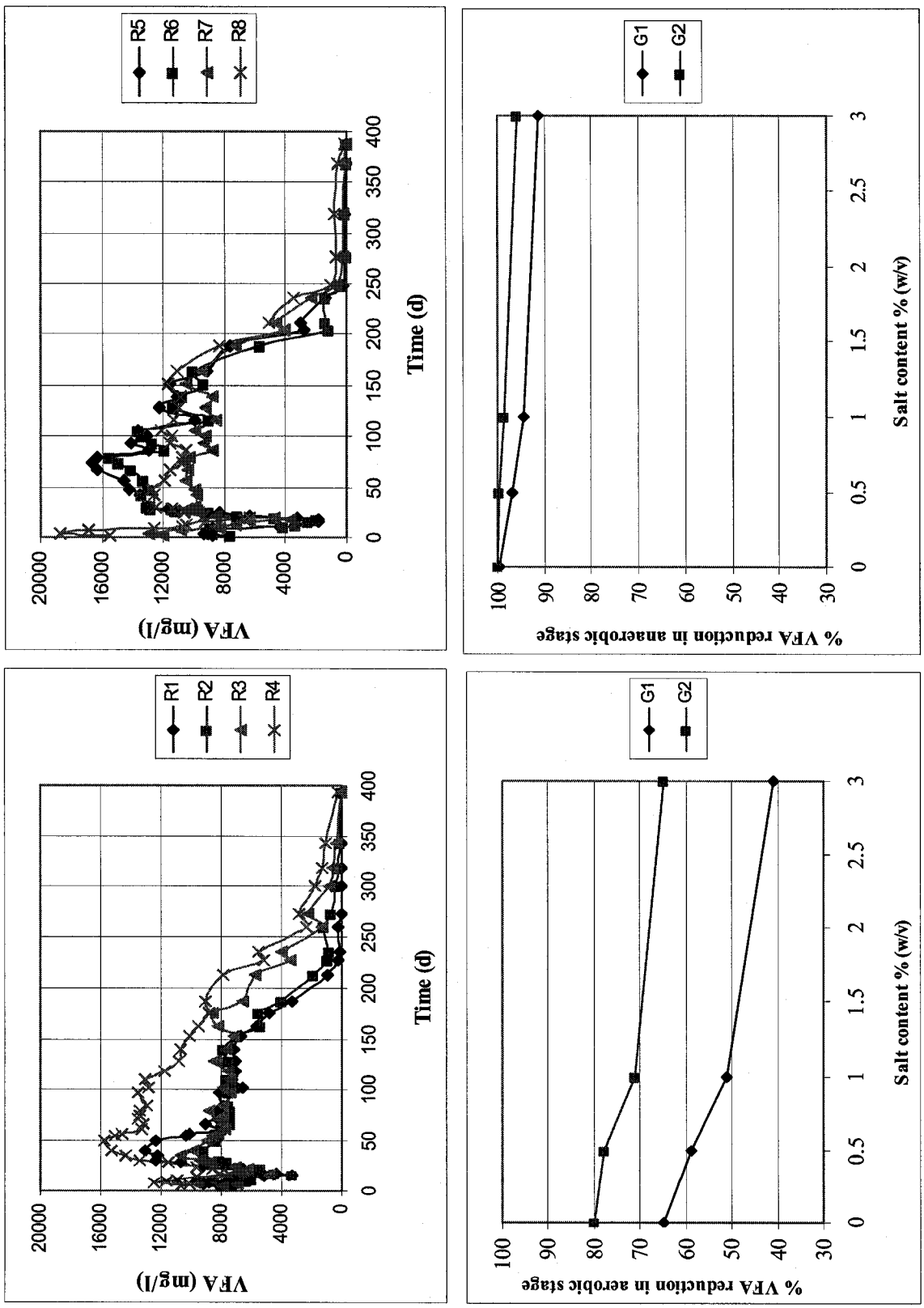


Figure 5.17: VFA variation in all bioreactors and percentage VFA peak reduction in two stages.

Table 5.18: Results of VFA concentration and percentage peak reduction in two stages

VFA(mg/l)	R1	R2	R3	R4	R5	R6	R7	R8
First peak	9205	7960	9810	12425	9389	8761	12940	18700
End of aerobic	3244	3272	4785	7372	1853	1929	3756	6449
% Reduction in aerobic[1]	65	59	51	41	80	78	71	65
Second peak	13090	9120	10754	15779	16686	15463	12604	15782
End of anaerobic[3]	37	290	600	1350	59	80	201	819
% Reduction in anaerobic[2]	100	97	94	91	100	99	98	95
Mean[4]	53.8[G1]				73.5[G2]			
Mean[5]	95.6 [G1]				98.0 [G2]			

(1) Percentage reduction in VFA peak concentration during the aerobic stage.
(2) Percentage reduction in VFA peak concentration during the anaerobic stage.
(3) Values of VFA on day 319.
(4) Mean VFA percentage peak reduction during aerobic stage.
(5) Mean VFA percentage peak reduction during anaerobic stage.

Statistical analysis

Table 5.19 shows the statistical analysis of VFA concentration and percentage peak reduction. The statistical analysis could be summarized as follows:

- VFA concentration

1) There was a significant difference in the mean VFA concentration in all bioreactors during the study (P-value of Bioreactors[1] <0.05), but there was no significant difference between the mean VFA concentration in the two groups (P-value of Group[2] >0.05). The significant difference was observed in R4 with respect to R1 as shown in Table 3.3.4 in Appendix B.

Table 5.19: Statistical analysis for the mean and percentage peak reduction in VFA concentration

P-value	Bioreactors[1]	0.000			
	Group[2]	0.085			
	Reduction[3]	Groups	0.002	Salt content	0.016
	Reduction[4]	Groups	0.073	Salt content	0.079

(1) Comparison of the mean VFA concentration in all bioreactors ($F_{7, 308}$).
(2) Comparison of the mean VFA concentration in the two groups ($F_{1, 314}$).
(3) Comparison of the mean VFA percentage peak reduction in the two groups and at different salt contents during the aerobic stage ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).
(4) Comparison of the mean VFA percentage peak reduction in the two groups and at different salt contents during the anaerobic stage ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).

- VFA percentage peak reduction

2) In the aerobic stage, there were significant differences in the mean VFA percentage peak reduction 1) between the two groups, and 2) at different salt contents (P-values of Reduction[3] <0.05). Table 3.3.5 in Appendix B shows that the difference occurred at 3% compared to 0% (w/v) salt content.

3) In the anaerobic stage, no significant differences were observed 1) between the mean VFA percentage peak reduction in the two groups, and 2) in the mean of VFA percentage peak reduction at different salt contents (P-values of Reduction[4] >0.05).

5.1.3.4 pH

The pH measured in leachate samples was in accordance with the conclusions withdrawn from the measurement of VFA concentration, in other words, when the VFA concentration increases the pH level drops. Figures 5.18 and 5.19 show the trend of pH in the leachate of all bioreactors, and Table 5.20 summarizes the results of pH during both stages, as well as the statistical analysis of the mean pH.

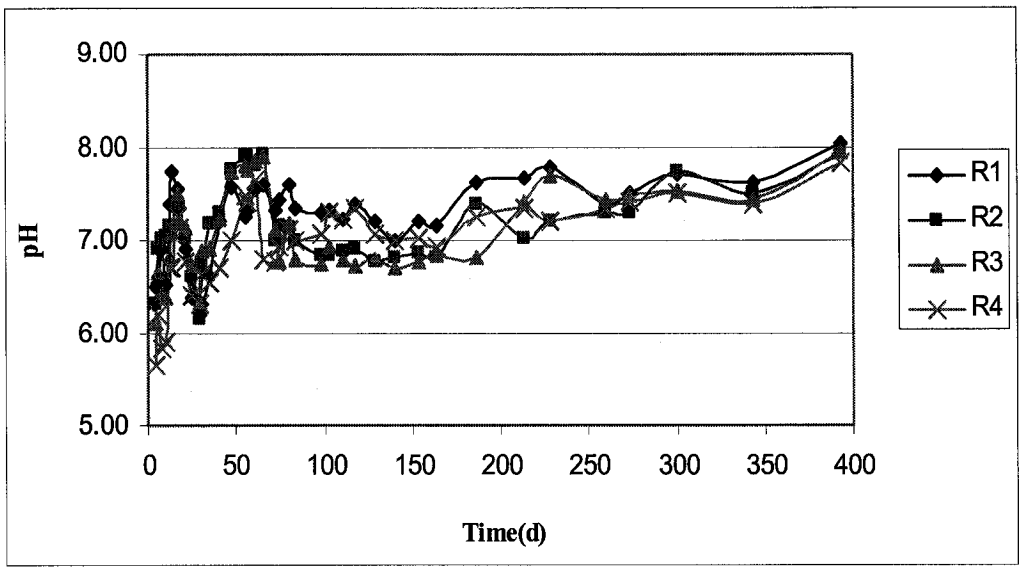


Figure 5.18: pH level in group one.

The initial pH level was 6.5, 6.3, 6.1, 5.7, 6.3, 6.7, 6.6 and 5.7 in the leachate samples collected from R1 through R8, respectively. Then the pH values increased in all bioreactors due to the addition of buffer to the leachate recycle and the decrease in VFA concentration in the aerobic stage, as mentioned in Section 5.1.2.2.

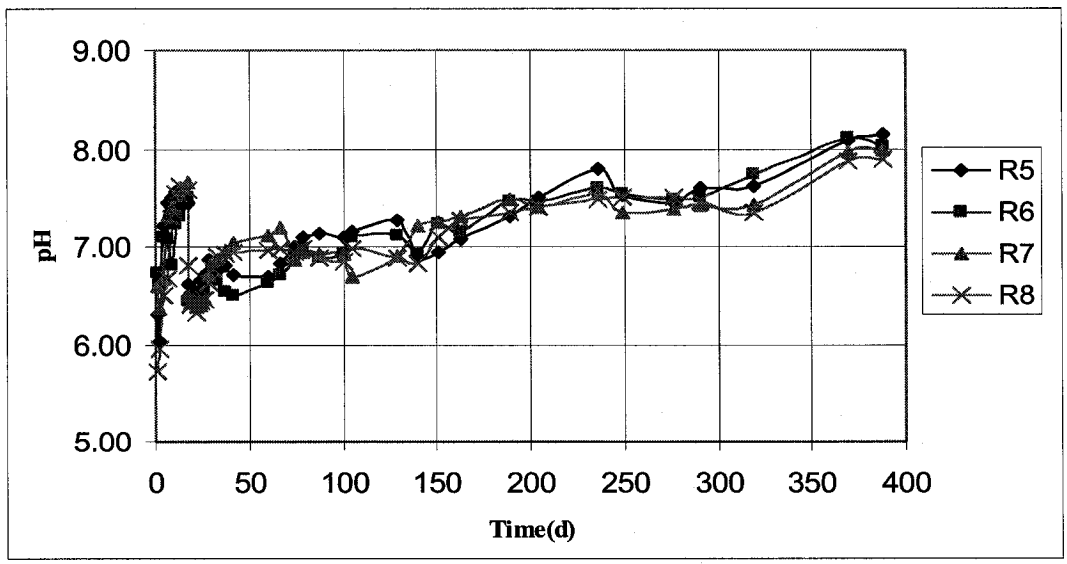


Figure 5.19: pH level in group two.

The leachate pH values at the end of the aerobic stage were 7.56, 7.42, 7.50, 7.26, 7.45, 7.50, 7.66 and 7.50 in R1 through R8, respectively. When the bioreactors shifted to the anaerobic condition (day 17), the pH decreased from approximately 7.5 to below 6.4 in all bioreactors due to the accumulation of acids from the hydrolyzation of MSW into organic acids and end products of acidogenic bacteria. The lowest pH values in the anaerobic stage were 6.20, 6.16, 6.33, 6.30, 6.20, 6.25, 6.38 and 6.33 in R1 through R8, respectively. As the daily methane production increased above 2 L/d, it caused a decrease in the VFA concentration, this in turn produced an increase in the pH level of leachate in all bioreactors.

Table 5.20: Results of pH values in leachate samples from all bioreactors

pH	R1	R2	R3	R4	R5	R6	R7	R8
Initial value	6.50	6.30	6.10	5.65	6.30	6.72	6.60	5.70
End of aerobic	7.56	7.42	7.50	7.26	7.45	7.50	7.66	7.20
Lowest in anaerobic	6.20	6.16	6.33	6.30	6.20	6.25	6.38	6.33
Maximum	8.03	7.92	7.94	7.83	8.14	8.10	8.00	7.90
Mean	7.23	7.15	7.08	6.95	7.11	7.04	7.07	7.00
P-value	Bioreactors[1]				0.223			
	Groups[2]				0.361			

(1) Comparison of the mean pH value in all reactors ($F_{7, 300}$).
(2) Comparison of the mean pH value in the two groups ($F_{1, 306}$).

The low value of pH at the beginning of the anaerobic stage was due to the hydrolysis of the solid waste into complex dissolved organic compounds and organic acids, which the acidogenic bacteria converted into hydrogen, CO_2 and VFA. Also the addition of anaerobic digested sludge to the leachate recycle in group two decreased the pH at the beginning of the anaerobic stage.

Ağdağ et al. (2005) found that the initial pH of leachate from a reactor operated with the addition of buffer was 5.3 and it reached approximately 7 after 20 days. Warith et al. (1998) found that the initial pH of the leachate sample with buffer addition was 6 and it stabilized at approximately 7 after 25 days. Chiemcharis et al. (2002) found that the pH of leachate from anaerobic bioreactors operated with the addition of buffer and anaerobic sludge reached 7 after 100 days in their experiments. Also, Rendra et al. (2003) found that the initial pH of leachate from their anaerobic bioreactor run with addition of buffer and anaerobic digested sludge was 5.7 and reached 7 after 112 days. The results from this study are consistent with results presented in the literature.

Statistical analysis

Table 5.20 summarizes the statistical analysis for the mean pH values during the study. The P-values of Bioreactors[1] and Groups[2] were more than 0.05. This indicates that there was no significant difference 1) in the mean pH values in all bioreactors and, 2) between the mean pH values in the two groups.

5.1.3.5 Variations in TVS

The TVS followed the same trend of COD concentration in all bioreactors, as shown in Figure 5.20. Table 5.21 summarizes the results of TVS concentration in all bioreactors and TVS percentage peak reduction during the aerobic and anaerobic stages.

In the aerobic stage, TVS percentage peak reduction was 63, 53, 47, 43, 78, 73, 71 and 63% in R1 through R8, respectively. The mean TVS peak reduction in group two (71.2%) was higher than group one (51.6%). The reason for the decrease in the TVS concentration during the

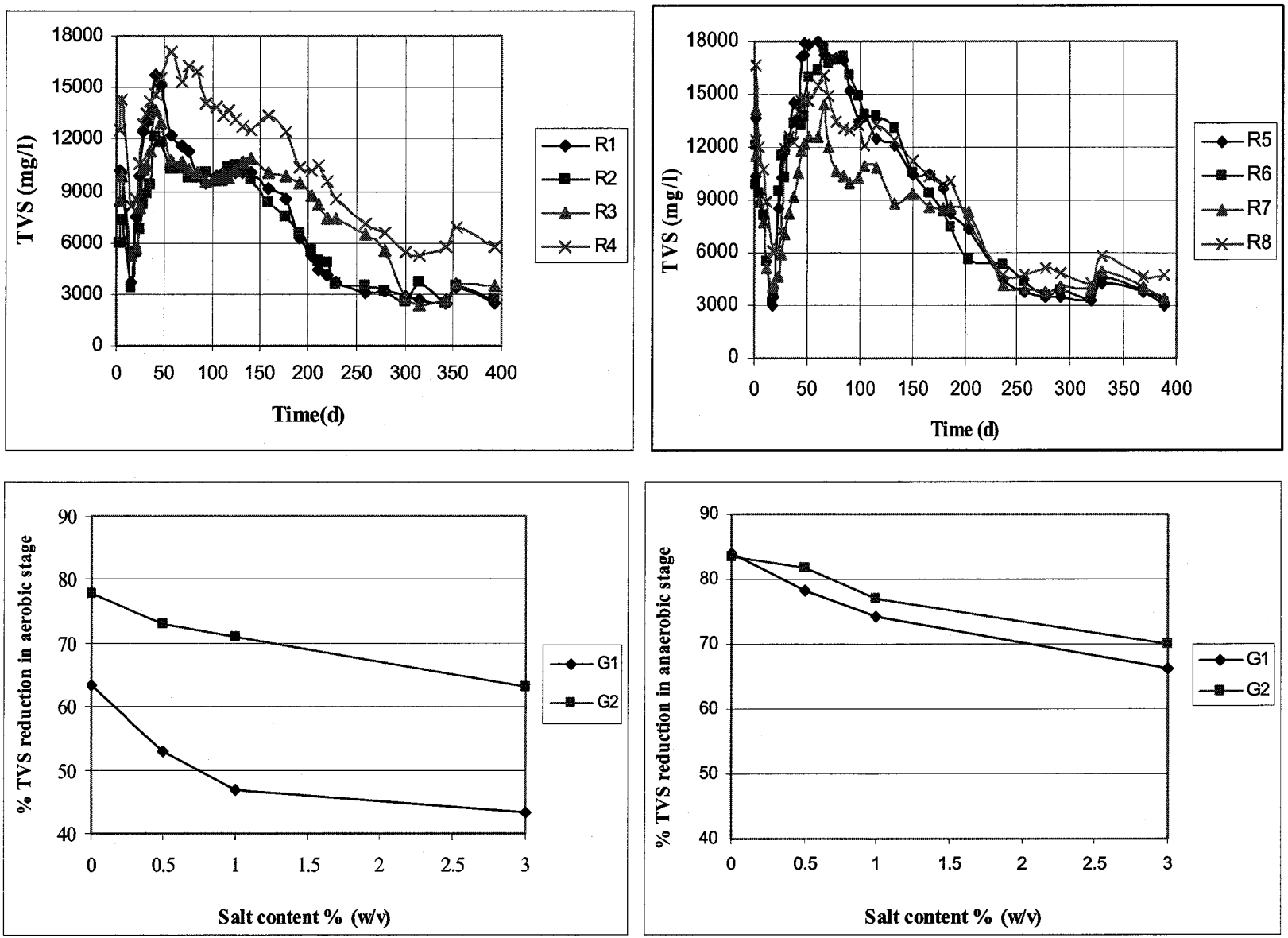


Figure 5.20: TVS variation in all bioreactors and percentage TVS peak reduction in two stages.

Table 5.21: Results of TVS concentration and percentage peak reduction in two stages

TVS(mg/l)	R1	R2	R3	R4	R5	R6	R7	R8
First peak	10088	7319	9876	14336	13652	12120	14136	16608
End of aerobic	3700	3436	5260	8130	3028	3240	4096	6132
% Reduction in aerobic[1]	63	53	47	43	78	73	71	63
Second peak	15739	12090	13707	17060	18028	17624	14460	16103
End of anaerobic	2516	2636	3520	5768	2972	3200	3372	4768
% Reduction in anaerobic[2]	84	78	74	66	84	82	77	70
Mean[3]	51.6^{G1}				71.2^{G2}			
Mean[4]	75.7^{G1}				78^{G2}			

(1) Percentage reduction in TVS peak concentration during the aerobic stage.
(2) Percentage reduction in TVS peak concentration during the anaerobic stage.
(3) Mean TVS percentage peak reduction during the aerobic stage.
(4) Mean TVS percentage peak reduction during the anaerobic stage.

aerobic stage was that the aerobic bacteria consumed the organic matter in the leachate to produce carbon dioxide and new cells.

In the anaerobic stage, the TVS concentration increased initially in all bioreactors due to the increase of organic matter in the leachate which is the end product in the hydrolysis and acidogenic steps. As the methanogenic bacteria started to consume the organic matter in the leachate to produce new cells, methane and carbon dioxide, the TVS concentration declined to low values at the end of the experiments. The mean TVS percentage peak reduction during the anaerobic stage in group two (78%) was higher than group one (75.7%).

The results of TVS percentage peak reduction showed the following:

1) The highest TVS percentage peak reduction was observed at 0% salt content during the aerobic and anaerobic stages, and decreased with increased salt content in both groups.

2) The addition of sludge into the bioreactors of group two caused an enhancement in solid waste biodegradation as suggested by the TVS percentage peak reduction in both stages.

Statistical analysis

Table 5.22 summarizes the statistical analysis for the mean TVS concentration and TVS percentage peak reduction during the aerobic and anaerobic stages.

Table 5.22: Statistical analysis for the mean and percentage peak reduction in TVS concentration

P-value	Bioreactors[1]	0.000			
	Group[2]	0.021			
	Reduction[3]	Groups	0.002	Salt content	0.03
	Reduction[4]	Groups	0.095	Salt content	0.005

(1) Comparison of the mean TVS concentration in all bioreactors ($F_{7, 292}$).
(2) Comparison of the mean TVS concentration in the two groups ($F_{1, 298}$).
(3) Comparison of the mean TVS percentage peak reduction in the two groups and at different salt contents during the aerobic stage ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).
(4) Comparison of the mean TVS percentage peak reduction in the two groups and at different salt contents during the anaerobic stage ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).

- TVS concentration

1) The P-values of Bioreactors[1] and Groups[2] were less than 0.05. This indicates that there was a significant difference in the mean TVS concentration 1) in all bioreactors, and 2) between the two groups. The difference was in R4 compared to R1, as shown in Table 3.5.5 in Appendix B.

- TVS percentage peak reduction

2) In the aerobic stage, significant differences were observed 1) between the mean TVS percentage peak reduction in the two groups, and 2) in the mean TVS percentage peak reduction at different salt contents. The difference in the mean TVS percentage peak reduction was at 3% compared to 0% (w/v) salt content, as shown in Table 3.5.6 in Appendix B.

3) In the anaerobic stage, there was no significant difference between the mean TVS percentage peak reduction in the two groups, but there was a significant difference in the mean TVS percentage peak reduction at different salt contents. The difference was in the mean TVS peak reduction at 1% and 3% compared to 0% (w/v) salt content, as shown in Table 3.5.7 in Appendix B.

5.1.3.6 Variations in TS

The TS concentration in the leachate samples from all bioreactors and TS percentage peak reduction during the aerobic and anaerobic stages are presented in Figure 5.21. The TS variation trends exhibited a similar behavior to TVS and COD variation trends. Table 5.23 summarizes the results of TS concentration in all bioreactors and TS percentage peak reduction during both stages.

In the aerobic stage, the TS peak reduction was 44, 37, 32, 21, 68, 50, 42, and 31% in R1 through R8, respectively. The highest TS percentage peak reduction was observed in R5 (68%) and the lowest in R4 (21%). Also, the mean TS percentage peak reduction in group two (47.8%) was higher than group one (33.5%). The reason for the low TS percentage peak reduction in bioreactors operated with saline water, especially R4 and

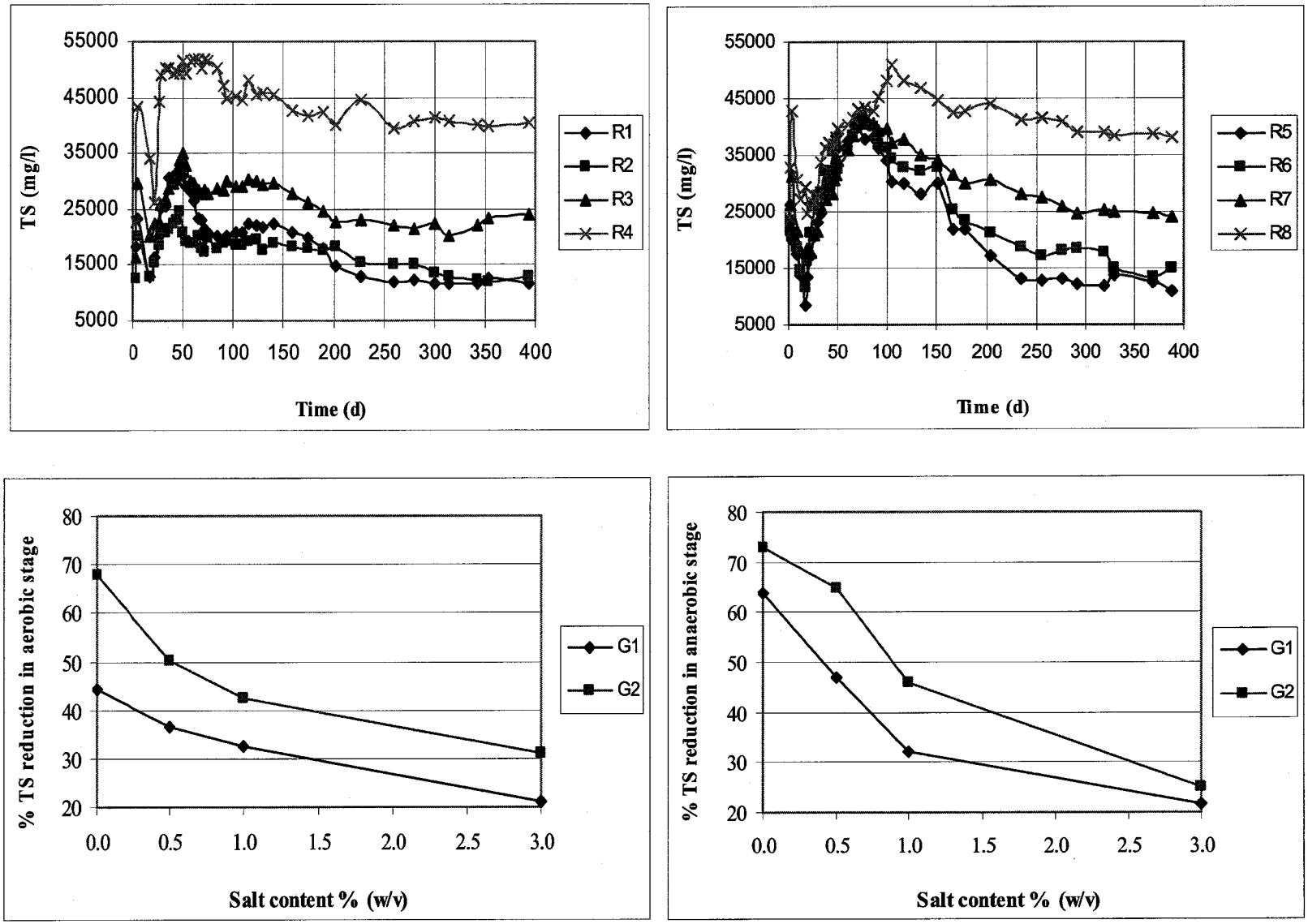


Figure 5.21: TS variations in all bioreactors and percentage TS peak reduction in two stages.

Table 5.23: Results of TS concentration and percentage peak reduction in two stages

TS(mg/l)	R1	R2	R3	R4	R5	R6	R7	R8
First peak	23408	20136	29736	43288	26252	23516	31184	42720
End of aerobic	13020	12756	20120	34082	8476	11716	17956	29424
% Reduction in aerobic[1]	44	37	32	21	68	50	42	31
Second peak	32364	24568	35048	51824	40560	42268	44800	50868
End of anaerobic	11680	13064	23844	40528	10928	14844	24164	38060
% Reduction in anaerobic[2]	64	47	32	22	73	65	46	25
Mean[3]	33.5[G1]				47.8[G2]			
Mean[4]	41.3 [G1]				52.3 [G2]			

(1) Percentage reduction in TS peak concentration during the aerobic stage.
(2) Percentage reduction in TS peak concentration during the anaerobic stage.
(3) Mean TS percentage peak reduction during the aerobic stage.
(4) Mean TS percentage peak reduction during the anaerobic stage.

R8, was that the addition of salt inhibited the aerobic bacteria and increased the total solids content. Consequently, any change in the TS concentration compared to the peak value was negligible.

In the anaerobic stage, TS concentration increased in all bioreactors as a result of an increase in the organic matter that was produced through the hydrolysis of MSW and acidogenic bacteria. Figure 5.16 shows that bioreactors operated with sludge addition (group two) had a higher TS percentage peak reduction than bioreactors without sludge addition (group one). The high TS concentration in R4 and R8 can be attributed to a high salt content.

Statistical analysis

Table 5.24 summarizes the statistical analysis for the mean TS concentration and TS percentage peak reduction during the aerobic and anaerobic stages.

- TS concentration

1) The P-value of Bioreactors[1] was less than 0.05. This indicates that there was a significant difference in the mean TS concentration in all bioreactors. Table 3.6.5 in Appendix B shows multiple comparisons between the mean TS concentrations in all bioreactors.

2) The P-value of Groups[2] was more than 0.05. This means that there was no significant difference between the mean TS concentration in the two groups.

Table 5.24: Statistical analysis for the mean and percentage peak reduction in TS concentration

TS concentration					
P-value	Bioreactors[1]	0.000			
	Group[2]	0.229			
	Reduction[3]	Groups	0.023	Salt content	0.028
	Reduction[4]	Groups	0.043	Salt content	0.007

(1) Comparison of the mean TS concentration in all reactors ($F_{7, 308}$).
(2) Comparison of the mean TS concentration in the two groups ($F_{1, 314}$).
(3) Comparison of the mean TS percentage peak reduction in the two groups and at different salt contents during the aerobic stage ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).
(4) Comparison of the mean TS percentage peak reduction in the two groups and at different salt contents during the anaerobic stage ($F^{G}_{1, 3}$ and $F^{S}_{3, 3}$).

- TS percentage peak reduction

3) In both aerobic and anaerobic stages, there was a significant difference in the mean TS percentage peak reduction 1) between the two groups, and 2) at different salt contents (P-values of Reduction[3] and Reduction[4] were less than 0.05). Tables 3.6.6 and 3.6.7 in

Appendix B show multiple comparisons of the mean TS percentage peak reduction at different salt contents during the aerobic and anaerobic stages, respectively. The difference was observed at 3% compared to 0% (w/v) salt content in the aerobic stage, while it was at 1% and 3% in the anaerobic stage.

5.1.3.7 Variations in NH_3-N

The results of the NH_3-N concentration in the leachate samples from all bioreactors, and the percentage NH_3-N peak reduction at different salt contents during the aerobic and anaerobic stages are shown in Figure 5.22. Also, Table 5.25 summarizes the results of NH_3-N concentration and percentage peak reduction in both stages.

The NH_3-N peak reduction during the aerobic stage was 80, 65, 60, 38, 97, 94, 94, and 92% in R1 through R8, respectively. These results could be attributed to 1) part of NH_3-N was consumed by aerobic bacteria to produce new cells and, 2) part of NH_3-N converted to nitrate through nitrification. The mean NH_3-N peak reduction in group two (94%) was higher than group one (61%). This indicates that the addition of sludge enhanced the NH_3-N peak reduction. The high salt content inhibited the NH_3-N peak reduction as in R4, and this agreed with results presented by Dincer et al. (1999). They found that the nitrification efficiency dropped dramatically and the effect of salt became significant as salt content increased above 2% (w/v).

In the anaerobic stage, the NH_3-N concentrations increased in the beginning of this stage due to the release of ammonia nitrogen from the biodegradation of protein and nitrogen compounds into the leachate. After day 70 and 45 in group one and two respectively, the NH_3-N concentration started to decrease, because the NH_3-N was utilized by the

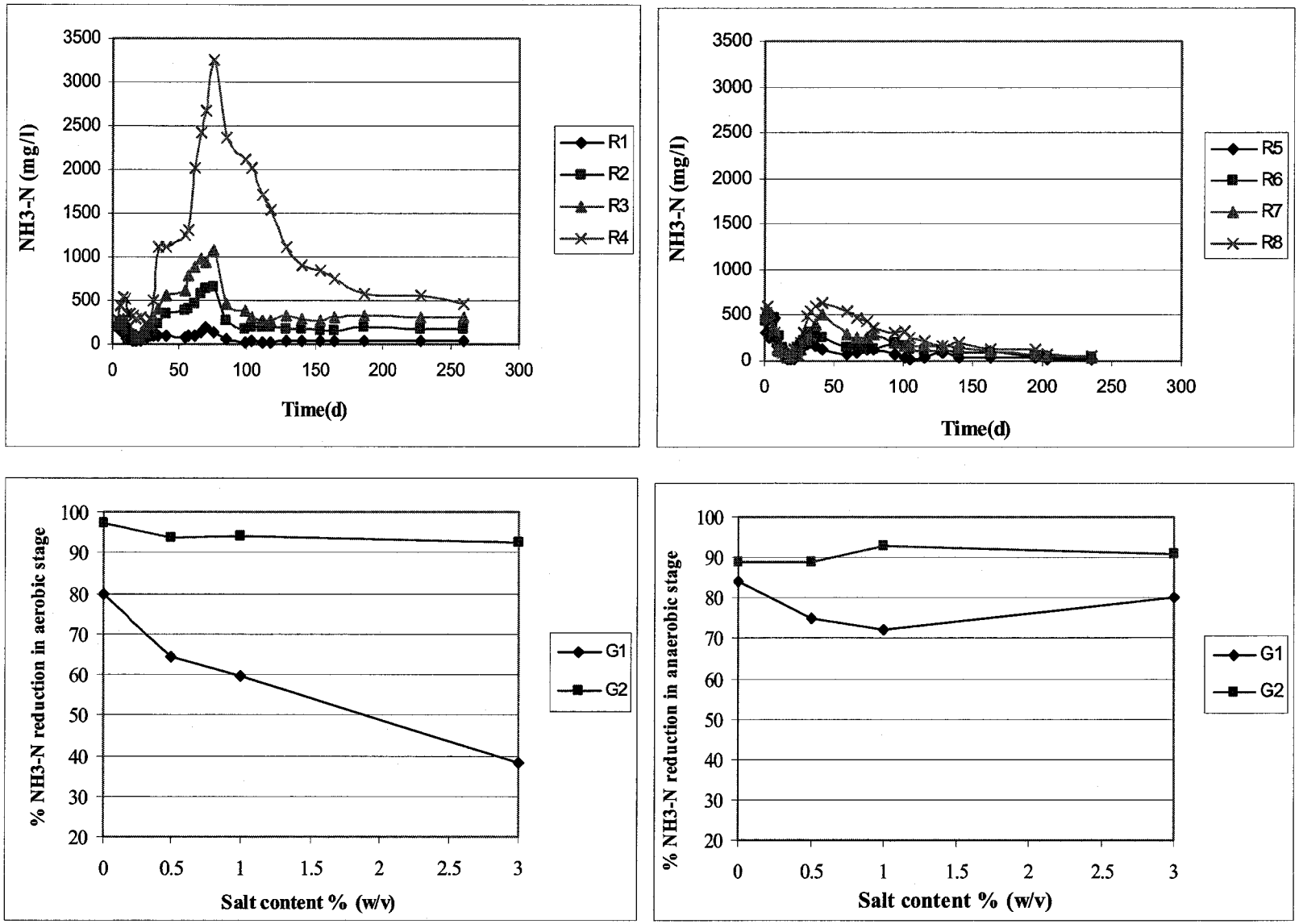


Figure 5.22: NH_3-N variation in all bioreactors and percentage NH_3-N peak reduction in two stages.

Table 5.25: Results of NH_3-N concentration and percentage peak reduction in two stages

NH_3-N (mg/l)	R1	R2	R3	R4	R5	R6	R7	R8
First peak	189	245	271	543	447	464	515	606
End of aerobic	38	87	109	335	12	29	31	46
% Reduction in aerobic[1]	80	65	60	38	97	94	94	92
Second peak	237	657	1086	3241	207	305	505	638
End of anaerobic	37	164	303	659	23	35	37	60
% Reduction in anaerobic[2]	84	75	72	80	89	89	93	91
Mean[3]	61^{G1}				94^{G2}			
Mean[4]	78^{G1}				90^{G2}			

(1) Percentage reduction in NH_3-N peak concentration during the aerobic stage.
(2) Percentage reduction in NH_3-N peak concentration during the anaerobic stage.
(3) Mean NH_3-N percentage peak reduction during the aerobic stage.
(4) Mean NH_3-N percentage peak reduction during the anaerobic stage.

anaerobic bacteria to grow and produce new cells. The NH_3-N peak reduction in this stage was 84, 75, 72, 80, 89, 89, 93 and 91% in R1 to R8, respectively.

Youcai et al. (2002) found the concentration of NH_3-N in bioreactors containing 76% (w/w) cooking and fruit wastes operated under anaerobic conditions, initially increased to 1500 mg/l and then dropped to less than 250 mg/l at the end of the study (250 days).

Sponza et al. (2004) observed the NH_3-N concentration in the leachate of bioreactors operated under anaerobic conditions initially increased up to 600 mg/l and then decreased to less than 300 mg/l at the end of study (day 57). The composition of waste that was used in the study contained 91% (w/w) kitchen waste.

The results of NH_3-N showed the following:

1) The highest NH_3-N percentage reduction occurred at 0% (w/v) salt content in both groups and the NH_3-N took longer time to be consumed in the bioreactors operating at

3% (w/v) salt content compared to other bioreactors.

2) The addition of sludge increased the NH_3-N percentage reduction and decreased the time required to utilize the NH_3-N in both stages and at different salt contents.

Statistical analysis

Table 5.26 summarizes the statistical analysis for the mean NH_3-N concentration and for the NH_3-N percentage peak reduction during the aerobic and anaerobic stages.

Table 5.26: Statistical analysis for the mean and percentage peak reduction of NH_3-N concentration

P-value	Bioreactors[1]	0.000			
	Group[2]	0.000			
	Reduction[3]	Groups	0.022	Salt content	0.364
	Reduction[4]	Groups	0.009	Salt content	0.391

(1) Comparison of the mean NH_3-N concentration in all bioreactors ($F_{7, 248}$).
(2) Comparison of the mean NH_3-N concentration in the two groups($F_{1, 254}$).
(3) Comparison of the mean NH_3-N peak reduction in two groups and at different salt contents during the aerobic stage ($F^G_{1, 3}$ and $F^S_{3, 3}$).
(4) Comparison of the mean NH_3-N peak reduction in two groups and at different salt contents during the anaerobic stage ($F^G_{1, 3}$ and $F^S_{3, 3}$).

- NH_3-N concentration

1) The P-values of Bioreactors[1] and Groups[2] were less than 0.05. This indicates that there was a significant difference in the mean NH_3-N concentration 1) in all bioreactors, and 2) between the two groups. The differences were in the mean NH_3-N concentration of R3 and R4 compared to R1, as shown in Table 3.7.5 in Appendix B.

- NH_3-N percentage peak reduction

1) In the aerobic and anaerobic stages there was a significant difference between the mean NH_3-N percentage peak reduction in the two groups, but there was no significant difference in the mean NH_3-N percentage peak reduction at different salt contents.

5.1.3.8 Salinity

The salinity concentration in the leachate samples from R2, R3, R4, R6, R7 and R8 are shown in Figures 5.23 and 5.24. The salinity concentrations remained approximately constant at the design operation salt conditions. The small variations that took place during the study can be attributed to changes in the volume of the leachate as a result of losses through analysis, consumption by the system and water make up.

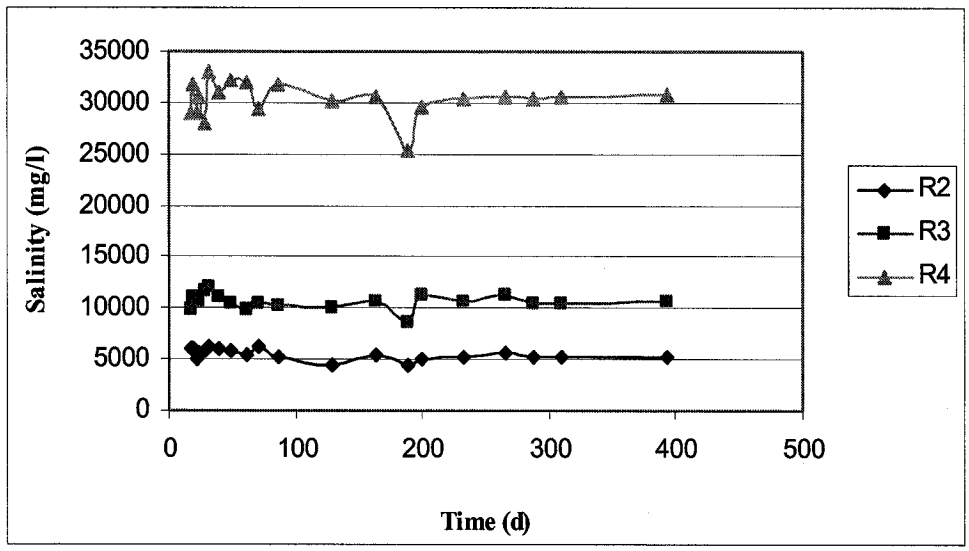


Figure 5.23: Salinity concentrations in group one.

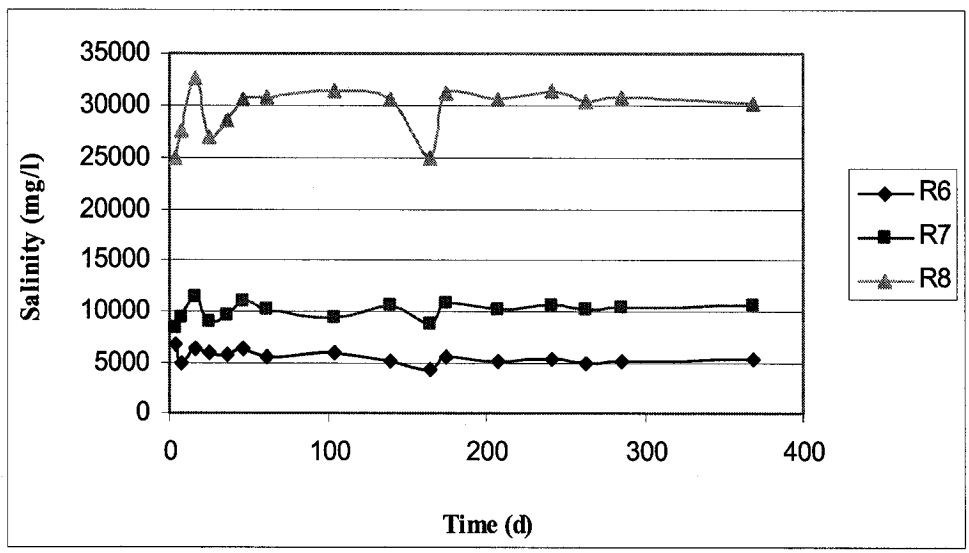


Figure 5.24: Salinity concentrations in group two.

5.1.3.9 Vertical Concentration profile in bioreactors

Table 5.27 summarizes the results of COD concentration at different ports in R1 and R5, and the statistical analysis. Small variations in the COD concentration among the vertical profile of bioreactors were observed. As shown in the table, the P-values were more than 0.05. This emphasizes that there were no significant differences in the mean COD concentration at different ports, in other words, there was no significant concentration variations along the vertical profile of the bioreactors.

Table 5.27: COD concentration in all ports at R1 and R5

COD (mg/l)		Port1 (Top)	Port2 (Mid)	Port3 (bottom)
R1	First analysis 3/11/2005	10200	10700	10200
		10300	10200	10100
		10500	10300	9700
	Average	10333	10400	10000
	P-value[1]		0.117	
	Second analysis 28/1/2006	3200	3400	3000
		3300	2900	3600
		3500	2600	3300
	Average	3333	2967	3300
	P-value[1]		0.549	
	Third analysis 25/3/2006	3000	2625	2850
		2925	2775	2700
		2775	3075	2625
	Average	2900	2825	2725
	P-value[1]		0.464	
R5	25/3/2006	3825	3525	3300
		3675	3225	3825
		3750	3750	3600
	Average	3750	3500	3575
	P-value[2]		0.414	

(1) Comparison of the mean COD concentration of all ports in R1.
(2) Comparison of the mean COD concentration of all ports in R5.

5.1.3.10 Shortcircuiting

The objective of this analysis was to estimate if shortcircuiting may have been taking place in the bioreactors. To evaluate the potential shortcircuiting, 7 liters of clear water were added to the bioreactors. If the system is assumed to operate as a continuously mixed system, the expected effluent can be estimated. If the system is assumed to operate as a plug flow system (in the short term), the expected effluent COD should be close to the effluent COD prior to adding the 7 liters of water.

Given the expected COD concentration and the measured concentration, the amount of shortcircuiting can be estimated using the following formulas:

- For the assumption of a completely mixed system

$$COD(measured) = \left(1 - \frac{x}{7}\right)\left(\frac{7l \cdot (0mg/l) + Vol.of\ leachate \cdot (COD^1)}{(Vol.\ of\ leachate + 7)}\right) + x(0) \qquad [27]$$

- For the assumption of a plug flow system

$$COD(measured) = \left(1 - \frac{x}{7}\right)(COD^1) + x(0) \qquad [28]$$

Where the COD^1 is the effluent COD prior to adding the 7 liters of water and x is the volume (L) that shortcircuiting based on each assumed operating conditions. The fraction of shortcircuiting is (x / 7).

Table 5.28 summarizes the results of the first shortcircuiting test which was carried out on day 187 for group one, and 163 for group two. The fraction of shortcircuiting was estimated to be 0.24, 0.21, 0.19, 0.16, 0.21, 0.23, 0.22, and 0.18 in R1 through R8, respectively based on the assumption of completed mixed conditions.

Also, Table 5.29 presents the results of the second shortcircuiting analysis which run on day 393 for group one, and 388 for group two. The fraction of shortcircuiting was

estimated to be 0.25, 0.23, 0.21, 0.19, 0.23, 0.23, 0.21, and 0.18 in R1 through R8, respectively based on the assumption of completed mixed conditions.

This means that the volume of leachate recycled in 1D bioreactors was not equal to 7L, but it was rather in the range of (4.7 - 5.9 L) due to the shortcircuiting. Given the negligible variation in the vertical concentration profiles within the 1D bioreactors, the bioreactors were assumed to operate as completely mixed systems. This is consistent with what is found in the literature (e.g. El-Fadel et al., 1996b; Katsiri et al., 1999; Pareek et al., 1999; Yadiz et al., 2004) and is the assumption made for the modeling present in Section 4.3.2. In addition, the shortcircuiting had no effect on the methane production and methane yield as compared to the methane production in the literature.

Table 5.28: First set of shortcircuiting analysis

COD (mg/l)	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**
COD[1]	9700	11050	15800	23100	25600	24050	20600	22850
Initial mass (kg)	33.5	34.3	36.1	36.2	35.1	34.5	35.3	36.2
M.C % (w/w)	62.48	61.52	63.64	60.58	62.50	62.84	62.94	64.68
Volume of leachate (L)	20.93	21.10	22.97	21.93	21.94	21.68	22.22	23.42
COD (expected)[2]	7269	8298	12110	17511	19408	18180	15665	17591
COD (measured)[3]	5540	6550	9775	14750	15250	13950	12175	14450
Fraction[4]	0.24	0.21	0.19	0.16	0.21	0.23	0.22	0.18
Fraction[5]	0.43	0.41	0.38	0.36	0.40	0.42	0.41	0.37

(1) COD concentration in the bioreactors prior to adding clean water.
(2) COD concentration based on mass balance for completely mixed bioreactors.
(3) Measured COD concentration after 24 hrs from adding clean water to the bioreactors.
(4) Fraction of shortcircuiting based on the assumption of a completely mixed system.
(5) Fraction of shortcircuiting based on the assumption of a plug flow system.

Table 5.29: Second set of shortcircuiting analysis

COD (mg/l)	R1	R2	R3	R4	R5	R6	R7	R8
COD[1]	2700	2725	3425	6250	3275	3525	4100	4475
Initial mass (kg)	33.5	34.3	36.1	36.2	35.1	34.5	35.3	36.2
M.C % (w/w)	62.48	61.52	63.64	60.58	62.50	62.84	62.94	64.68
Volume of leachate (L)	20.93	21.10	22.97	21.93	21.94	21.68	22.22	23.42
COD (expected)[2]	2023	2046	2625	4738	2483	2665	3118	3445
COD (measured)[3]	1510	1575	2085	3825	1715	1800	2145	2615
Reduction[4]	0.25	0.23	0.21	0.19	0.31	0.32	0.31	0.24
Reduction[5]	0.44	0.42	0.39	0.39	0.48	0.49	0.48	0.42

(1) COD concentration in the bioreactors prior to adding clean water.
(2) COD concentration based on mass balance for completely mixed bioreactors.
(3) Measured COD concentration after 24 hrs from adding clean water to the bioreactors.
(4) Fraction of shortcircuiting based on the assumption of a completely mixed system.
(5) Fraction of shortcircuiting based on the assumption of a plug flow system.

5.1.3.11 Summary of leachate quality analysis

- The percentage of peak reduction in all leachate parameters decreased with increasing salt contents. In other words, the salt inhibited the biodegradation of MSW.
- The highest COD, BOD, VFA, NH_3-N, TVS, and TS percentage peak reductions were observed in R5 (0%), and the lowest in R4 (3%).
- The addition of sludge in both the aerobic and anaerobic stages improved the performance of the MSW bioreactors operated under saline conditions, as shown by the results of percentage reduction in all leachate parameters.
- There was a significant difference in the mean of COD, BOD, VFA, TVS, TS, and NH3-N concentrations in all bioreactors. The difference was observed in R4 compared to R1 in COD, BOD, VFA, and TVS.

- A significant difference was observed in the mean of COD, BOD, VFA, TVS, and TS percentage peak reductions at different salt contents during the aerobic stage. The difference was at 3% compared to 0% (w/v) salt content. Also, a significant difference was observed in the mean of COD, BOD, TVS, and TS percentage peak reductions at different salt contents during the anaerobic stage. The difference was at 3% compared to 0% (w/v) salt content in the COD and BOD, whereas the difference was for 1% and 3% in the TVS and TS. This indicates that the high salt contents inhibited the MSW biodegradation.
- There was significant difference in the mean NH_3-N percentage peak reduction in the two groups during the aerobic and anaerobic stages.
- There was no significant difference in the COD concentration along the vertical profile of bioreactors.
- Shortcircuiting was observed in the bioreactors and it was in the range of 0.16- 0.32 based on the assumption of a completely mixed system.

5.2 Hydrolysis rate constant

Two sets of BMP assays were used to estimate the hydrolysis rate constant (k_h). The first set consisted of eight BMP assays (BR1 through BR8) with addition of 20% (v/v) of two different inoculums (normal and acclimatized anaerobic digested sludge). The second set consisted of four BMP assays (BR9 through BR12) with addition of 30% (v/v) normal anaerobic digested sludge as an inoculum.

5.2.1 First set

The first set of BMP assays was divided into two groups. The first group consisted of four BMP assays (BR1, BR2, BR3 and BR4) which were run with addition of 20% (v/v) normal anaerobic digested sludge and at 0, 1, 2, and 3 % (w/v) salt contents, respectively. The second group also consisted of four BMP assays (BR5, BR6, BR7 and BR8) which were run with addition of 20% (v/v) acclimatized anaerobic digested sludge and at 0, 1, 2, and 3 % (w/v) salt contents, respectively.

The accumulative methane production and methane concentration of the first set are shown in Figure 5.25. Table 5.30 summarizes the results of methane production and the estimated hydrolysis rate constant from the first set of BMP assays.

The initial TVS concentration of supernatant was 6.23 g/l and the TVS concentration of the inoculums was 12.2 and 10.5 g/l for normal and acclimatized anaerobic digested sludge, respectively. The ratio of VS in the supernatant to the inoculum was 2.2 and 2.9 (g TVS of supernatant / g TVS of inoculums) for the first and second groups, respectively.

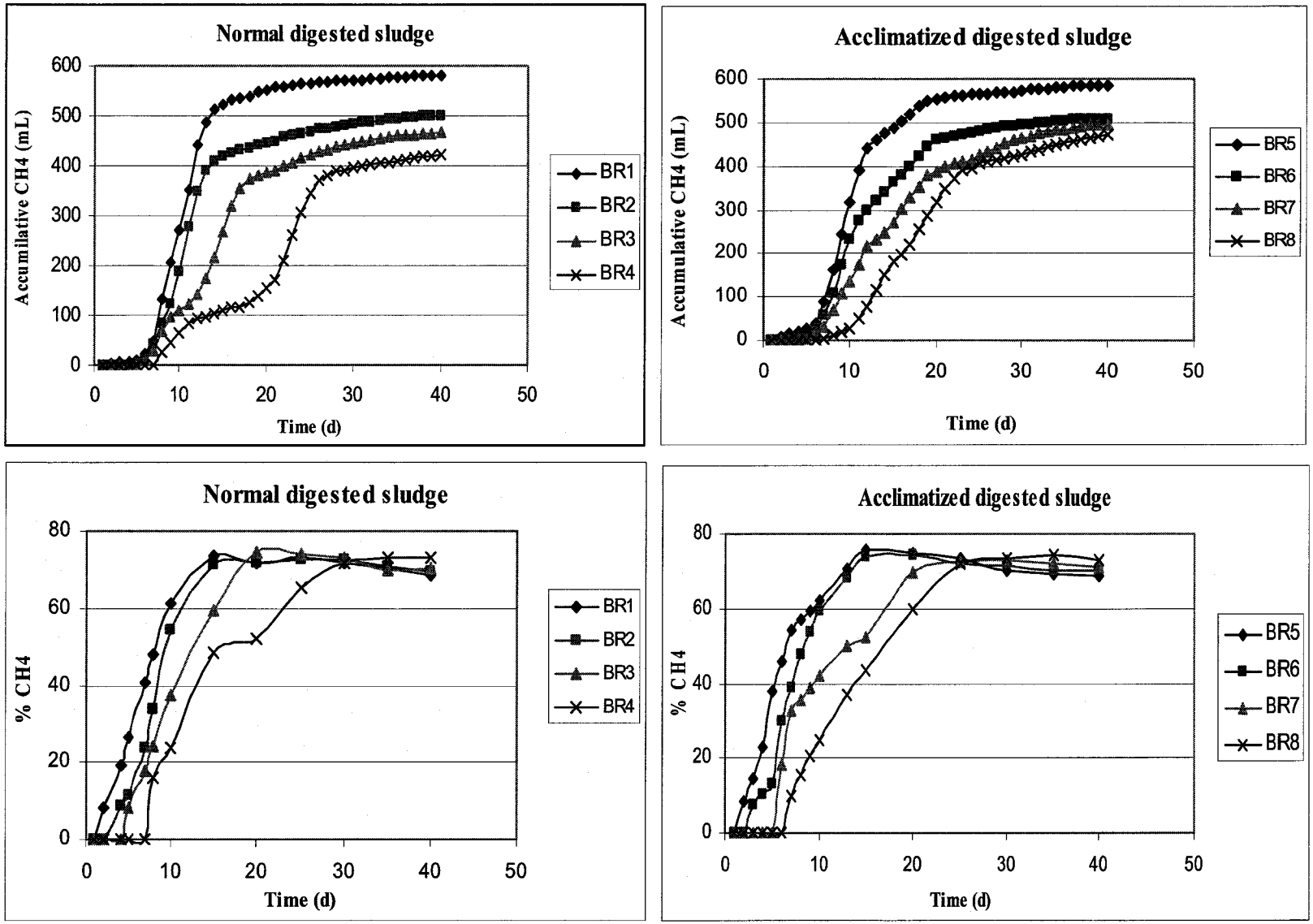


Figure 5.25: Accumulative methane production and methane concentration in first set of k_h.

Table 5.30: Results of methane produced from BMP to estimate k_h using 20% (v/v) of two types of inoculums

	Normal digested sludge				Acclimatized digested sludge			
	BR1	BR2	BR3	BR4	BR5	BR6	BR7	BR8
Initial TVS of substrate (g/l)	6.226							
TVS of inoculums (g)	14.2 (TVS= 1.42%)				10.5 (TVS= 1.04%)			
VS of substrate / VS of inoculums	2.2				2.9			
Duration time(d)	40							
Lag time (d)	1	3	4	7	1	2	4	6
Peak (mL)	91.9	81.77	54.1	51.6	81.1	65	43.4	38
Time (d) to reach peak	8	11	15	23	9	9	12	13
Total CH4 (mL)	582	501	466	423	585	508	493	471
k_h (d^{-1})	0.085	0.076	0.060	0.042	0.086	0.073	0.058	0.049
Y (mL/g VS_{added})	374.1	322.8	300.0	272.2	376.1	326.3	318.9	300.8
P-values	0.83[1]				0.640[2]			

(1) Comparison between the mean k_h in the two groups of inoculums.
(2) Comparison between the mean Y in the two groups of inoculums.

By assuming the hydrolysis rate constant followed first order kinetics, the accumulative methane production can be described by equation (11).

$$Y = Y_u \cdot (1 - \exp(-k_h \cdot t)) \qquad [11]$$

The hydrolysis rate constant was estimated using the nonlinear regression method for the accumulative methane production. The hydrolysis rate constant for the first group was 0.085, 0.076, 0.06, and 0.042 d^{-1} for BR1, BR2, BR3 and BR4 respectively at 35°C. In the second group, it was 0.086, 0.073, 0.058, and 0.049 d^{-1} for BR5, BR6, BR7 and BR8

respectively at 35°C. The results of nonlinear regression are presented in Tables 4.1 through 4.8 in Appendix B.

The methane yield was 374, 323, 300, and 272 (mL /g VS_{added}) for BR1, BR2, BR3 and BR4, respectively. In the second group, it was 376, 326, 319, and 301 (mL /g VS_{added}) for BR5, BR6, BR7 and BR8, respectively.

There was no statistical difference between the mean hydrolysis rate constant and mean methane yield in the two groups of inoculums, as suggested by the P-values shown in Table 5.30. This is consistent with the results found earlier for the BMP assays completed for the leachate samples of the 1D bioreactors.

5.2.2 Second set

This set consisted of four BMP assays (BR9, BR10, BR11 and BR12) which were run at 0, 1, 2, and 3% (w/v) salt contents, respectively. The volume of anaerobic digested sludge used was 30% (v/v) of the supernatant or 75 mL. The initial TVS concentration of supernatant was 7.15 g/l and the TVS concentration of inoculum was 12.58 g/l.

Figure 5.26 shows the accumulative methane production and methane concentration in the second set of BMP assays and hydrolysis rate constant at different salt contents. Also, Table 5.31 summarizes the results of methane production and hydrolysis rate constant.

Using the same formula as in the first set, the hydrolysis rate constant (k_h) was estimated with nonlinear regression to fit the accumulative methane production. The k_h was 0.086, 0.073, 0.058 and 0.049 d^{-1} for BR9, BR10, BR11 and BR12, respectively at 35°C. The results of nonlinear regression are presented in Tables 4.9 through 4.12 in Appendix B.

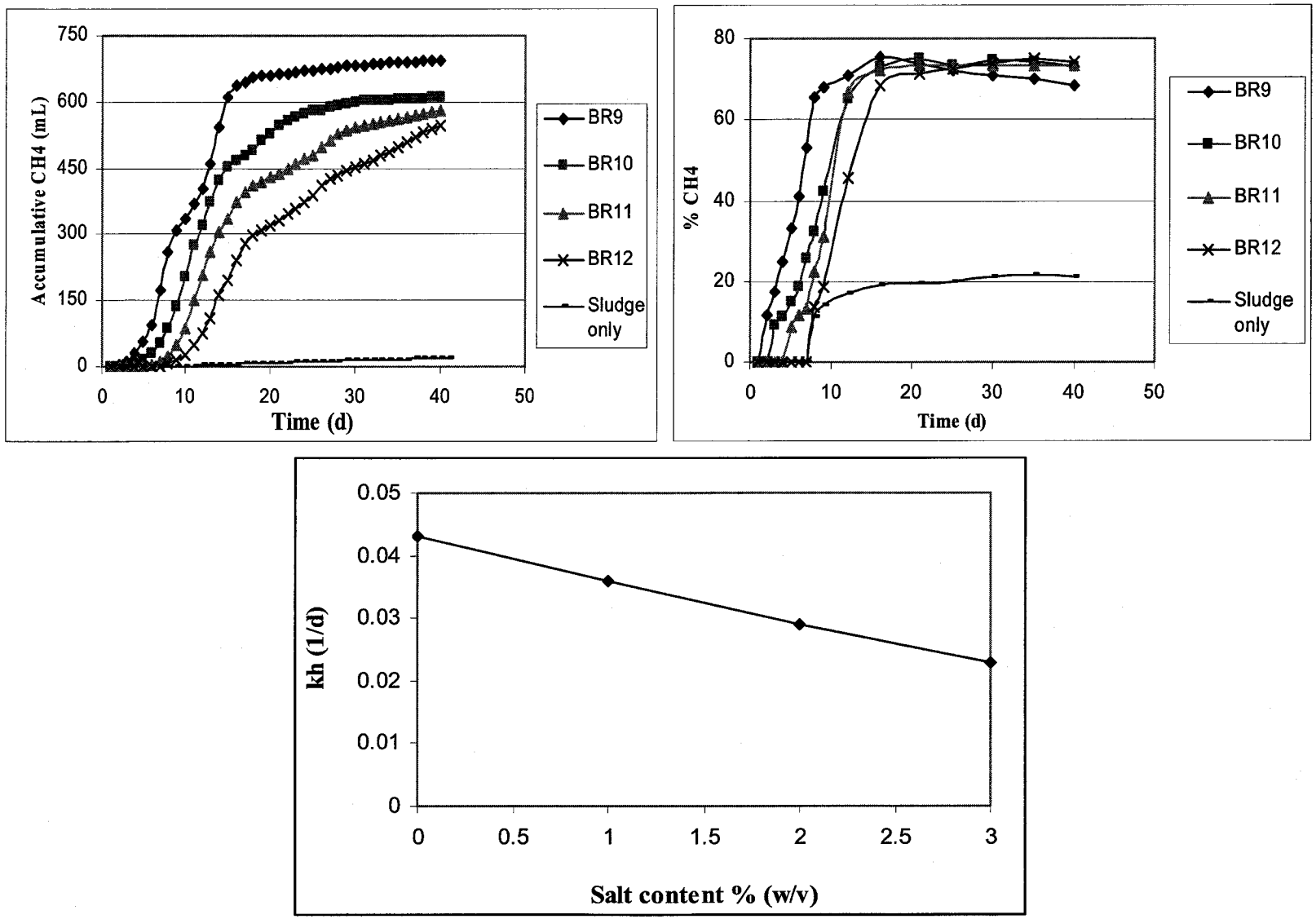


Figure 5.26: Accumulative methane production and methane concentration for the second set and hydrolysis rate constant at 23°C.

Table 5.31: Results of methane produced from BMP to estimate k_h using 30% (v/v) anaerobic digested sludge

	Normal digested sludge			
	BR9	BR10	BR11	BR12
Initial TVS of substrate (g/l)	7.15			
TVS of inoculums (g)	12.58 (TVS= 1.3%)			
VS of substrate/ VS of biomass	1.9			
Duration time (d)	40			
Lag time (d)	1	2	4	7
Peak (mL)/d	84.5	74.1	63.7	51.84
Time (d) to reach peak	8	11	12	14
Total CH4 (mL)	694	611	578	548
k_h (d^{-1})	0.086	0.073	0.058	0.049
Y (mL /g VS_{added})	388.2	341.8	324.5	306.5
Statistical analysis	0.95^1		0.44^2	

(1) Comparison between the mean k_h of group one in the first set and second set.
(2) Comparison between the mean Y of group one in first set and second set.

The methane yield was 388, 342, 325, and 307 (mL /g VS_{added}) for BR9, BR10, BR11 and BR12, respectively.

These results agreed with results presented by Jokela et al. (2005), Veeken et al. (1999) and Owens et al. (1993). Jokela et al. (2005) found that the hydrolysis rate constant was in the range of 0.021 – 0.107 d^{-1} at 35°C for ten different types of waste compounds. Also, they found that the methane yield was 58, 217, 228 and 527 (mL /g VS_{added}) for newsprint, cardboard, textile and food waste, respectively. Veeken et al. (1999) found the

hydrolysis rate constant was in the range of 0.03 – 0.15 d^{-1} at 35°C for leaves, straw, organic peeling and grass wastes.

Owens et al. (1993), found the k_h was 0.075 and 0.065 d^{-1} at 35°C and the methane yield was 222 and 215 (mL /VS_{added}) for the fresh and dry waste, respectively.

P-values, as shown in Table 5.31, were more than 0.05, which means that there was no significant difference between the mean k_h and Y of group one in the first set and the second set.

The average hydrolysis rate constant (group one of the first set and the second set) was 0.0855, 0.074, 0.059, and 0.046 d^{-1} for 0, 1, 2, and 3 % (w/v) salt contents, respectively, at 35°C. Since the 1D bioreactors operated approximately at 23°C, the hydrolysis rate constant could be calculated at 23°C by using the following formula (Metcalf et al., 2003):

$$k_{h\ (23°C)} = k_{h\ (35°C)} \cdot 1.06^{(23-35)} \qquad [29]$$

The k_h at 23°C was 0.043, 0.036, 0.029, and 0.023 d^{-1} for 0, 1, 2, and 3 % (w/v) salt content, respectively, as shown in Figure 5.26.

The following equation can be used to predict the hydrolysis rate constant at different salt contents (0-3) % (w/v).

$$k_{h(23°C)} = 0.043 - 0.0067 \cdot X \qquad [30]$$

Where,

$k_{h(23°C)}$: hydrolysis rate constant at 23°C

X: salt content % (w/v)

5.3 Model calibration

The purpose of model calibration was to estimate the kinetics of the acidogenic and methanogenic biomasses (μ, k_d, and K_S), and the inhibition constants (K_I and m) to account for salt contents. The results obtained from 1D bioreactors and BMP assays were used in the model calibration. The calibration procedure was divided into two steps. In the first step, the biomass kinetics (μ, k_d, and K_S) were estimated by calibrating the model results with the 1D bioreactor measurements (VFA, daily and accumulative methane production) operated without salt content (R1 and R5). In the second step, the inhibition constants (K_I and m) were estimated by calibrating the model result with 1D bioreactors operated under different salt contents (0.5, 1, and 3)% (w/v).

The data required for the calibration was classified into five categories. First, the required initial conditions were the initial concentrations of solid biodegradable carbon (C_S), aqueous organic acids (C_{aq}), VFA (C_{VFA}), acidogenic biomass (C_{XA}), and methanogenic biomass (C_{XM}) in terms of mass of carbon per unit volume. Second, the input parameter that were assumed fixed and equal to the values published in the literature, which only included the VFA carbon fractional formation yield coefficient (Y_{HAC}). Third, the input parameters estimated in the laboratory were methane fraction (Y_{CH4}) and hydrolysis rate constant at different salt contents. Fourth, the range of values to be adjusted to calibrate the model were the kinetics of the acidogenic and methanogenic biomasses (μ, k_d, and K_S), and yield coefficients of acidogenesis (Y_A) and methanogenesis (Y_M). Fifth, the experimental results against which the model will be calibrated were VFA, and daily and accumulative methane production in terms of kg carbon per kg dry waste.

The initial solid biodegradable carbon for individual waste components was estimated using the following formula (see Table 5.32 for results):

$$(C)_{bi} = (C)_i \cdot BF_i \cdot M_i \qquad [31]$$

Where,

$(C)_{bi}$: biodegradable carbon in the i component of waste, kg biodegradable C/kg dry i component.

$(C)_i$: carbon content in the i component of waste, kg C/ kg dry i component, from Table 2.2.

BF_i: biodegradable fraction of carbon content, kg biodegradable C/kg C, from Table 2.3

M_i: dry mass of i component, kg dry i component.

There was a reduction in the initial solid biodegradable carbon mass (C_S) during the aerobic stage. Therefore, the initial conditions of (C_S) used in the model calibration have been estimated based on the total biogas produced from R5 (CH_4 and CO_2) at the end of the anaerobic stage. Based on this and taking into account the loss of biogas during the leachate recycle, the initial (C_S) was estimated to be approximately 0.12 kg carbon per kg dry waste. Therefore, the loss during the aerobic stage was assumed to be approximately 12.5 %.

Table 5.32: Initial biodegradable carbon content in waste components.

Waste components	Wet weight (kg)	Moisture content % (w/w)	Dry weight (kg)	C (kg C /kg dry weight)	BF (kg bio. C /kg C)	C_b (kg biod. C/ kg of dry waste)
Food	0.6	0.6	0.21	0.48	0.8	0.09216
Paper	0.2	0.09	0.18	0.44	0.52	0.04004
Plastics	0.15	0.02	0.1485	0.6	0	0
Textile	0.05	0.11	0.045	0.55	0.2	0.0049

However, the remaining initial conditions (C_{aq}, C_{VFA}, C_{XA}, and C_{XM}) were adjusted to get the closest match between the simulation results and the experimental results of R1 for the first group and R5 for the second group. The methane fraction (Y_{CH4}) and hydrolysis rate constant at different salt contents used to calibrate the model were estimated and presented in Section 5.1.22 and 5.2.2, respectively. The range of kinetics and yield coefficient of biomasses (acidogenic and methanogenic) used in the model calibration are shown in Table 5.33. Finally, the experimental results of VFA, daily and accumulative methane production which were used to compare with the model results are presented in Appendix A.

The trial and error procedure has been used in the model calibration to obtain the best match between the model and experimental results. Three scenarios have been conducted to achieve the best fit of VFA, daily and accumulative methane production. In the first scenario, the total carbon content was assumed to exist as solid biodegradable carbon (C_S). In the second scenario, the carbon content was divided into solid carbon, aqueous acids and VFA to represent the effect of the initial aerobic stage. In the third scenario, two hydrolysis constants were used to match the two peaks of daily methane production which were evident in the experimental results.

Table 5.33: Range of kinetic parameters used in model calibration

Parameter	Unit	Literature
Acidogenesis		
Growth rate, μ_A	d^{-1}	(0.5-30)[a, b, c, d]
Half saturation constant, K_{SA}	kg m^{-3}	(0.03-5) [b, c]
Rate of decay, k_{dA}	d^{-1}	(0.004-0.4)[a, b, c]
Yield, Y_A	kg kg^{-1}	(0.1-0.5)[a, c]
Methanogenesis		
Growth rate, μ_M	d^{-1}	(0.1-0.5)[a, b, c, d]
Half saturation constant, K_{SM}	kg m^{-3}	(0.0003-2.5)[a, b]
Rate of decay, k_{dM}	day^{-1}	(0.005-0.04)[a, b, c, d]
Yield, Y_M	kg kg^{-1}	(0.05-0.82)[a, b, c]
VFA formation yield, Y_{HAC}	kg kg^{-1}	0.9[a]

a, El-Fadel et al. 1996.
b, Yildiz et al. 2004.
c, Naranjo et al. 2004.
d, Haarstrick et al. 2001.

5.3.1 First scenario

The model was run while varying model parameters for each simulation to achieve the best match between the simulation and experimental results. The profiles that best fit the results are shown in Figures 5.27 through 5.30, and the model parameters and inhibition constants (K_I and m) used in the calibrated model are presented in Table 5.34.

CH_4: A comparison between the predicted and measured accumulative methane production was reasonably reproduced by the model in all bioreactors, except the first peak in the daily methane production. The model was not able to simulate the two peak daily methane production rates since the conceptual model did not include any processes that could simulate a second peak.

VFA: Slight deviations between the predicted and measured peak of VFA concentrations and the time required to reach the peak of VFA concentrations are observed. The best fit model simulations underestimated the VFA concentrations at early times and overestimated the VFA concentrations at later times. Also, the predicted peak VFA concentrations occurred later than the measured peak concentrations. This may be attributed to the fact that the model assumed all the carbon was initially present in the solid phase and did not account for the aerobic degradation. To improve this, the second model scenario used initial concentrations which reflected the experimental conditions in the 1D bioreactors after the aerobic stage.

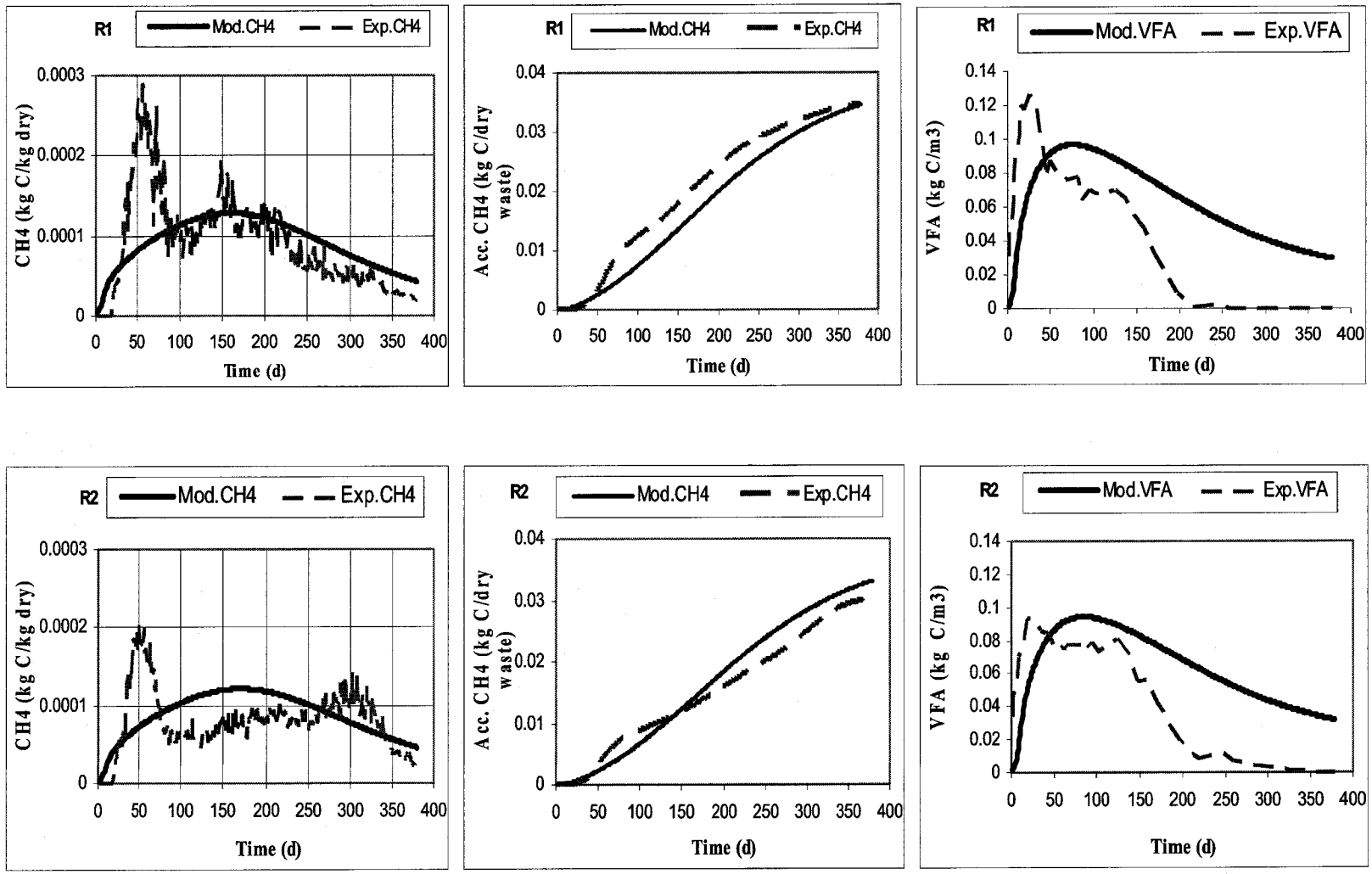


Figure 5.27: Model calibration first scenario.

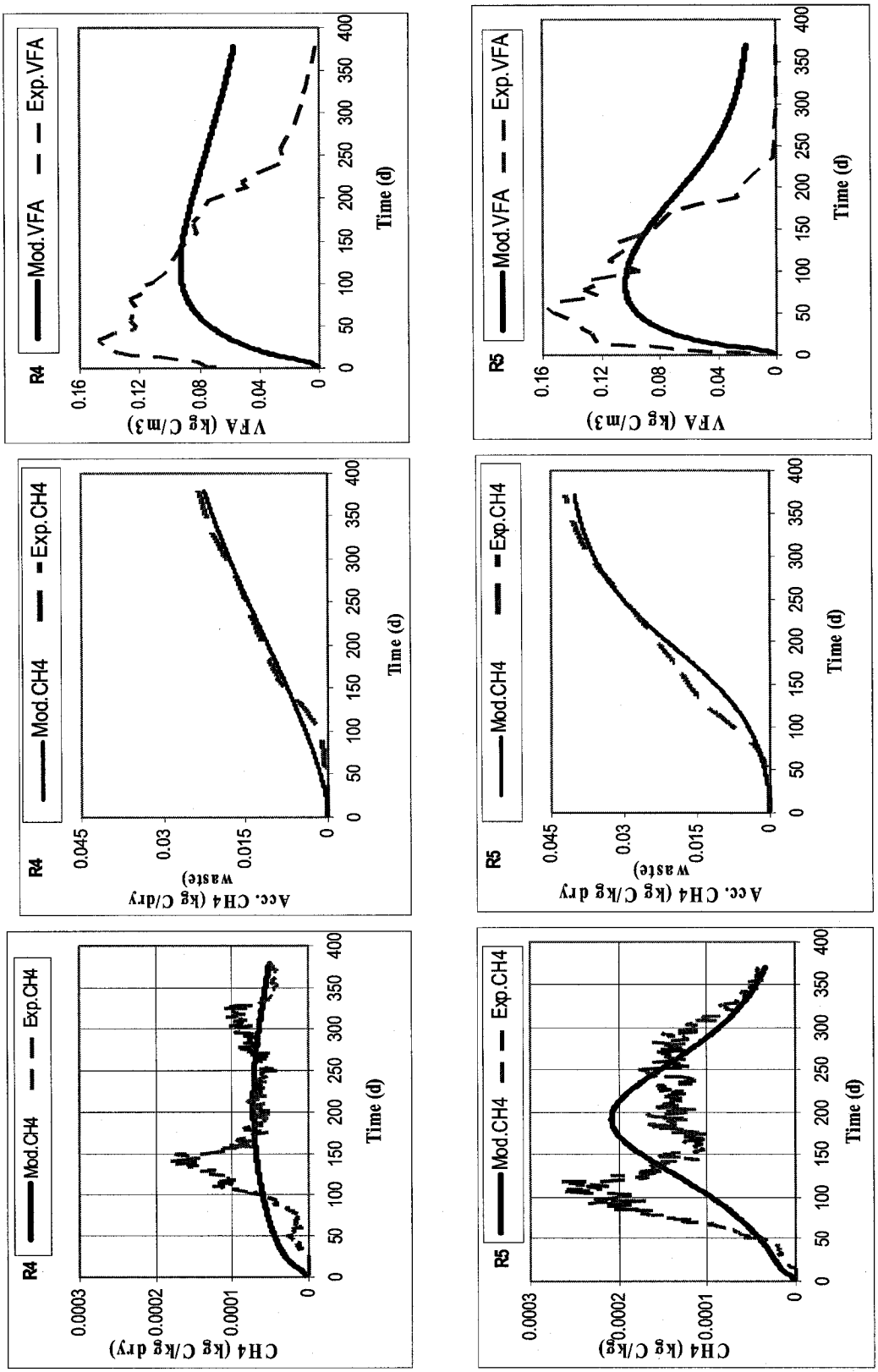


Figure 5.28: Model calibration first scenario.

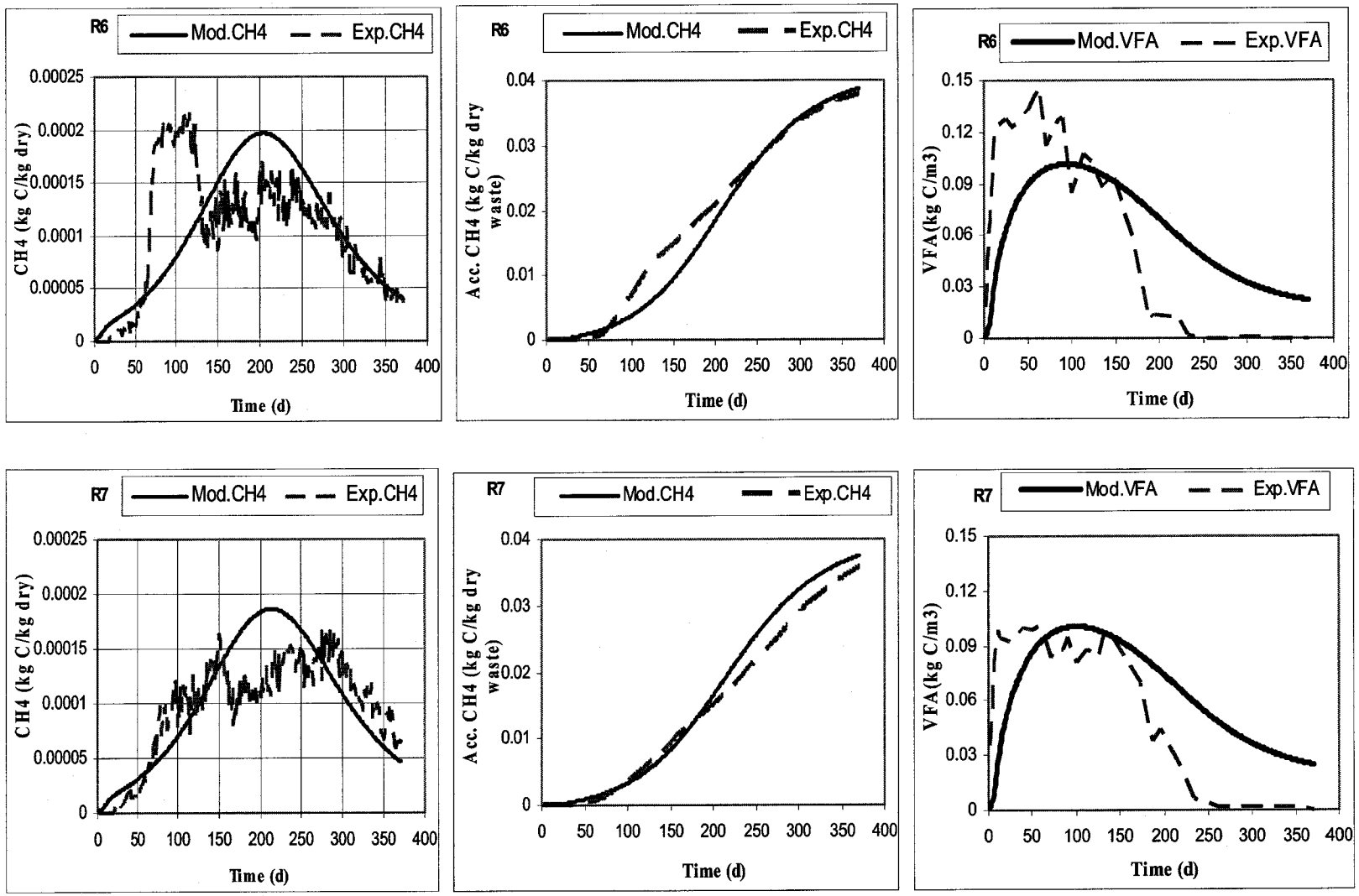


Figure 5.29: Model calibration first scenario.

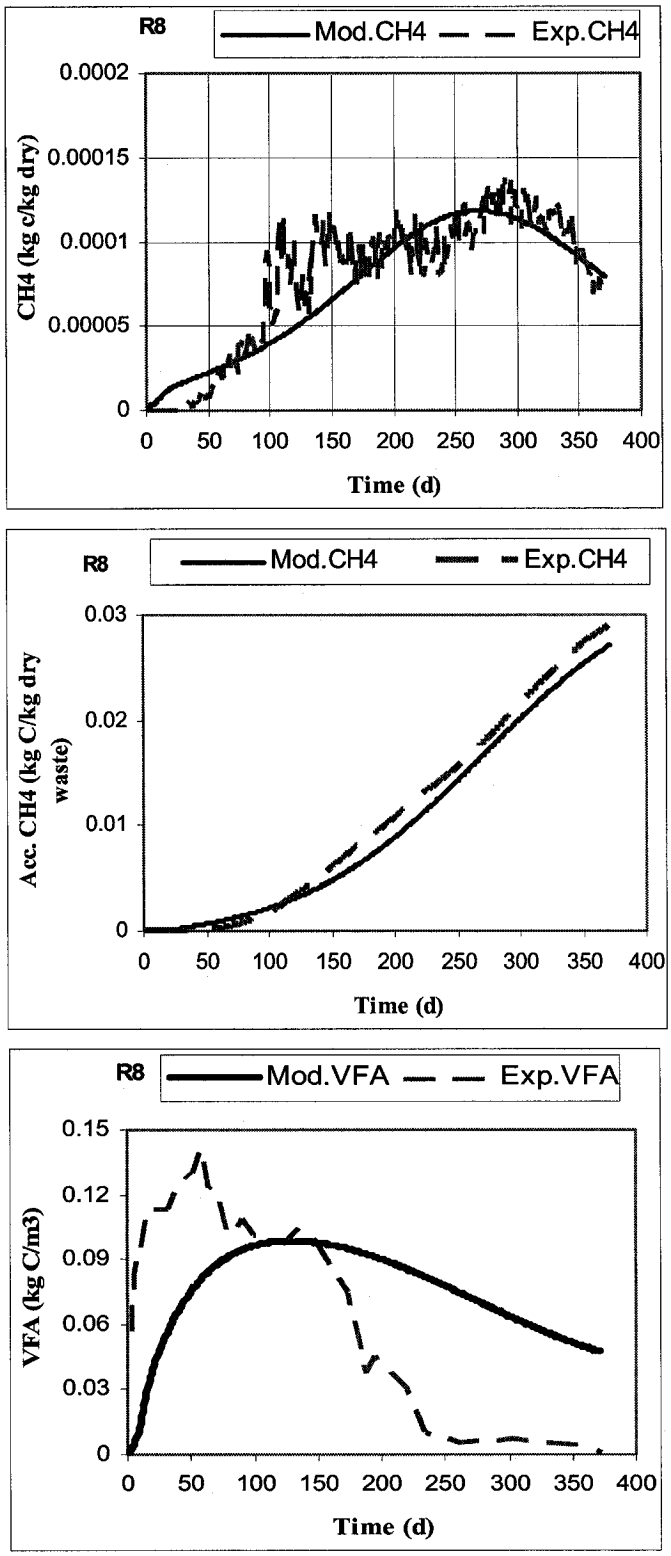


Figure 5.30: Model calibration first scenario.

Table 5.34: Parameters used in the model calibration of the first scenario

Parameter	Unit	Applied values			
Hydrolysis					
I	(w/v)	0%	0.5%	1%	3%
k_h	d^{-1}	0.043	0.036	0.033	0.023
K_I	(w/v)	6			
m		2			
Acidogenesis					
Growth rate, μ_A	d^{-1}	5			
Half saturation constant, K_{SA}	kg m^{-3}	0.3			
Rate of decay, k_{dA}	d^{-1}	0.04			
Yield, Y_A	kg kg^{-1}	0.15			
		First group		Second group	
Methanogenesis					
Growth rate, μ_M	d^{-1}	0.135		0.22	
Half saturation constant, K_{SM}	kg m^{-3}	0.7		0.53	
Rate of decay, k_{dM}	day^{-1}	0.01		0.019	
Yield, Y_M	kg kg^{-1}	0.07		0.1	
Methane fraction yield, Y_{CH4}	kg kg^{-1}	0.41		0.43	
VFA formation yield, Y_{HAC}	kg kg^{-1}	0.9		0.9	
Initial conditions					
$\mathbf{C_{(s)}}$	Kg C m^{-3}	0.12		0.12	
$\mathbf{C_{(aq)}}$	Kg C m^{-3}	0.0009		0.0009	
$\mathbf{C_{(VFA)}}$	Kg C m^{-3}	0.0009		0.0009	
$\mathbf{C_{(XA)}}$	Kg C m^{-3}	0.0009		0.0009	
$\mathbf{C_{(XM)}}$	Kg C m^{-3}	0.0009		0.00025	

5.3.2 Second scenario

The initial biodegradable carbon content was divided into solid carbon (C_S), aqueous acids (C_{aq}) and VFA (C_{VFA}) at time zero (t = 0) to represent the experimental conditions in the 1D bioreactors after the aerobic stage. The best fit of the model calibration is shown in Figures 5.31 through 5.34, and Table 5.35 summarizes the value of the model parameters and inhibition constants (K_I and m) used in the current scenario to get the best fit.

CH_4: The results of the model in this scenario gave a better match between the predicted and measured accumulative methane production than the first scenario. However, the model did not show the lag phase in the methane production which was observed in the experimental results. In other words, the results of the model showed that methane started to be produced from day one. This could be attributed to the high initial concentration of VFA and the presence of methanogenic biomass. The model has been used to simulate the system with a methanogens lag time, but this had a limited impact on the magnitude of methane production and time to reach its peak. This impact was observed in the early stage of methane production.

In addition to that, the model could not predict the two peaks of methane production. To improve this, the third model scenario used two hydrolysis rate constants (readily and slowly) to match the two peaks of daily methane production.

VFA: There was an improvement in the simulation results of VFA concentration (time to reach the peak) compared to the first scenario. The underestimation of VFA concentrations in the early times has been eliminated in all bioreactors and the overestimation of VFA concentrations in the later times has been slightly decreased.

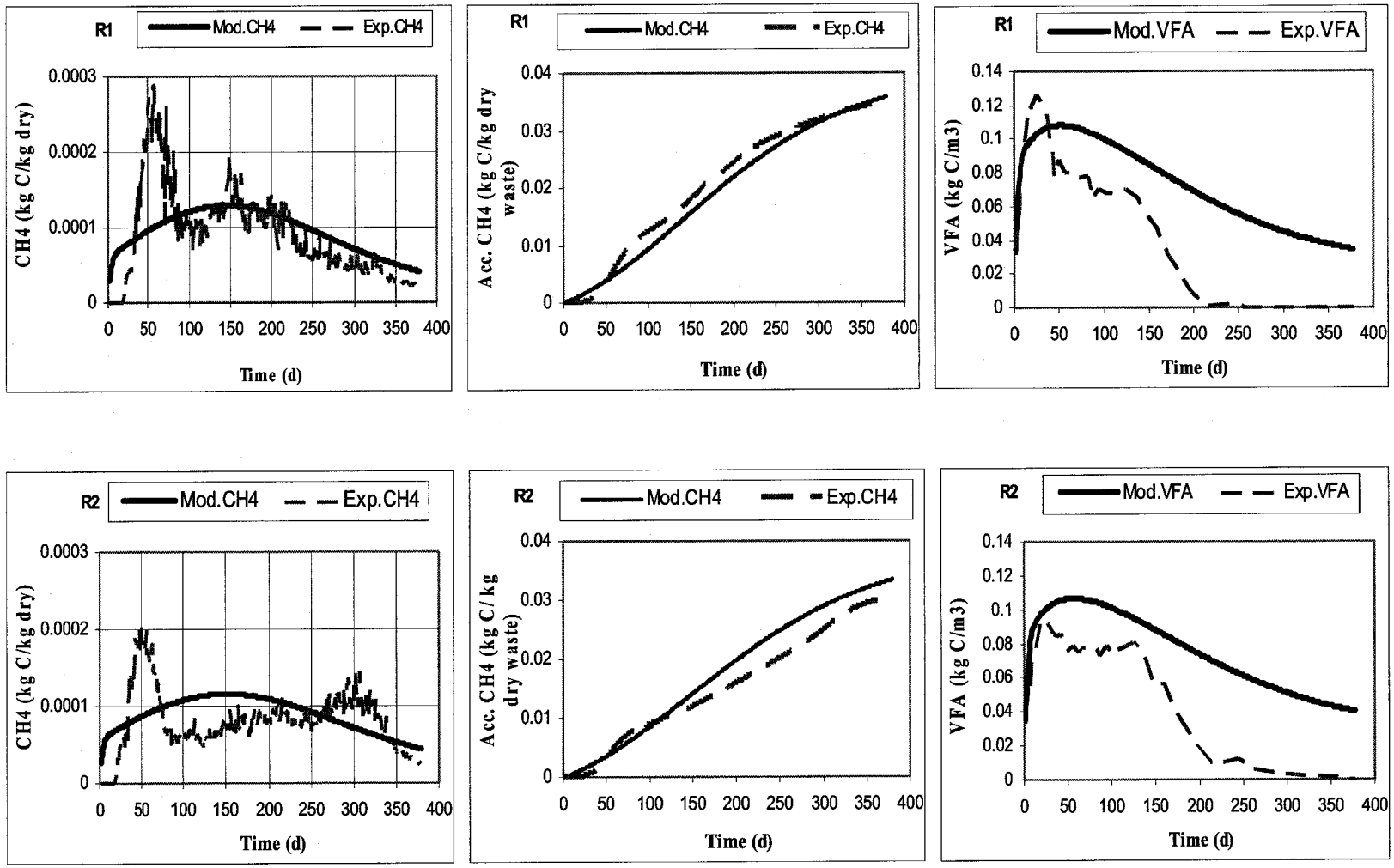


Figure 5.31: Model calibration second scenario.

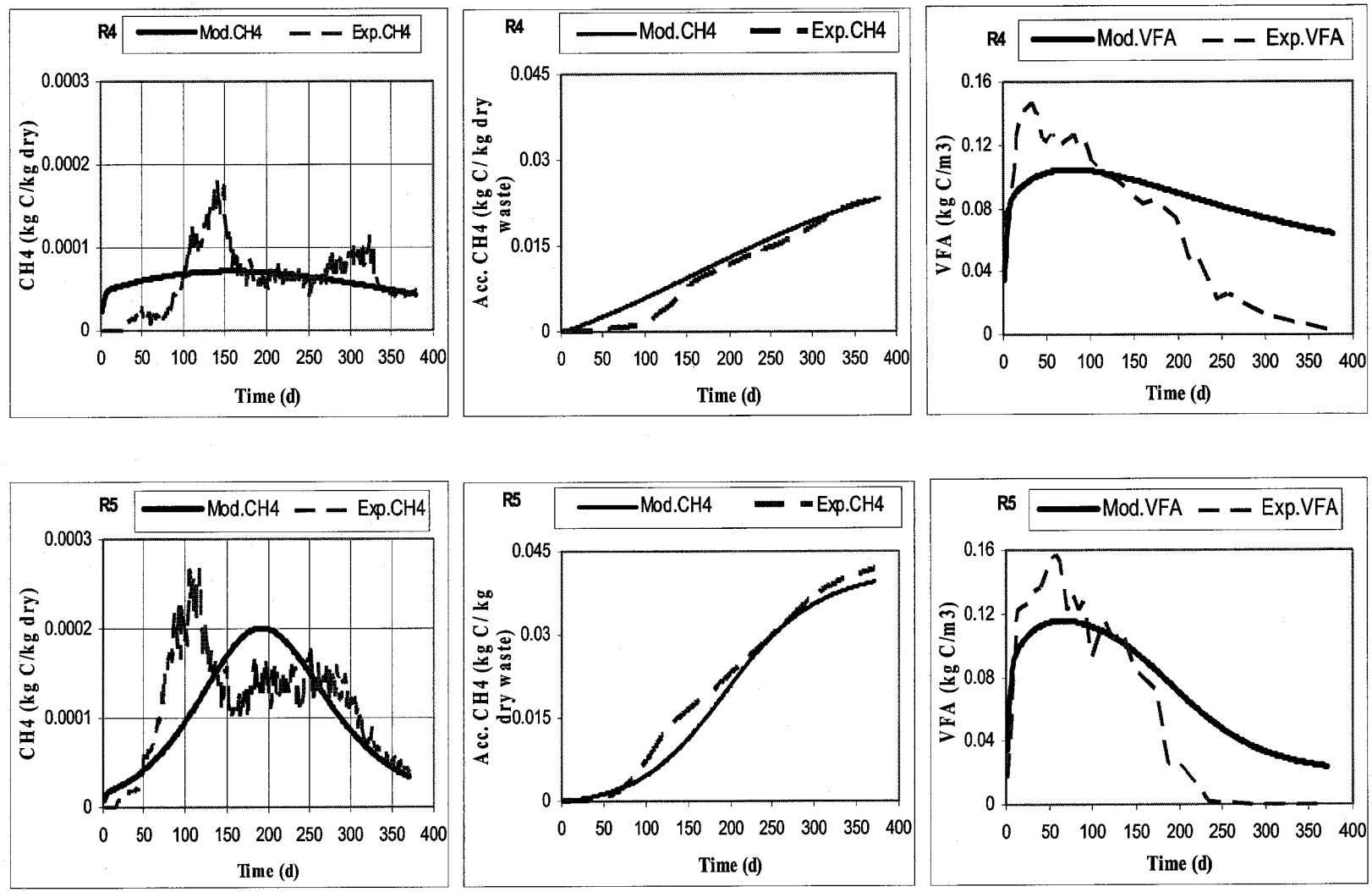


Figure 5.32: Model calibration second scenario

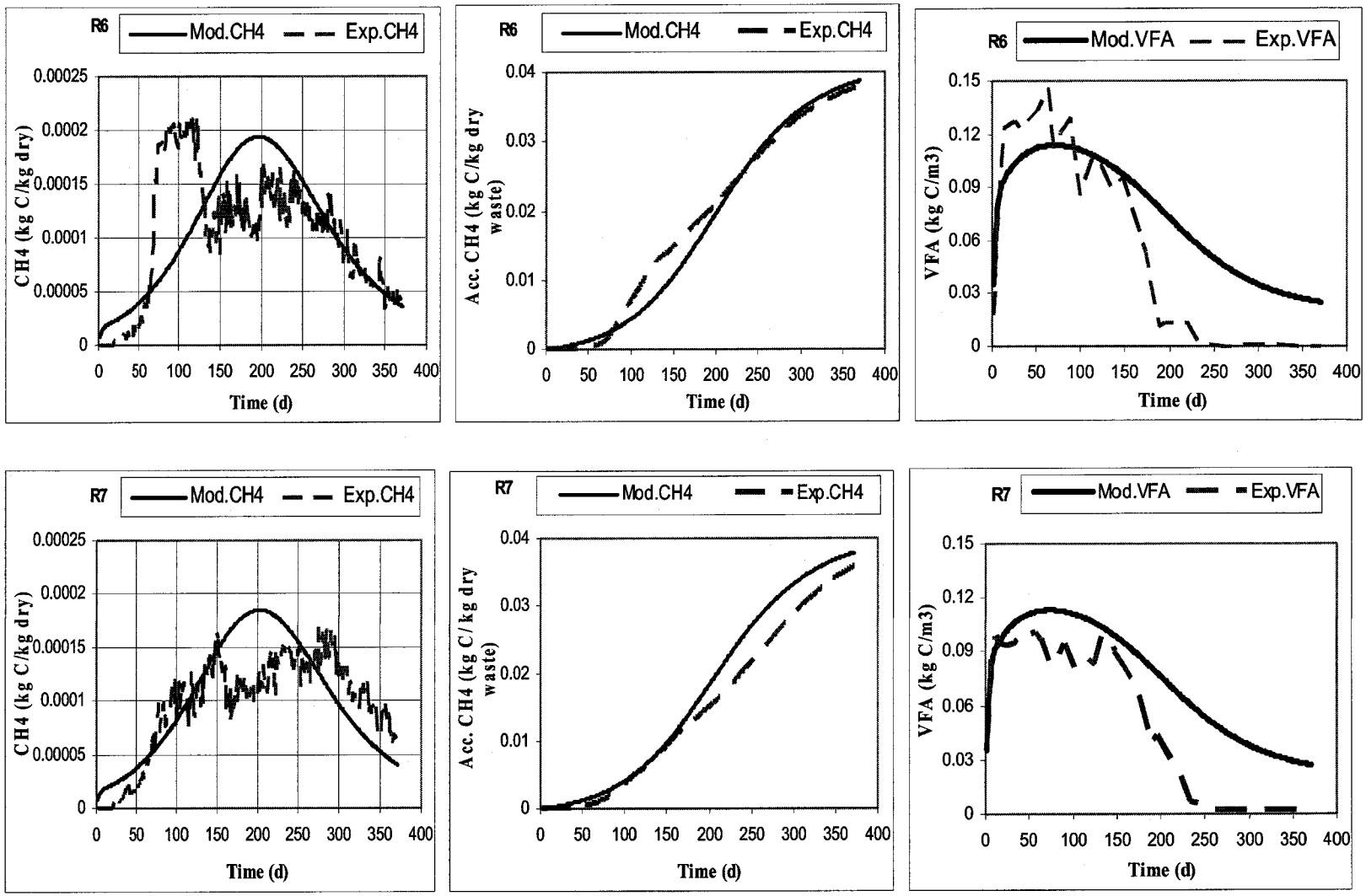


Figure 5.33: Model calibration second scenario.

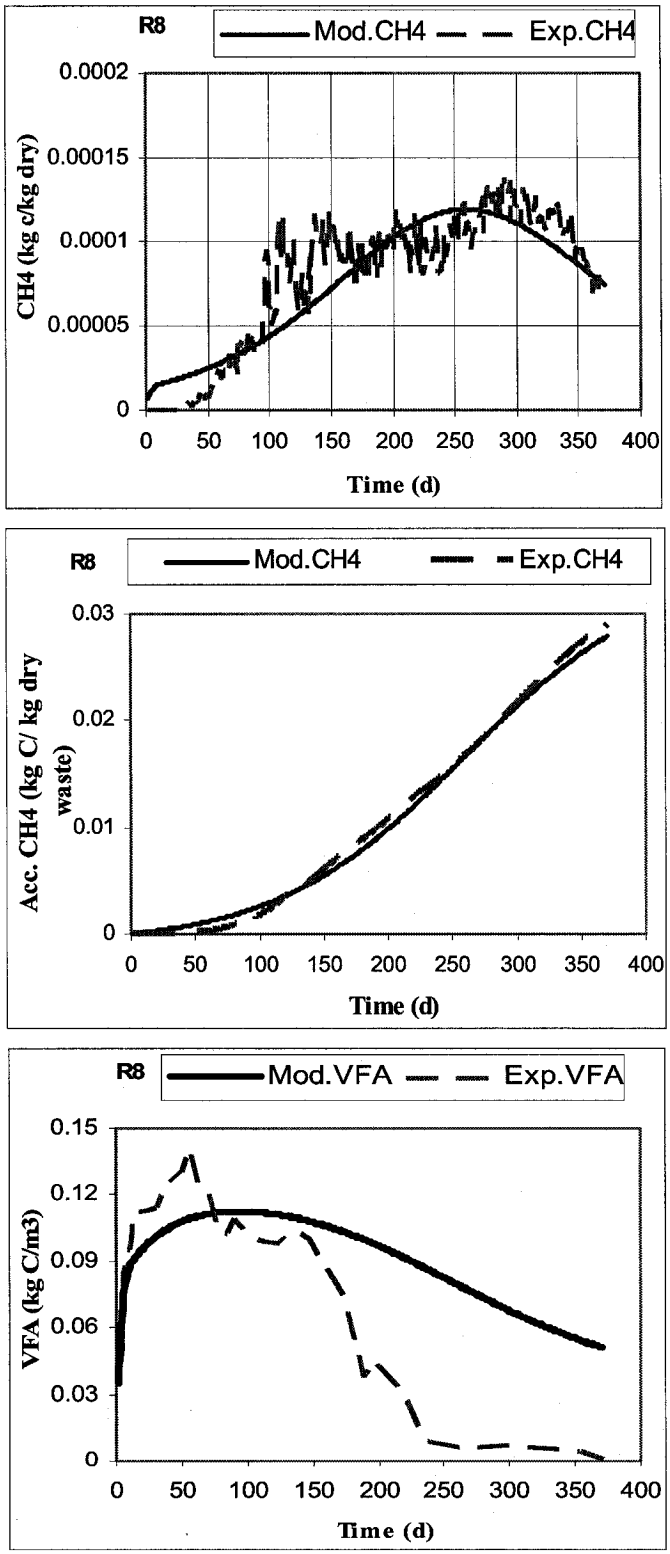


Figure 5.34: Model calibration second scenario.

Also, there was a better match between the predicted and measured peak VFA concentrations and time to reach this peak compared to the first scenario.

Table 5.35: Parameters used in the model calibration of the second scenario

Parameter	Unit	Applied values			
Hydrolysis					
I	(w/v)	0%	0.5%	1%	3%
k_h	d^{-1}	0.043	0.036	0.033	0.023
K_I	(w/v)	6			
m		2			
Acidogenesis					
Growth rate, μ_A	d^{-1}	5			
Half saturation constant, K_{SA}	kg m^{-3}	0.3			
Rate of decay, k_{dA}	d^{-1}	0.04			
Yield, Y_A	kg kg^{-1}	0.15			
		First group		Second group	
Methanogenesis					
Growth rate, μ_M	d^{-1}	0.13		0.22	
Half saturation constant, K_{SM}	kg m^{-3}	0.73		0.53	
Rate of decay, k_{dM}	day^{-1}	0.011		0.02	
Yield, Y_M	kg kg^{-1}	0.08		0.16	
Methane fraction yield, Y_{CH4}	kg kg^{-1}	0.41		0.43	
VFA formation yield, Y_{HAC}	kg kg^{-1}	0.9		0.9	
Initial conditions					
$C_{(s)}$	Kg C m^{-3}	0.04		0.04	
$C_{(aq)}$	Kg C m^{-3}	0.05		0.05	
$C_{(VFA)}$	Kg C m^{-3}	0.03		0.03	
$C_{(XA)}$	Kg C m^{-3}	0.0009		0.0009	
$C_{(XM)}$	Kg C m^{-3}	0.0009		0.00025	

5.3.3 Third scenario

In this scenario, the model simulates two different hydrolysis rate constants (readily and slowly) to match the two peaks of daily methane production observed in the experimental results. Based on the best matches between the predictive and measured results, the fraction of readily and slowly biodegradable matter was set to be 50% (w/w).

The best fits of the calibrated model to the experimental results are shown in Figures 5.35 through 5.38, and Tables 5.36 summarizes the value of the parameters and inhibition constants (K_I and m) used to get the best fit in this scenario. The parameters of methanogenic biomass were adjusted to achieve this fit.

CH_4: Improves the estimated time to reach the peak methane production. There was an improvement in the results of daily methane production. Simulation results of daily methane production showed two peaks. These peaks are clearer in R5 through R8. The value of peaks decreased with increasing the salt contents whereas, the time required to reach these peaks increased. These observations agreed with conclusions drawn from the experimental results (1D bioreactors and BMP assays).

VFA: The model exhibited lower VFA concentrations than those measured in all bioreactors. This may be attributed to the VFA that was produced from the readily biodegradable fraction which occurred in the early times and was consumed by the methanogenic biomass to produce the first peak of daily methane production, whereas the VFA produced from the slowly biodegradable fraction took a longer time to reach its peak.

The values of inhibition constants (K_I and m) used to get the best fit of calibrated model to the experimental results in all scenarios were 6% (w/v) and 2, respectively as presented in Tables 5.34 through 5.36.

In spite of the above comments, the match of model prediction to the laboratory experimental data indicates that the model was useful when employed to simulate the total methane production from lab scale bioreactors operating under saline conditions. Although the model shows good performance of a lab scale bioreactor, its application to actual bioreactor landfills needs modification to include the effect of waste composition fluctuation and weather conditions on gas production.

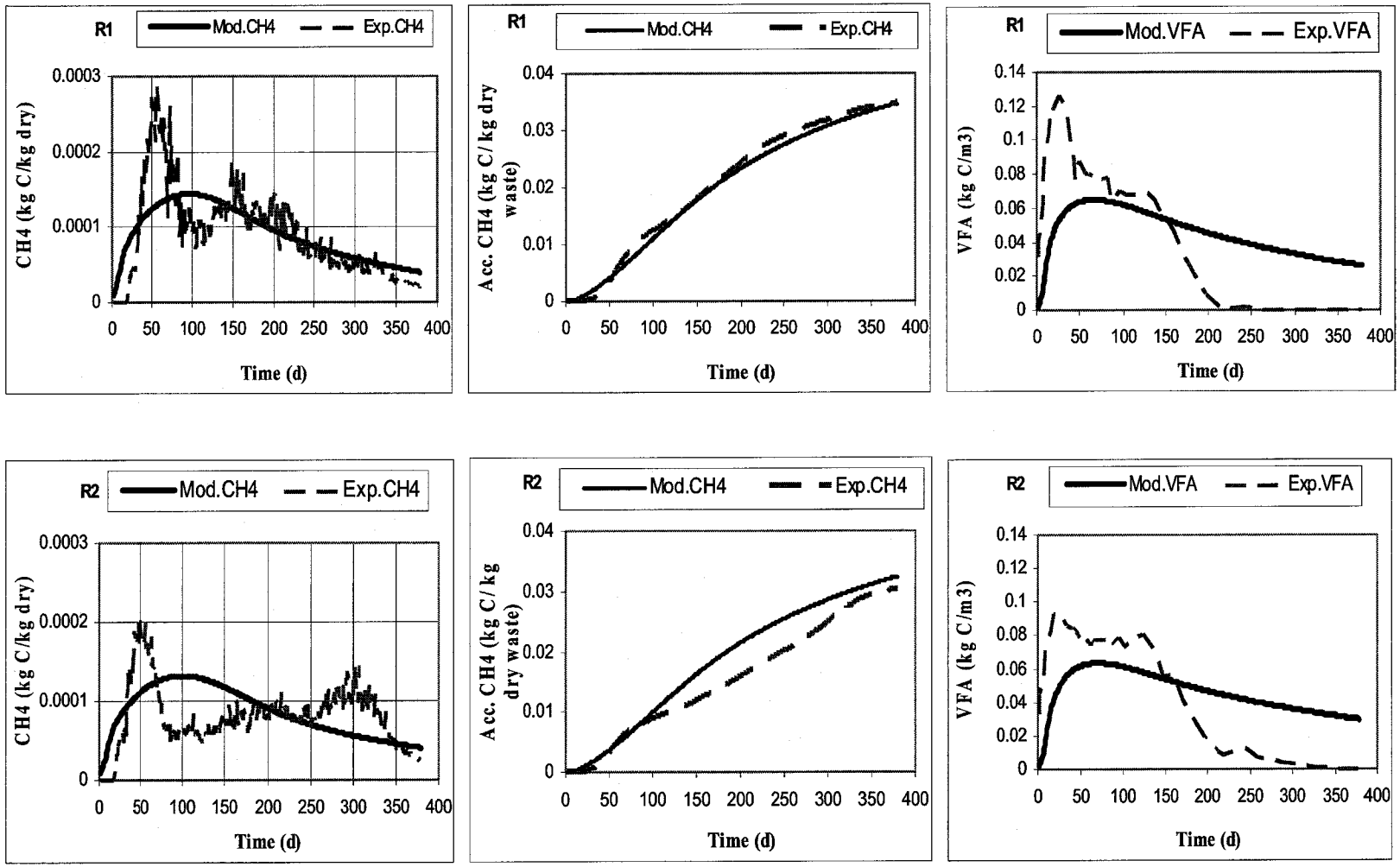


Figure 5.35: Model calibration third scenario.

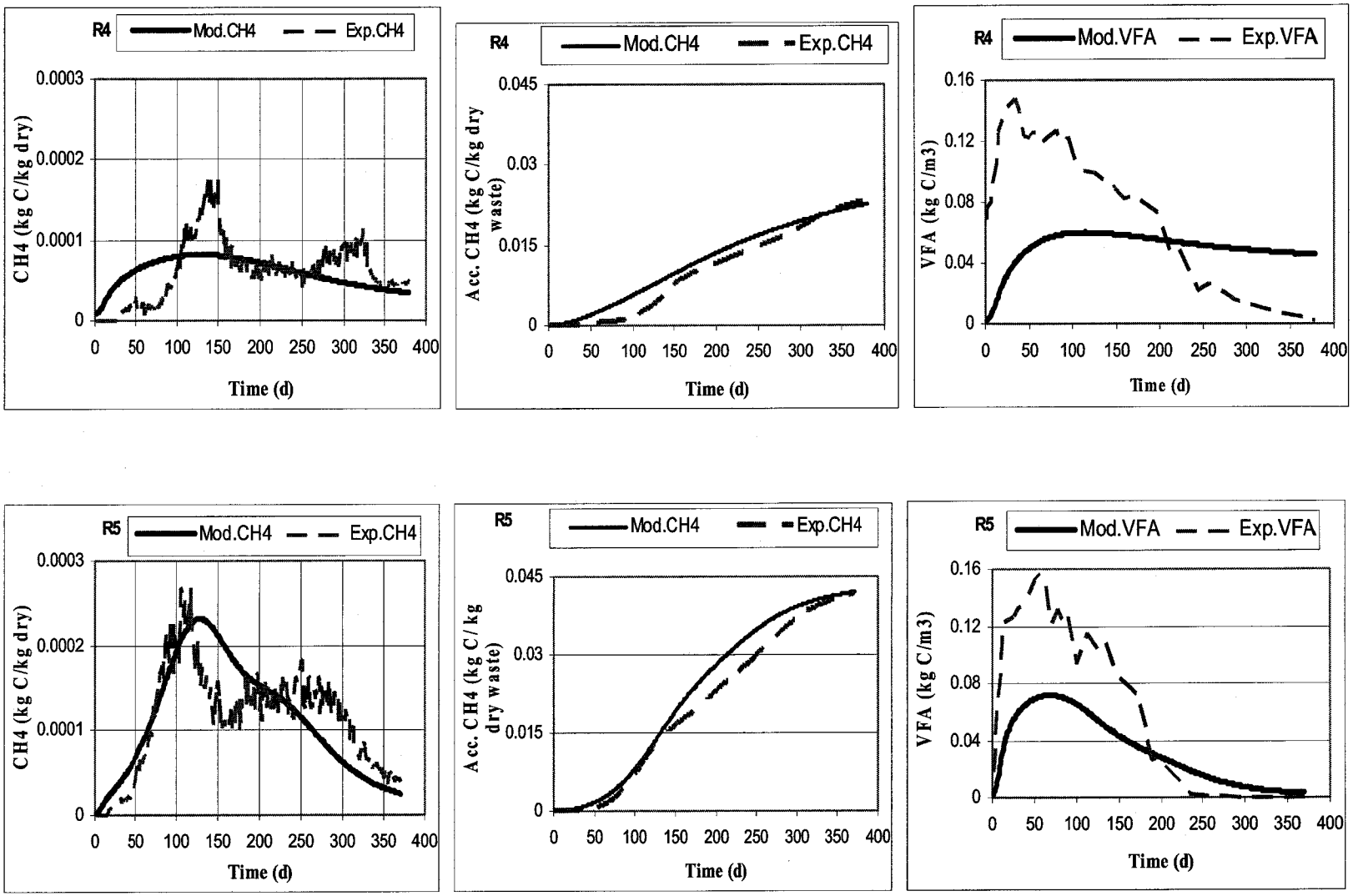


Figure 5.36: Model calibration third scenario.

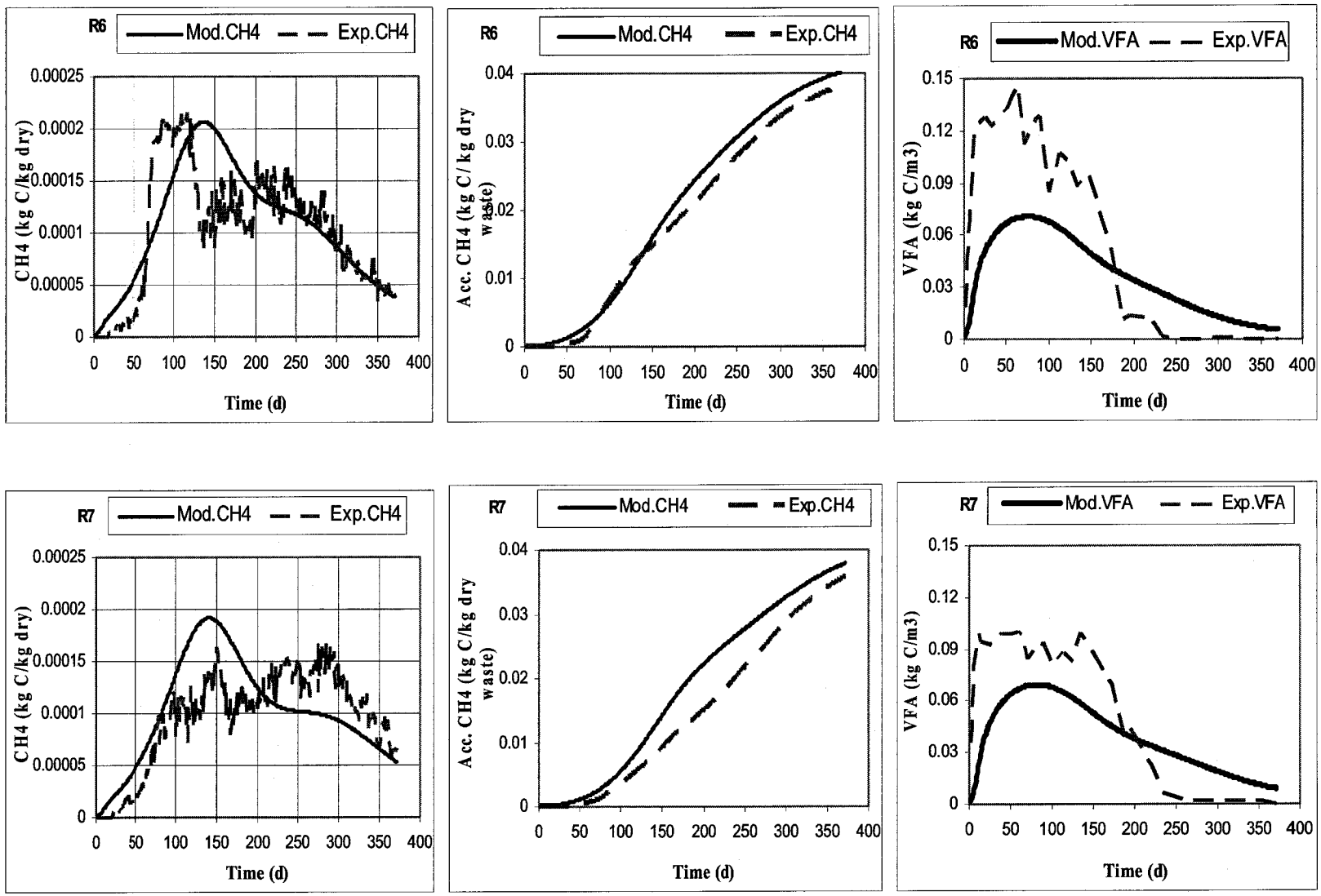


Figure 5.37: Model calibration third scenario.

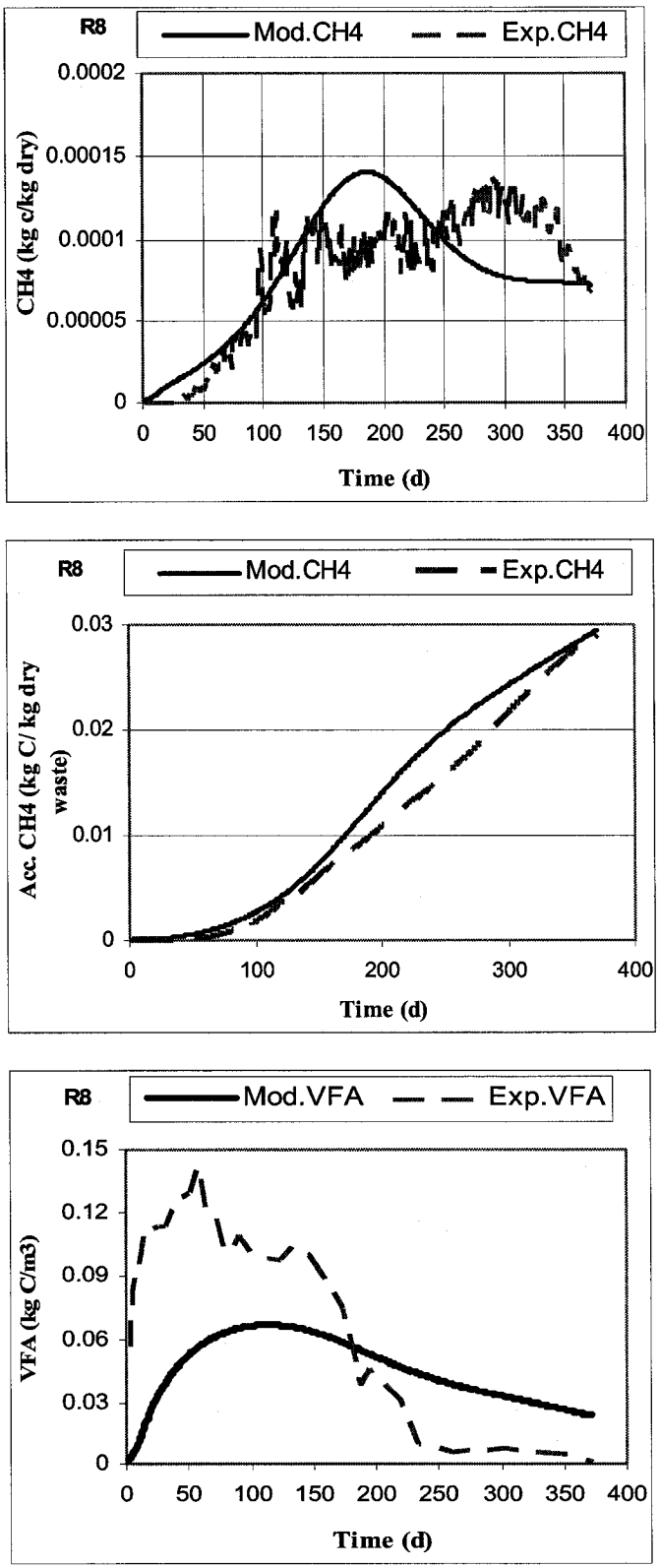


Figure 5.38: Model calibration third scenario.

Table 5.36: Parameters used in the model calibration of the third scenario

Parameter	Unit	Applied values			
Hydrolysis					
I	(w/v)	0%	0.5%	1%	3%
k_h (Readily)	d^{-1}	0.08	0.07	0.06	0.033
k_h (Slowly)	d^{-1}	0.008	0.007	0.006	0.0044
K_I	(w/v)	6			
m		2			
Acidogenesis					
Growth rate, μ_A	d^{-1}	5			
Half saturation constant, K_{SA}	kg m^{-3}	0.3			
Rate of decay, k_{dA}	d^{-1}	0.04			
Yield, Y_A	kg kg^{-1}	0.15			
		First group		Second group	
Methanogenesis					
Growth rate, μ_M	d^{-1}	0.15		0.18	
Half saturation constant, K_{SM}	kg m^{-3}	0.34		0.22	
Rate of decay, k_{dM}	day^{-1}	0.01		0.007	
Yield, Y_M	kg kg^{-1}	0.08		0.15	
Methane fraction yield, Y_{CH4}	kg kg^{-1}	0.41		0.43	
VFA formation yield, Y_{HAC}	kg kg^{-1}	0.9		0.9	
Initial conditions					
$\mathbf{C_{(s)}}$	Kg C m^{-3}	0.12		0.12	
$\mathbf{C_{(aq)}}$	Kg C m^{-3}	0.0009		0.0009	
$\mathbf{C_{(VFA)}}$	Kg C m^{-3}	0.0009		0.0009	
$\mathbf{C_{(XA)}}$	Kg C m^{-3}	0.0009		0.0009	
$\mathbf{C_{(XM)}}$	Kg C m^{-3}	0.0009		0.00025	

Chapter 6

Conclusions and recommendations

6.1 Summary

Bioreactor landfills offer great advantages in the biodegradation of MSW. They can be an excellent alternative to the traditional sanitary landfill method presently used in arid and semi-arid regions. However, they require an optimum amount of moisture to initiate the biodegradation process, which is problematic in arid regions where fresh water supplies are scarce. A solution to this problem could be to use brackish water in bioreactor landfills. This study therefore aimed to determine the effect of salinity on the biodegradation of municipal solid waste under different operational conditions, and to enhance the performance of bioreactor landfills operating under saline conditions by sludge addition. In doing so, this study also undertook to develop a mathematical model to simulate the long term performance of these bioreactor landfills and to estimate the hydrolysis rate constant of MSW at different salt contents.

Two types of experiments were used to accomplish the aims of this study. The first type consisted of 1D bioreactors. These bioreactors were divided into two groups. The first group (R1 through R4) was designed to study the impact of salinity on the biodegradation of MSW under different operational conditions (0, 0.5, 1, and 3%) (w/v). The second group (R5 through R8) was aimed at studying the effect of sludge addition on the performance of bioreactor landfills operating at different salt contents (0, 0.5, 1, and 3%) (w/v). The second type of experiments was the BMP assays which were conducted to estimate the anaerobic hydrolysis rate constant of the biodegradation process.

A mathematical model was developed to predict the leachate strength (aqueous organic and VFA) and the volume of landfill gas (CH_4 and CO_2) produced.

The model described the biodegradation in three steps: hydrolysis, acidogenesis, and methanogenesis. The hydrolysis is the rate limiting step in the solid waste biodegradation process and is assumed to follow first order kinetics with respect to solid organic concentration. Monod kinetics were used to simulate the growth rate of the acidogenic and methanogenic biomasses. An inhibition term to simulate the effect of saline environment was included in the Monod kinetics which in turn was used to simulate the methanogenic biomass. The acidogenic kinetics (μ_A, k_{dA}, and K_{SA}) had no significant effect on the VFA concentration and methane production, as suggested by the results of the sensitivity analysis.

The output from the model was concentration of solid carbon, aqueous acids, VFA, acidogenic and methanogenic biomasses, daily CH_4 and CO_2, accumulation of CH_4 and CO_2, and total biogases produced over time. All concentrations were expressed in terms of mass of carbon per unit volume.

A sensitivity analysis was performed to asses the significance of change (hydrolysis rate constant, biomass kinetics and initial conditions) on the C_{aq}, C_{VFA}, C_{XA}, C_{XM}, and CH_4. The sensitivity analysis indicates that the hydrolysis rate constant, methanogenic parameters (μ_M, k_{dM}, K_{SM}), and initial concentration of methanogenic biomass had a significant impact on peaks of the VFA and daily methane produced, as well as the time required to reach them.

Experimental data obtained from 1D bioreactors and BMP assays were applied in the model calibration. The purpose of model calibration was to estimate the kinetics (μ, k_d, and K_S) of biomass, and the inhibition constants (K_I and m). These were utilized in two steps. In the first step, results of 1D bioreactors operated without salt content were used to estimate the kinetics (μ, k_d, and K_S) of biomass. In the second step, the results of 1D bioreactors operated under different salt contents (0.5, 1, and 3%) (w/v) were used to estimate the inhibition constants (K_I and m).

The results of this study revealed that saline water up to 1-2 % (w/v) concentration could be used to bring the moisture content up to optimum levels in the biodegradation of MSW. Sludge addition had several advantages in the enhancement of bioreactor landfill performance operated under saline conditions. This could serve as a starting point for further research and investigation in the use of sludge as an enhancement method for MSW biodegradation in saline environments.

6.2 Conclusions

Based on the analysis of 1D bioreactor results, the following conclusions can be drawn:

- The average settlement in the aerobic stage was greater than in the anaerobic stage. The total settlements were higher in bioreactors operated with sludge addition and it decreased with increasing the salt content. This emphasizes that sludge addition enhances the biodegradation in terms of settlement. Statistically, there were significant differences in the mean settlements at 1% and 3%, compared to the mean of settlement at 0% (w/v) salt contents. This indicates that high salt contents inhibited the biodegradation of MSW, as suggested by the results of settlement.

- The results of biogas showed the highest methane production was recorded in R5, bioreactor with sludge addition and 0% (w/v) salt content, and it decreased by increasing the salt content in all bioreactors. The increase in salt content causes a reduction in the volume of total and daily methane productions and methane yield; and an increase in the lag time, the time to reach the peak of daily methane production and the stabilization time. Bioreactors in group two, which operated with sludge addition, showed a higher methane yield and total methane production than in group one, which operated without sludge addition. In other words, addition of anaerobic digested sludge enhanced the biodegradation of MSW operated at different salt conditions. Statistically, there were significant differences in the mean daily methane production, methane concentration and methane yield 1) between the two groups, 2) in all bioreactors, and 3) at different salt contents (0, 0.5, 1 and 3%) (w/v).
- Results from the BMP assays were consistent with the results from the 1D bioreactors. The increase in salt concentration caused an increase in the lag phase of methane production, and a decrease in the daily volume of methane production. Using acclimatized anaerobic digested sludge as an inoculum in BMP assays, causes a reduction in the lag time of methane production at different salt contents. Statistically speaking, no significant difference was observed when using the two types of inoculums salt acclimatized anaerobic digested sludge vs. the normal anaerobic digested sludge, in BMP assays.
- The results of leachate quality showed the percentage peak reduction in all leachate parameters (COD, BOD, VFA, NH_3-N, TVS and TS) decreased with increasing the salt contents. In other words, salt inhibited the biodegradation of MSW. The highest

COD, BOD, VFA, NH_3-N, TVS and TS percentage peak reductions were observed in R5 (0%), and the lowest in R4 (3%). Bioreactors operated with sludge addition (group two) showed a higher percentage peak reduction in all leachate parameters in both the aerobic and anaerobic stages compared with bioreactors of group one. That meant that the addition of sludge improved the performance of bioreactors operated under different saline conditions. Statistically, there was a significant difference between the mean of COD, BOD, VFA, TVS, and TS percentage peak reductions at different salt contents during the aerobic stage. The difference was at 3% compared to 0% (w/v) salt content. Also, a significant difference was observed in the mean of COD, BOD, TVS, and TS percentage peak reductions at different salt contents during the anaerobic stage. The difference was at 3% compared to 0% (w/v) salt content in the COD and BOD, whereas the difference was for 1% and 3% in the TVS and TS. This indicates that the high salt contents inhibited the MSW biodegradation.

- From the results of settlement, the landfill biogas quality and quantity, and leachate quality, it can be concluded that saline water inhibited the MSW biodegradation and that the enhancement of MSW biodegradation occurred with sludge addition.
- The hydrolysis rate constant was 0.043, 0.036, 0.029, and 0.023 d^{-1} for 0, 1, 2, and 3 % (w/v) salt content, respectively, at 23°C.

There were other important findings from the 1D bioreactor experiments:

- There was no statistical difference in the moisture content along the vertical profile of bioreactors.
- There was no statistical difference in the temperature among the bioreactors.

- There was no significant difference in the concentration along the vertical profile of bioreactors.
- Shortcircuiting was observed in the bioreactors and the fraction of shortcircuiting based on the assumption of a completely mixed system was in the range of 0.16 to 0.32.

Based on the sensitivity analysis and model calibration, the following points should be highlighted:

- The model results were highly sensitive to the hydrolysis rate constant followed by kinetics (μ, k_d, and K_S) and initial condition of methanogenic biomass.
- No significant impact was observed when changing the acidogenic biomass parameters on the peak VFA and daily methane production. There was only a variation in the time to reach the peaks.
- The initial concentration of the methanogenic biomass had a greater impact on the methane production than other initial concentrations (C_{aq}, C_{VFA}, and C_{XA}).
- The model showed good agreement with the results of methane production from the 1D bioreactors.
- The developed model able to predict the two peaks of daily methane production and simulate the effect of salt on the value of these peaks, as well as the time to reach them. The model has the potential to simulate the effect of salt on MSW biodegradation.
- The value of the inhibition constants K_I and m were 6% (w/v) and 2, respectively.

If designers of bioreactor landfills plan to use saline water to increase the moisture content to optimum levels in the biodegradation of MSW, they should expect the time for waste stabilization to increase and the methane yield to decrease. The lab-scale bioreactors used in this study indicated a 33% reduction in the volume of methane produced when the salt concentration was increased to 3% (w/v) without sludge (R4). The reduction was 13% in the volume of total methane produced when the salt concentration was raised to 3% (w/v) with sludge addition (R8).

6.3 Recommendations

Based on the experience gained with experiments from this study, several recommendations are suggested to improve the performance of bioreactor landfills operating under saline conditions.

- Use sea sediment as potential enhancement method because it contains biomass which is already acclimatized to salt conditions.
- Sludge addition improved the biodegradation of MSW. The leachate produced from bioreactors (in the methanogenic stage) operated with salt addition could be added to fresh MSW as a source of acclimatized biomass. This may reduce the lag phase for methane production and increase the daily methane production. In other words, it may enhance the MSW biodegradation in the presence of salt media.
- Study the effect of saline water on the heavy metal concentrations in the leachate.
- Estimate the hydrolysis rate constant for individual waste fraction (paper, textile, food, etc.) at different salt contents.

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Appendix A: Results of experimental works

1. Solid waste

1.1 Moisture content

➢ Initial moisture content

Reactors	Plate (g)	Plate +sample	M(105°C) (g)	% Moisture content
R1	26.905	32.587	30.37	39.02%
R2	26.561	32.12	29.89548	40.02%
R3	29.731	32.852	31.72527	36.10%
R4	26.65	32.832	30.11192	44.00%
R5	26.937	34.329	31.22343	42.01%
R6	28.929	40.563	35.69412	41.85%
R7	26.6131	44.249	36.66556	43.00%
R8	29.696	50.4968	41.93467	41.16%

➢ Final moisture content

R1	Plate (g)	Plate +sample (g)	M(105°C) (g)	% Moisture content
R1-1-1	58.9212	102.0802	75.275	62.11%
R1-1-2	58.8459	98.7225	76.909	54.70%
R1-1-3	60.2342	100.7861	76.003	61.11%
R1-2-1	59.955	107.2716	78.939	59.88%
R1-2-2	66.716	109.3606	85.228	56.59%
R1-2-3	56.6513	100.768	71.839	65.57%
R1-3-1	58.279	99.2207	70.812	69.39%
R1-3-2	61.748	108.5869	77.591	66.18%
R1-3-3	61.8319	101.8786	75.133	66.79%

R2	Plate (g)	Plate +sample (g)	M(105°C) (g)	% Moisture content
R2-1-1	62.354	122.8582	82.253	67.11%
R2-1-2	57.1088	115.1513	85.191	51.62%
R2-1-3	61.2062	109.2186	83.023	54.56%
R2-2-1	55.8064	99.7867	73.363	60.08%
R2-2-2	55.876	108.8835	75.705	62.59%
R2-2-3	62.2299	116.827	80.605	66.34%
R2-3-1	59.47	102.137	73.427	67.29%
R2-3-2	58.6815	103.4571	76.294	60.66%
R2-3-3	65.3155	107.1807	80.611	63.46%

R3	Plate (g)	Plate +sample (g)	M(105°C) (g)	% Moisture content
R3-1-1	57.116	105.9366	75.017	63.33%
R3-1-2	62.92	107.4989	82.673	55.69%
R3-1-3	58.9381	117.308	80.344	63.33%
R3-2-1	60.3574	108.4138	77.17	65.01%
R3-2-2	57.0083	106.5306	75.34	62.98%
R3-2-3	59.2551	103.297	74.58	65.20%
R3-3-1	66.9	132.5614	90.4793	64.09%
R3-3-2	56.2571	108.0442	73.304	67.08%
R3-3-3	58.7662	104.928	74.463	66.00%

R4	Plate (g)	Plate +sample (g)	M(105°C) (g)	% Moisture content
R4-1-1	58.4782	104.589	75.017	64.13%
R4-1-2	59.201	105.257	82.673	49.04%
R4-1-3	59.912	108.327	80.344	57.80%
R4-2-1	61.3245	104.31	80.5793	55.21%
R4-2-2	57.536	104.982	73.804	65.71%
R4-2-3	59.216	104.4846	75.063	64.99%
R4-3-1	56.475	101.149	77.07	53.90%
R4-3-2	57.6471	108.559	75.14	65.64%
R4-3-3	57.093	112.209	74.28	68.82%

R5	Plate (g)	Plate +sample (g)	M(105°C) (g)	% Moisture content
R5-1-1	59.953	107.186	79.564	58.48%
R5-1-2	66.713	106.829	81.9029	62.14%
R5-1-3	56.645	101.673	74.203	61.01%
R5-2-1	58.845	107.724	76.671	63.53%
R5-2-2	58.915	108.309	76.376	64.65%
R5-2-3	60.232	113.926	81.186	60.98%
R5-3-1	58.274	103.305	75.1722	62.47%
R5-3-2	61.7478	114.951	80.0556	65.59%
R5-3-3	61.828	107.286	78.3335	63.69%

R6	Plate (g)	Plate +sample (g)	M(105°C) (g)	% Moisture content
R6-1-1	62.354	108.321	80.2733	61.02%
R6-1-2	57.095	106.451	75.099	63.52%
R6-1-3	61.206	113.041	81.213	61.40%
R6-2-1	55.808	105.095	74.888	61.29%
R6-2-2	55.801	103.21	72.883	63.97%
R6-2-3	62.225	112.548	80.6839	63.32%
R6-3-1	59.471	104.106	75.826	63.36%
R6-3-2	58.681	107.233	76.2055	63.91%
R6-3-3	65.313	115.4	83.4774	63.73%

R7	Plate (g)	Plate +sample (g)	M(105°C) (g)	% Moisture content
R7-1-1	57.107	101.269	74.5835	60.43%
R7-1-2	62.918	110.093	80.719	62.27%
R7-1-3	58.935	104.667	76.278	62.08%
R7-2-1	66.897	119.766	87.448	61.13%
R7-2-2	56.255	101.877	72.4306	64.54%
R7-2-3	58.756	115.224	79.527	63.22%
R7-3-1	61.498	120.77	83.851	62.29%
R7-3-2	56.999	104.4334	74.782	62.51%
R7-3-3	59.243	107.5171	74.6901	68.00%

R8	Plate (g)	Plate +sample (g)	M(105°C) (g)	% Moisture content
R8-1-1	58.471	108.892	75.191	66.84%
R8-1-2	59.196	108.862	80.052	58.01%
R8-1-3	59.891	108.909	77.392	64.30%
R8-2-1	61.3211	132.37	87.559	63.07%
R8-2-2	57.467	114.009	76.519	66.30%
R8-2-3	59.21	123.239	82.829	63.11%
R8-3-1	56.464	110.791	76.129	63.80%
R8-3-2	57.635	110.887	74.332	68.65%
R8-3-3	57.076	115.806	75.823	68.08%

1.2 Temperature profile

Time (d)	R1 (°C)			R2 (°C)		
Time	T(bottom)	T(mid)	T(top)	T(bottom)	T(mid)	T(top)
3	26	26.2	28.3	25.3	25.5	26.3
4	24.2	25	25.6	24.2	24.9	24.8
5	24.9	25.2	26.6	24.5	24.9	25.7
6	24.3	24.7	25.6	24.1	24.5	25.6
10	25.0	28.0	33.7	24.6	27.4	29.0
11	27.7	38.2	34.5	26.4	30.1	29.4
14	24.6	26.4	22.0	24.0	25.6	22.0
15	25.5	26.9	23.5	24.8	26.4	25.6
17	24.1	26.4	22.5	24.3	25.8	25.5
22	24.3	24.6	24.3	24.3	24.5	24.5
28	24.2	24.2	24.2	24.1	24.5	24.5
31	23.8	24.1	24.0	23.8	24.2	24.1
32	24.3	24.5	24.4	24.1	24.4	24.4

	R3 (°C)			R4 (°C)		
Time	T(bottom)	T(mid)	T(top)	T(bottom)	T(mid)	T(top)
3	26.4	27.1	26.4	24.1	24.4	24.2
4	24.2	25.2	25.3	24.0	24.0	24.2
5	25.2	26.3	25.3	23.4	23.5	23.3
6	23.9	24.6	24.8	24	24.2	23.9
10	25.5	28.5	27.9	24	32.3	24.4
11	26.1	30.8	27.5	27.4	30.9	29.9
14	24.2	26.8	26.5	24.9	25.2	26.1
15	25.7	26.7	23.8	25.2	25.1	22
17	24.1	27.1	22.5	24.5	26.6	23.8
22	24.4	24.7	24.8	24.3	24.5	24.9
28	24.2	24.4	24.5	24.1	24.4	24.6
31	23.8	23.9	24.1	23.9	24.1	24.1
32	24.1	24.4	24.4	24.0	23.8	24.3

	R5 (°C)			R6 (°C)		
Time	T(bottom)	T(mid)	T(top)	T(bottom)	T(mid)	T(top)
3	26.4	25.2	26.2	25.7	25.2	25.3
4	24.4	27.6	24.2	24.4	24.2	24.6
7	27.8	32.6	28.0	27.9	32.2	27.9
10	24.5	24.2	24.0	24.2	24.9	24.5
11	25.5	24.4	25.1	25.1	24.7	25
14	20.3	25.5	23.4	21.3	24.4	21
15	20.0	24.0	22.7	21	23.5	20.6
17	20.8	22.8	25.5	24.4	24.5	25.9
19	24.1	23.9	23.8	23.1	23.6	23.6
22	23.8	23.8	23.6	23	23.4	23.3
23	23.4	23.3	23.8	23.2	23.3	23.3
25	23.3	23.2	23.1	23.1	23.6	23.6
26	23.8	23.6	23.8	23.1	23.6	23.6

	R7 (°C)			R8 (°C)		
Time	T(bottom)	T(mid)	T(top)	T(bottom)	T(mid)	T(top)
3	22.6	23.9	24.5	23.4	23.7	25.0
4	24.1	25.5	27.5	24.2	25.9	24.7
7	23.8	25.1	25.8	24.1	25.6	24.7
10	23.9	24.5	24.6	24.4	25.2	24.1
11	23.0	27.3	22.6	24.5	26.4	24.6
14	27.3	33.4	23.6	25.7	32.5	27.8
15	24.5	29.0	25.1	26.4	29.4	26.5
17	20.7	23.1	21.6	24.6	26.2	24.3
19	22.6	23.5	24.2	24.0	26.4	25.1
22	24.1	24.0	26.1	24.2	24.8	24.7
23	23.9	24.1	24.1	23.9	23.8	25.4
25	23.0	23.6	23.8	23.1	23.6	23.4
26	22.6	22.9	23.1	22.6	23.0	23.0

1.3 Settlement

Reactors	Aerobic stage (cm)				Anaerobic stage (cm)					
R1	20.50	22.00	21.20	21.80	13.73	16.83	14.63	13.03	10.93	13.63
R2	23.00	18.50	19.80	22.60	11.72	13.42	13.72	12.72	11.72	14.46
R3	18.30	18.30	18.70	16.30	13.43	17.33	9.43	13.63	10.63	9.03
R4	16.00	17.00	15.00	15.30	10.38	9.47	7.58	10.48	8.38	9.26
R5	22.30	22.00	22.00	21.60	17.53	19.13	21.23	18.83	19.23	19.19
R6	21.00	20.30	20.10	21.50	19.18	17.38	17.68	16.98	19.48	18.14
R7	17.25	18.65	18.25	18.45	16.60	15.60	17.90	15.40	16.38	16.38
R8	16.70	15.80	15.40	16.40	15.06	13.26	14.46	15.46	16.56	14.96

2. Landfill gas

2.1 Methane production

➢ Group one

	Daily methane production (ml)			Accumulative methane (ml)		
Time	**R1**	**R2**	**R4**	**R1**	**R2**	**R4**
18	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00
20	792.79	936.12	0.00	792.79	936.12	0.00
21	701.93	817.61	0.00	1494.72	1753.73	0.00
22	1158.70	1348.58	0.00	2653.42	3102.31	0.00
23	1227.07	1315.06	0.00	3880.49	4417.37	0.00
24	1509.20	1745.73	0.00	5389.69	6163.10	0.00
25	1575.42	2063.94	0.00	6965.11	8227.04	0.00
26	1736.03	2479.68	0.00	8701.14	10706.72	0.00
27	1752.60	2531.34	0.00	10453.74	13238.06	0.00
28	1915.91	2736.85	0.00	12369.65	15974.91	0.00
29	1718.64	2477.41	0.00	14088.29	18452.32	0.00
30	2571.03	1970.64	0.00	16659.32	20422.96	0.00
31	2772.00	2532.60	0.00	19431.32	22955.56	0.00
32	2721.18	2737.10	0.00	22152.50	25692.66	0.00
33	3431.71	2157.06	0.00	25584.20	27849.72	0.00
34	4889.90	3992.36	524.05	30474.11	31842.08	524.05
35	3662.85	4842.12	326.34	34136.96	36684.20	850.39
36	5448.52	5422.21	364.38	39585.48	42106.42	1214.77
37	6115.34	6143.76	420.20	45700.82	48250.18	1634.97
38	4422.61	5114.59	436.23	50123.43	53364.76	2071.20
39	6905.93	5556.84	615.38	57029.36	58921.60	2686.58
40	6819.17	5740.09	647.91	63848.52	64661.69	3334.50
41	5285.03	5400.79	423.24	69133.56	70062.48	3757.74
42	6655.57	7098.76	651.20	75789.13	77161.25	4408.94
43	8057.28	7860.43	828.80	83846.41	85021.68	5237.74
44	7145.60	7505.91	626.93	90992.01	92527.60	5864.67
45	7946.15	7750.66	874.27	98938.16	100278.26	6738.94
46	9038.75	7351.85	978.27	107976.92	107630.11	7717.20
47	8290.59	8320.16	841.66	116267.51	115950.27	8558.86
48	8631.86	8380.89	847.64	124899.37	124331.16	9406.50
49	8244.78	7210.73	997.22	133144.15	131541.88	10403.73
50	9444.73	**8444.14**	880.88	142588.88	139986.03	11284.61
51	10560.77	8293.53	951.94	153149.64	148279.56	12236.54
52	11282.35	7462.73	1217.12	164431.99	155742.29	13453.66
53	10482.04	7430.94	632.90	174914.03	163173.23	14086.56
54	10132.69	7361.52	797.69	185046.72	170534.75	14884.25
55	9903.43	7087.06	767.01	194950.16	177621.81	15651.26
56	8838.52	7219.95	612.56	203788.68	184841.76	16263.82
57	11599.60	8400.67	852.75	215388.27	193242.43	17116.57
58	**11973.19**	7002.00	672.64	227361.47	200244.43	17789.21

59	11679.11	7172.78	623.42	239040.58	207417.21	18412.63
60	10739.28	7272.97	882.23	249779.86	214690.18	19294.86
61	10165.76	6519.05	721.50	259945.62	221209.23	20016.36
62	9362.15	6407.10	298.37	269307.77	227616.33	20314.72
63	10514.70	6770.23	417.36	279822.47	234386.56	20732.08
64	10505.65	7584.57	886.48	290328.12	241971.13	21618.57
65	8711.53	6015.67	523.03	299039.65	247986.80	22141.60
66	10172.50	6542.05	500.83	309212.15	254528.85	22642.43
67	9398.60	5950.58	772.75	318610.75	260479.43	23415.18
68	8332.75	5843.12	520.08	326943.50	266322.55	23935.26
69	8484.12	6125.56	746.54	335427.62	272448.11	24681.80
70	7709.16	5088.28	632.65	343136.79	277536.39	25314.45
71	4618.41	4925.39	712.91	347755.20	282461.78	26027.36
72	9389.74	5516.85	753.78	357144.94	287978.63	26781.14
73	8841.49	4505.57	625.15	365986.42	292484.20	27406.29
74	10836.61	4082.06	493.09	376823.04	296566.26	27899.38
75	6534.91	4094.43	784.27	383357.94	300660.69	28683.65
76	8663.19	4082.65	890.45	392021.13	304743.35	29574.10
77	7598.36	3400.37	569.32	399619.49	308143.72	30143.42
78	7621.04	3486.04	658.64	407240.53	311629.76	30802.06
79	5668.62	3047.39	671.02	412909.15	314677.15	31473.07
80	5822.92	2700.32	604.04	418732.07	317377.46	32077.11
81	5278.93	2894.29	883.74	424011.00	320271.75	32960.85
82	6297.11	2602.76	766.04	430308.10	322874.51	33726.90
83	8354.98	2947.97	1111.81	438663.09	325822.48	34838.71
84	7096.01	2717.21	1151.86	445759.10	328539.69	35990.56
85	5804.98	3123.40	993.84	451564.08	331663.10	36984.40
86	3655.59	3111.04	1252.46	455219.67	334774.14	38236.86
87	5496.13	**2060.12**	970.51	460715.79	336834.26	39207.37
88	3075.94	2214.93	1183.30	463791.73	339049.19	40390.68
89	4419.69	2790.49	1754.26	468211.42	341839.68	42144.94
90	5075.07	2718.58	1857.96	473286.49	344558.26	44002.89
91	4039.63	2398.14	1660.88	477326.12	346956.40	45663.77
92	5151.81	2590.54	1791.08	482477.93	349546.94	47454.85
93	3578.29	2159.81	1642.49	486056.23	351706.75	49097.34
94	4289.75	2236.72	1641.04	490345.98	353943.47	50738.38
95	3987.54	2176.37	1736.10	494333.51	356119.84	52474.48
96	4446.33	2450.16	1910.09	498779.85	358570.00	54384.57
97	4164.76	2779.94	1908.31	502944.61	361349.94	56292.88
98	5248.47	2664.33	2227.58	508193.08	364014.28	58520.46
99	4263.15	2371.37	2056.61	512456.23	366385.65	60577.06
100	4504.96	2528.66	2355.65	516961.20	368914.31	62932.71
101	3862.94	2539.00	2477.78	520824.14	371453.31	65410.49
102	3889.53	2525.03	2630.93	524713.67	373978.34	68041.42
103	4509.94	2726.29	3306.14	529223.61	376704.63	71347.56
104	3376.01	2423.09	2889.00	532599.62	379127.72	74236.55
105	2943.86	2427.10	2622.41	535543.49	381554.82	76858.96
106	3163.91	2451.71	3160.40	538707.40	384006.53	80019.36
107	4175.71	2589.95	3766.97	542883.11	386596.48	83786.34
108	4260.26	2864.82	4184.34	547143.37	389461.30	87970.68

109	4782.13	2730.55	3763.88	551925.49	392191.85	91734.56
110	4101.53	2345.56	4395.09	556027.03	394537.40	96129.65
111	4131.46	2438.56	4740.91	560158.49	396975.96	100870.56
112	4572.09	2349.23	4520.54	564730.58	399325.20	105391.10
113	4355.79	2602.16	5147.19	569086.36	401927.35	110538.29
114	3234.62	3495.10	4093.29	572320.98	405422.45	114631.58
115	**3156.81**	2440.75	4227.38	575477.79	407863.20	118858.96
116	4673.13	2368.88	4928.36	580150.92	410232.08	123787.32
117	3303.30	2638.37	4279.22	583454.22	412870.45	128066.53
118	3638.71	2566.40	4800.75	587092.93	415436.85	132867.28
119	3621.23	2355.61	3916.67	590714.16	417792.46	136783.96
120	4102.56	2371.81	4232.99	594816.72	420164.26	141016.94
121	4236.85	2293.52	4365.74	599053.57	422457.78	145382.68
122	4288.28	2126.32	4381.11	603341.85	424584.10	149763.80
123	3579.11	2161.08	4155.01	606920.97	426745.18	153918.80
124	3938.70	2084.54	4622.93	610859.67	428829.73	158541.73
125	4090.59	1907.72	4557.88	614950.26	430737.45	163099.61
126	4879.88	2611.82	5371.66	619830.13	433349.27	168471.27
127	4602.14	2407.64	5044.54	624432.27	435756.91	173515.81
128	4881.18	2406.11	5193.51	629313.45	438163.02	178709.32
129	5356.34	2546.99	5809.37	634669.79	440710.01	184518.69
130	4915.68	2489.68	5506.13	639585.47	443199.69	190024.82
131	4729.22	2504.27	5027.80	644314.69	445703.96	195052.62
132	5313.92	2946.39	5609.50	649628.61	448650.35	200662.12
133	4916.60	2201.52	5961.20	654545.21	450851.87	206623.32
134	4926.43	2283.76	5917.29	659471.65	453135.64	212540.61
135	5395.21	2534.05	6490.20	664866.85	455669.69	219030.81
136	5145.53	2306.22	6396.08	670012.38	457975.90	225426.88
137	4413.56	2317.44	5961.38	674425.94	460293.34	231388.26
138	5502.41	2886.58	7204.50	679928.35	463179.92	238592.76
139	5254.74	2510.51	7171.52	685183.09	465690.44	245764.28
140	4727.46	2498.07	6025.20	689910.56	468188.50	251789.48
141	5045.04	2854.50	6951.15	694955.60	471043.01	258740.63
142	5539.97	3064.94	**7435.81**	700495.56	474107.95	266176.44
143	4392.64	2749.92	5925.10	704888.20	476857.87	272101.54
144	5308.04	2911.45	6581.15	710196.25	479769.32	278682.70
145	4981.79	2533.25	6238.93	715178.04	482302.57	284921.63
146	5273.91	2825.27	5781.24	720451.95	485127.84	290702.87
147	6168.01	3097.03	6413.10	726619.96	488224.87	297115.96
148	6497.85	3335.26	6581.23	733117.80	491560.12	303697.19
149	7025.59	3202.91	6893.48	740143.40	494763.03	310590.67
150	**8085.34**	3589.60	7169.92	748228.73	498352.64	317760.60
151	6631.39	3205.98	5661.69	754860.13	501558.62	323422.28
152	6160.92	2858.28	5053.18	761021.05	504416.90	328475.46
153	5945.19	3272.17	5124.45	766966.24	507689.08	333599.91
154	5180.24	2874.95	4396.90	772146.47	510564.03	337996.82
155	5957.96	3119.99	4864.19	778104.43	513684.01	342861.00
156	5600.14	3975.67	4521.30	783704.57	517659.69	347382.30
157	7380.14	3551.59	4610.71	791084.71	521211.27	351993.01
158	7233.95	2713.78	4004.32	798318.66	523925.05	355997.33

159	6117.93	3250.29	3802.92	804436.59	527175.34	359800.25
160	5355.67	2774.31	2965.97	809792.26	529949.65	362766.22
161	5829.34	2788.45	4266.32	815621.60	532738.10	367032.54
162	5129.60	2670.20	3236.64	820751.20	535408.30	370269.18
163	6050.24	3405.61	3427.70	826801.44	538813.91	373696.87
164	7164.25	4220.01	3793.45	833965.69	543033.92	377490.32
165	6006.77	3956.86	3600.89	839972.46	546990.78	381091.21
166	5049.14	3033.81	2690.03	845021.60	550024.60	383781.25
167	4278.93	2914.42	3646.50	849300.53	552939.01	387427.75
168	4791.56	2964.65	3825.00	854092.09	555903.67	391252.75
169	4713.59	3369.69	3092.80	858805.68	559273.36	394345.55
170	3968.59	3607.86	2926.28	862774.27	562881.22	397271.82
171	4411.83	3349.45	2725.16	867186.10	566230.67	399996.99
172	4642.06	3117.52	2958.92	871828.16	569348.19	402955.90
173	3847.89	3701.44	2896.23	875676.04	573049.63	405852.13
174	3904.36	3424.74	3050.79	879580.40	576474.36	408902.92
175	5021.05	3041.13	2854.47	884601.46	579515.50	411757.39
176	4639.35	3103.72	**2178.77**	889240.81	582619.22	413936.16
177	5505.40	3055.69	2809.52	894746.21	585674.91	416745.68
178	5180.62	2467.02	2512.73	899926.83	588141.92	419258.40
179	5234.74	3021.83	2783.89	905161.57	591163.75	422042.29
180	5605.87	2361.62	3418.87	910767.44	593525.37	425461.16
181	5493.61	3142.98	3502.16	916261.05	596668.35	428963.33
182	5003.05	3347.56	3352.28	921264.10	600015.91	432315.61
183	5152.17	3483.59	3035.90	926416.27	603499.50	435351.51
184	5447.14	3857.55	3110.03	931863.41	607357.05	438461.54
185	4314.18	4021.21	2486.25	936177.60	611378.26	440947.79
186	4579.80	3636.20	2905.10	940757.39	615014.46	443852.89
187	5020.93	3583.53	2805.33	945778.33	618597.99	446658.22
188	4557.11	3143.24	2441.37	950335.44	621741.23	449099.58
189	4864.56	3762.89	2423.40	955200.00	625504.12	451522.98
190	4458.14	3924.86	2485.12	959658.14	629428.98	454008.10
191	5121.33	3863.47	2159.92	964779.47	633292.46	456168.02
192	4630.39	3583.74	2298.60	969409.85	636876.20	458466.62
193	4166.52	3302.39	2606.43	973576.37	640178.59	461073.05
194	4028.37	3555.11	2135.14	977604.75	643733.70	463208.18
195	4846.84	3833.60	2908.58	982451.58	647567.30	466116.76
196	4499.65	3697.33	2459.82	986951.23	651264.64	468576.58
197	5263.40	3216.50	2294.62	992214.64	654481.14	470871.20
198	5820.01	3151.52	2921.63	998034.65	657632.65	473792.82
199	4777.04	3135.50	2116.42	1002811.69	660768.16	475909.24
200	5547.34	3342.17	2300.61	1008359.03	664110.32	478209.85
201	5804.93	3450.62	2553.87	1014163.96	667560.94	480763.72
202	5850.47	3559.61	2053.33	1020014.43	671120.55	482817.04
203	6018.38	3469.46	2676.48	1026032.81	674590.01	485493.52
204	4721.96	3162.70	2426.59	1030754.77	677752.71	487920.10
205	4022.75	3413.02	2413.82	1034777.52	681165.73	490333.92
206	5449.28	4026.16	3109.34	1040226.80	685191.90	493443.26
207	4259.49	3683.77	2458.85	1044486.29	688875.67	495902.11
208	3403.92	3820.16	2510.26	1047890.21	692695.83	498412.37

209	2885.20	3754.30	2465.76	1050775.41	696450.13	500878.13
210	4229.95	3586.29	2943.51	1055005.37	700036.42	503821.64
211	5176.13	4182.40	2355.46	1060181.50	704218.82	506177.11
212	4907.89	4116.81	2719.97	1065089.40	708335.63	508897.07
213	5609.75	3589.33	3265.15	1070699.15	711924.96	512162.22
214	3958.71	3316.05	3005.19	1074657.85	715241.01	515167.41
215	4472.61	3685.63	3338.57	1079130.46	718926.64	518505.98
216	3568.11	3695.32	2536.69	1082698.57	722621.96	521042.67
217	5286.40	4275.02	2589.72	1087984.97	726896.98	523632.39
218	5436.30	4613.68	2753.10	1093421.27	731510.65	526385.49
219	5073.25	3782.96	3015.00	1098494.51	735293.62	529400.49
220	4711.50	3808.39	2864.50	1103206.01	739102.00	532264.98
221	4609.86	3728.83	2307.93	1107815.87	742830.83	534572.91
222	4506.48	3592.99	2661.59	1112322.35	746423.82	537234.50
223	5073.34	3827.02	3058.50	1117395.68	750250.84	540293.00
224	4450.60	3884.52	2572.80	1121846.28	754135.36	542865.80
225	4093.03	3292.37	2734.48	1125939.32	757427.73	545600.29
226	3795.87	2964.38	2413.01	1129735.19	760392.11	548013.30
227	3240.23	3074.10	2614.34	1132975.42	763466.21	550627.64
228	4206.96	3132.49	2433.58	1137182.38	766598.70	553061.21
229	4363.23	3502.43	2735.52	1141545.61	770101.12	555796.73
230	4422.25	3067.94	2715.66	1145967.85	773169.06	558512.39
231	3127.10	3256.88	2212.97	1149094.95	776425.94	560725.36
232	2768.95	3446.60	2233.30	1151863.90	779872.54	562958.66
233	3312.07	3166.11	2857.28	1155175.97	783038.65	565815.94
234	2954.58	3330.16	2414.83	1158130.55	786368.81	568230.77
235	2854.58	3232.11	2777.32	1160985.14	789600.91	571008.09
236	3267.36	3449.61	2455.54	1164252.50	793050.52	573463.63
237	2591.34	3377.72	2355.13	1166843.84	796428.24	575818.76
238	3003.38	3067.50	2254.69	1169847.22	799495.74	578073.45
239	3222.89	3391.94	3040.10	1173070.11	802887.69	581113.55
240	2549.50	3000.73	2476.61	1175619.61	805888.42	583590.16
241	2832.67	3672.28	2617.80	1178452.27	809560.69	586207.95
242	4195.84	3626.61	2396.52	1182648.12	813187.30	588604.47
243	3396.78	3928.11	2416.88	1186044.90	817115.41	591021.36
244	2377.84	3347.17	2094.83	1188422.74	820462.59	593116.19
245	2596.41	3917.61	2397.20	1191019.16	824380.20	595513.38
246	2498.18	3387.95	2498.15	1193517.33	827768.15	598011.53
247	2400.19	3691.34	2256.61	1195917.53	831459.49	600268.14
248	2523.23	3266.96	2518.78	1198440.76	834726.45	602786.92
249	2582.95	3977.12	2357.80	1201023.71	838703.57	605144.72
250	2453.75	3497.29	2438.63	1203477.46	842200.86	607583.35
251	2262.05	2798.13	2116.37	1205739.51	844999.00	609699.72
252	2541.48	3239.41	1673.10	1208280.99	848238.41	611372.82
253	3290.20	3109.63	2681.24	1211571.18	851348.04	614054.06
254	2628.71	3170.63	1875.03	1214199.90	854518.67	615929.08
255	2844.04	3286.63	2318.80	1217043.93	857805.31	618247.89
256	2746.67	3156.08	2298.86	1219790.60	860961.39	620546.74
257	2369.00	3409.97	2319.24	1222159.60	864371.36	622865.98
258	3268.65	3471.97	2440.47	1225428.25	867843.33	625306.46

259	3606.32	3589.41	2743.27	1229034.57	871432.74	628049.73
260	2204.40	3375.31	2622.49	1231238.98	874808.05	630672.22
261	2294.51	3659.31	2461.34	1233533.49	878467.36	633133.55
262	2415.34	3222.20	2481.75	1235948.82	881689.56	635615.30
263	2769.98	3664.97	2602.58	1238718.81	885354.53	638217.87
264	2637.58	3875.23	2830.32	1241356.39	889229.76	641048.20
265	2475.55	3419.69	2734.49	1243831.94	892649.44	643782.69
266	2684.68	3825.66	2293.27	1246516.62	896475.10	646075.96
267	2769.51	4066.76	2826.33	1249286.13	900541.87	648902.29
268	2546.97	3943.63	2424.29	1251833.10	904485.50	651326.58
269	2876.43	4526.56	2204.40	1254709.53	909012.05	653530.98
270	1800.35	3693.71	3087.95	1256509.87	912705.76	656618.93
271	3620.97	3766.66	3093.82	1260130.84	916472.42	659712.75
272	1911.57	4814.45	2052.78	1262042.41	921286.87	661765.53
273	2087.68	3453.55	2653.10	1264130.09	924740.42	664418.64
274	2262.77	3988.44	3317.50	1266392.87	928728.86	667736.14
275	2075.82	3657.01	2745.72	1268468.68	932385.88	670481.86
276	2489.86	3701.55	3040.46	1270958.54	936087.43	673522.32
277	2363.07	3892.67	3647.12	1273321.61	939980.10	677169.44
278	2565.06	3820.75	3010.37	1275886.67	943800.85	680179.81
279	1933.12	4603.96	3619.22	1277819.78	948404.81	683799.03
280	2164.76	3971.05	3813.54	1279984.54	952375.85	687612.57
281	1774.54	4790.54	2672.00	1281759.08	957166.39	690284.57
282	2459.19	4657.26	3209.08	1284218.28	961823.66	693493.65
283	2700.36	4524.19	2993.13	1286918.63	966347.85	696486.78
284	2318.14	4901.22	2838.43	1289236.77	971249.07	699325.21
285	2291.91	4345.36	3512.23	1291528.68	975594.43	702837.44
286	2235.79	4269.96	3122.97	1293764.48	979864.39	705960.41
287	2209.34	4102.74	3052.17	1295973.82	983967.13	709012.58
288	2033.30	3903.74	3153.32	1298007.11	987870.88	712165.90
289	2275.96	3642.03	3624.24	1300283.07	991512.90	715790.14
290	1769.54	5405.41	3009.23	1302052.62	996918.31	718799.37
291	2012.53	4037.40	2957.84	1304065.14	1000955.72	721757.21
292	2196.07	4298.87	2839.79	1306261.21	1005254.59	724597.00
293	1657.07	5431.03	3472.50	1307918.28	1010685.61	728069.51
294	2051.83	5325.23	3422.16	1309970.11	1016010.85	731491.66
295	1752.73	5718.57	2768.39	1311722.84	1021729.42	734260.06
296	1846.16	5048.36	3207.45	1313569.00	1026777.78	737467.50
297	2455.13	4310.51	3965.92	1316024.13	1031088.29	741433.43
298	2580.24	4577.78	3803.12	1318604.36	1035666.07	745236.54
299	1763.27	4023.13	3570.42	1320367.63	1039689.19	748806.97
300	2192.15	4481.75	3838.04	1322559.78	1044170.94	752645.01
301	2042.96	4273.63	3740.76	1324602.75	1048444.57	756385.77
302	2168.16	5280.01	3965.18	1326770.91	1053724.58	760350.96
303	2110.22	4912.42	3844.12	1328881.12	1058637.00	764195.08
304	2358.38	5959.70	3977.68	1331239.50	1064596.70	768172.76
305	1901.77	4234.17	3060.85	1333141.27	1068830.87	771233.61
306	2641.85	4637.37	4224.46	1335783.12	1073468.24	775458.06
307	1968.93	4099.60	3559.55	1337752.05	1077567.84	779017.61
308	1817.79	4276.33	3480.53	1339569.84	1081844.17	782498.14

309	2190.74	**5993.44**	3852.53	1341760.58	1087837.61	786350.67
310	1637.30	4469.93	3631.28	1343397.88	1092307.54	789981.95
311	1703.68	4392.84	4009.31	1345101.56	1096700.38	793991.26
312	1522.13	3628.81	3338.50	1346623.69	1100329.18	797329.76
313	1837.95	3977.39	3645.66	1348461.64	1104306.57	800975.42
314	1468.26	3836.32	3261.87	1349929.90	1108142.89	804237.29
315	2286.90	4765.85	4472.66	1352216.80	1112908.74	808709.96
316	1853.50	4558.58	4112.59	1354070.31	1117467.32	812822.55
317	1669.67	3610.87	4156.89	1355739.97	1121078.19	816979.44
318	1547.96	3407.85	3180.50	1357287.93	1124486.04	820159.94
319	1964.09	4231.80	3510.05	1359252.03	1128717.84	823669.99
320	2033.07	5146.96	3933.87	1361285.10	1133864.81	827603.86
321	2070.55	4080.42	3788.71	1363355.64	1137945.23	831392.57
322	1884.60	4450.31	4140.66	1365240.25	1142395.54	835533.23
323	1793.70	4152.37	4042.84	1367033.95	1146547.91	839576.07
324	2087.68	4172.14	4417.65	1369121.63	1150720.05	843993.72
325	2737.51	4065.65	**4721.05**	1371859.14	1154785.70	848714.77
326	1969.93	3205.48	4292.78	1373829.07	1157991.18	853007.55
327	2169.88	4511.51	3300.50	1375998.94	1162502.69	856308.05
328	2348.27	4185.81	4252.52	1378347.21	1166688.50	860560.57
329	1853.39	3923.36	3882.05	1380200.60	1170611.87	864442.62
330	1999.73	3414.20	2774.89	1382200.33	1174026.07	867217.51
331	1891.71	3496.06	2495.11	1384092.04	1177522.13	869712.62
332	1941.55	3546.49	2618.98	1386033.59	1181068.62	872331.60
333	1866.12	3657.99	2504.76	1387899.71	1184726.61	874836.35
334	1575.33	2910.78	2629.09	1389475.04	1187637.39	877465.44
335	1564.46	2992.94	2274.94	1391039.50	1190630.33	879740.38
336	1614.51	3165.82	2279.31	1392654.01	1193796.15	882019.69
337	1633.46	2791.37	2115.40	1394287.47	1196587.52	884135.09
338	1742.09	2721.72	2167.61	1396029.55	1199309.25	886302.71
339	1699.90	3617.01	2099.36	1397729.45	1202926.26	888402.06
340	1510.09	3214.51	2030.83	1399239.54	1206140.77	890432.89
341	1205.25	2634.95	1986.24	1400444.79	1208775.72	892419.13
342	1284.06	2476.97	1868.67	1401728.85	1211252.69	894287.80
343	1159.00	2230.20	1920.49	1402887.86	1213482.89	896208.29
344	1127.69	2166.59	1991.30	1404015.55	1215649.47	898199.58
345	1212.28	2251.32	1844.05	1405227.83	1217900.79	900043.63
346	1527.06	2128.74	1672.79	1406754.89	1220029.54	901716.42
347	1294.25	2036.13	1889.40	1408049.14	1222065.67	903605.82
348	1205.81	2150.03	1766.80	1409254.95	1224215.70	905372.62
349	1089.02	1910.73	1910.41	1410343.97	1226126.43	907283.02
350	1058.46	1760.35	1812.15	1411402.43	1227886.78	909095.17
351	1199.34	1669.10	1762.34	1412601.77	1229555.87	910857.51
352	1168.68	1519.74	1688.49	1413770.45	1231075.61	912546.00
353	1081.21	1604.30	1735.27	1414851.66	1232679.91	914281.27
354	1221.27	1572.06	1661.56	1416072.93	1234251.97	915942.83
355	1275.76	1685.22	1708.28	1417348.69	1235937.19	917651.11
356	1216.85	1478.94	1827.03	1418565.54	1237416.14	919478.14
357	1271.14	1533.94	1993.62	1419836.68	1238950.08	921471.77
358	1156.04	1704.24	1919.94	1420992.72	1240654.32	923391.70

359	1013.21	1499.10	1966.27	1422005.94	1242153.42	925357.97
360	983.27	1438.61	2012.51	1422989.21	1243592.02	927370.48
361	1009.52	1320.91	1795.36	1423998.72	1244912.93	929165.84
362	1091.64	1576.23	1746.00	1425090.36	1246489.16	930911.84
363	1117.57	1515.91	1887.90	1426207.94	1248005.07	932799.74
364	1171.30	1427.27	1766.91	1427379.23	1249432.33	934566.65
365	1002.12	1310.48	1741.54	1428381.35	1250742.81	936308.19
366	1028.06	1251.00	1906.91	1429409.41	1251993.81	938215.10
367	1081.62	1333.63	1810.02	1430491.03	1253327.44	940025.12
368	968.89	1415.93	1594.31	1431459.92	1254743.37	941619.43
369	939.46	1469.61	1664.27	1432399.38	1256212.98	943283.71
370	1020.45	1579.49	1710.36	1433419.84	1257792.47	944994.07
371	908.44	1463.72	1780.10	1434328.28	1259256.18	946774.17
372	961.70	1404.59	1731.14	1435289.98	1260660.77	948505.31
373	1069.97	1233.54	1659.00	1436359.95	1261894.31	950164.31
374	985.48	1091.15	1988.58	1437345.43	1262985.46	952152.89
375	1038.28	1005.18	1892.26	1438383.70	1263990.64	954045.15
376	932.79	981.23	1990.80	1439316.50	1264971.87	956035.95
377	816.61	917.67	1747.33	1440133.11	1265889.54	957783.28
378	869.41	1026.81	1840.19	1441002.51	1266916.34	959623.47
379	823.05	981.23	2038.20	1441825.57	1267897.57	961661.67
380	**784.92**	**1077.89**	**1954.77**	**1442610.49**	**1268975.45**	**963616.45**

➢ Group two

	Daily methane production (ml)				**Accumulative methane production**			
Time	**R5**	**R6**	**R7**	**R8**	**R5**	**R6**	**R7**	**R8**
17	360	0	0	0	360	0	0	0
18	346	0	0	0	706	0	0	0
19	356	178	0	0	1063	89	0	0
20	341	207	0	0	1404	296	0	0
21	336	187	190	0	1740	483	190	0
22	448	242	135	0	2187	725	326	0
23	385	163	207	0	2572	888	532	0
24	405	192	119	0	2977	1080	652	0
25	386	245	128	0	3364	1324	779	0
26	376	209	159	0	3740	1533	938	0
27	513	304	209	0	4253	1837	1147	0
28	559	372	153	0	4811	2209	1301	0
29	590	374	266	0	5401	2584	1567	0
30	697	458	244	0	6098	3042	1811	0
31	796	376	318	0	6893	3418	2129	0
32	587	422	374	0	7480	3840	2503	0
33	693	219	387	0	8173	4059	2890	0
34	736	207	501	164	8909	4266	3392	164
35	743	368	522	184	9652	4633	3914	348
36	786	529	699	155	10438	5163	4612	503

37	811	411	780	76	11250	5574	5392	578
38	744	402	765	184	11993	5976	6157	763
39	763	414	818	186	12756	6390	6975	949
40	787	512	493	162	13544	6902	7468	1111
41	891	477	893	209	14435	7380	8362	1320
42	845	774	530	184	15280	8154	8891	1504
43	758	334	561	262	16038	8488	9453	1766
44	774	442	500	403	16812	8930	9953	2169
45	791	539	566	341	17603	9468	10519	2510
46	1012	776	559	210	18615	10244	11078	2720
47	1117	608	669	409	19732	10852	11747	3129
48	1258	553	635	280	20989	11405	12381	3409
49	1403	515	685	345	22393	11921	13066	3755
50	1691	474	842	414	24083	12395	13908	4169
51	2293	691	718	319	26376	13086	14626	4487
52	2396	848	796	459	28772	13934	15422	4946
53	2238	918	708	518	31010	14852	16130	5464
54	2462	1136	937	598	33472	15988	17067	6063
55	2152	922	889	547	35624	16910	17956	6610
56	2582	811	951	563	38206	17721	18907	7173
57	2628	1307	1015	574	40834	19028	19921	7747
58	2497	1514	1196	876	43331	20542	21117	8624
59	2578	1598	1340	1017	45909	22140	22458	9640
60	2716	1416	1254	844	48625	23556	23712	10484
61	2880	1609	1112	764	51505	25165	24824	11247
62	2867	2092	1218	846	54373	27256	26042	12093
63	3013	1604	1429	1015	57386	28860	27471	13108
64	3261	2479	1648	1025	60646	31339	29119	14133
65	3131	2080	1922	1256	63778	33419	31042	15389
66	3585	2633	1642	1116	67363	36053	32684	16505
67	3765	3063	1924	1430	71128	39115	34608	17935
68	4108	3409	2132	1106	75236	42524	36740	19041
69	4023	3810	2273	1354	79258	46334	39013	20395
70	3868	5716	2050	1167	83126	50140	41063	21563
71	4419	6298	2477	1232	87545	53862	43540	22794
72	5139	6094	2640	1088	92683	58456	46180	23882
73	5342	6686	2823	1314	98026	61965	49003	25196
74	4624	7294	2144	857	102650	66353	51147	26053
75	5714	7631	2895	1705	108365	70413	54042	27758
76	5674	7546	3213	1612	114038	75198	57255	29369
77	6427	7602	3469	1745	120465	80245	60724	31115
78	6367	7696	3793	1604	126832	85045	64517	32719
79	6230	7620	4032	1624	133062	90170	68549	34343
80	6795	7885	2878	1375	139857	94079	71427	35718
81	7002	7692	3160	1569	146859	98643	74587	37287
82	7237	7539	3421	1962	154096	103430	78008	39248
83	6861	7401	3344	1552	160957	109127	81352	40801
84	7480	7807	3959	1604	168437	113663	85312	42405
85	6696	8300	3709	1855	175134	117121	89021	44260
86	7491	8363	4070	1803	182625	120958	93091	46063

87	8275	8465	3066	1498	190899	125771	96157	47561
88	9018	8207	3171	1677	199918	131620	99328	49239
89	8900	8055	3448	1740	208818	137392	102776	50979
90	8323	8126	3519	1851	217141	142931	106295	52829
91	7507	8376	3458	1768	224648	147463	109753	54597
92	7381	8346	3597	1704	232028	151702	113351	56301
93	9474	8388	3954	1796	241502	157522	117305	58097
94	9680	8066	4054	1716	251182	163773	121358	59813
95	9050	8288	4623	2077	260232	168309	125982	61890
96	6907	7858	4407	3180	267139	174361	130389	65070
97	9381	7760	4913	3597	276520	180244	135301	68667
98	9289	7584	4806	4113	285809	184636	140107	72780
99	8918	7459	4265	3534	294727	189559	144372	76313
100	8153	8208	3209	2618	302879	194348	147581	78932
101	7717	8389	4317	2531	310596	198873	151898	81462
102	7695	7922	3480	2172	318292	204068	155377	83634
103	8301	7868	4418	2278	326593	209366	159795	85912
104	7443	8014	4815	2591	334036	214300	164610	88503
105	9776	8287	4458	2438	343812	219774	169069	90941
106	**11039**	8096	3787	2727	354850	226267	172856	93668
107	10750	8191	4787	3718	365600	231154	177643	97386
108	9660	7874	4402	4945	375260	236864	182045	102331
109	10272	7969	4488	3882	385532	243058	186533	106214
110	10721	8728	4837	4252	396253	247954	191370	110466
111	9033	8488	4371	**5066**	405286	252740	195741	115532
112	9306	8224	4371	3996	414592	257073	200112	119528
113	9771	8285	4081	4231	424362	262312	204193	123758
114	8712	8227	4002	4022	433074	266675	208196	127780
115	10313	8614	2954	3656	443387	272232	211150	131436
116	9908	8512	4354	3860	453295	276720	215504	135296
117	10392	**8849**	3807	3260	463686	282251	219310	138556
118	11098	7808	4778	3791	474784	288018	224088	142347
119	9079	7568	5193	4390	483863	292957	229282	146737
120	8244	7024	4012	3506	492108	297529	233294	150243
121	8109	8606	4764	3149	500217	302066	238058	153392
122	7216	7344	4412	3109	507433	306192	242470	156501
123	6879	8384	3534	2611	514312	310214	246003	159112
124	7366	7467	3433	2542	521678	314437	249436	161654
125	8669	6528	4227	**2501**	530347	319056	253663	164155
126	7640	6485	4740	3437	537988	323268	258403	167592
127	6919	6616	4607	3479	544907	327546	263010	171070
128	6548	5804	4351	2667	551455	331720	267361	173737
129	7427	6002	4035	2866	558882	336347	271395	176603
130	6248	5229	4208	3067	565130	340338	275604	179670
131	7276	5645	3864	2459	572406	344235	279468	182129
132	6311	4129	4098	3120	578717	349025	283565	185249
133	6343	4566	4815	3978	585060	353689	288380	189227
134	6167	4076	3988	3010	591226	358873	292367	192237
135	6283	3806	5636	4452	597509	363695	298003	196688
136	6795	3722	5051	4752	604304	368774	303054	201441

137	6674	4595	5302	**5049**	610978	374204	308356	206490
138	6091	3509	5373	4514	617069	378952	313729	211004
139	6204	4388	5106	4595	623274	383901	318835	215599
140	5628	4060	5729	4552	628901	388643	324564	220150
141	6039	4785	5400	4351	634940	393956	329964	224502
142	6265	5047	5882	4275	641205	398661	335847	228777
143	5286	4800	5754	4766	646491	403448	341601	233542
144	4450	5125	5693	4880	650941	407779	347293	238423
145	5196	3909	4969	3691	656137	412498	352263	242114
146	4950	4563	5460	4537	661087	417018	357723	246650
147	5247	4787	5186	4049	666335	421673	362909	250699
148	6376	5697	5472	4358	672711	426996	368381	255057
149	6203	4537	6532	5077	678914	432092	374914	260134
150	6548	**3458**	6434	4718	685461	437412	381348	264852
151	5609	3837	**6688**	4606	691070	442360	388036	269457
152	5818	4813	6449	4765	696888	447105	394485	274223
153	4808	5849	5962	4366	701696	451614	400447	278589
154	4452	5772	5757	4038	706149	456464	406204	282626
155	4706	5539	5693	4028	710855	461598	411897	286655
156	**4213**	4532	5841	4356	715068	465854	417738	291011
157	4603	4239	5139	3645	719671	470628	422877	294655
158	4335	5820	5503	3995	724006	475015	428380	298651
159	4632	6251	5337	3870	728638	479899	433717	302520
160	4770	4537	4823	3745	733409	484897	438540	306265
161	4572	6052	5391	3842	737981	489412	443931	310108
162	4353	5883	5158	3856	742334	493710	449089	313963
163	4667	4392	3798	3623	747001	499449	452887	317586
164	4427	4923	4371	4512	751428	504975	457258	322098
165	4957	4790	4043	3978	756385	510040	461301	326076
166	5198	4525	3845	4731	761584	515774	465146	330807
167	4219	5195	4637	3941	765803	520459	469783	334748
168	4721	5298	**3278**	3234	770524	525693	473061	337982
169	5003	4934	3638	3554	775527	531108	476699	341536
170	4359	5474	4169	3898	779886	536050	480868	345434
171	5345	6493	3652	3223	785231	541832	484520	348657
172	4641	4887	4325	4273	789872	547674	488845	352930
173	5390	5710	3931	3762	795262	553247	492776	356692
174	5501	6194	4109	3448	800763	559566	496885	360140
175	4194	4896	5062	4390	804957	564915	501947	364530
176	5794	4786	4033	3509	810751	571173	505981	368039
177	4488	4333	4611	3889	815239	576775	510592	371928
178	5287	5239	4348	3465	820526	583068	514940	375393
179	5647	4364	4942	4032	826172	588798	519882	379425
180	5238	5557	4564	3447	831410	595416	524446	382872
181	5969	4488	5089	3701	837379	602828	529536	386573
182	6318	5531	4991	4375	843698	609417	534527	390948
183	6836	5767	4459	4222	850534	615876	538986	395170
184	5432	4938	4941	4504	855966	623357	543927	399674
185	6589	4572	4780	3708	862555	630682	548707	403381
186	**6833**	4537	4863	4253	869387	638644	553570	407634

187	5736	4125	4179	3415	875123	646210	557749	411048
188	5523	4023	4526	4225	880647	654007	562276	415273
189	6004	4223	4433	4566	886650	660693	566709	419839
190	5312	4619	4629	3660	891963	667987	571338	423500
191	5650	4212	4246	4241	897613	675618	575585	427741
192	5030	4279	4595	4106	902642	683164	580179	431847
193	6230	4174	4427	4362	908872	690765	584607	436209
194	5201	4627	4703	4106	914073	698462	589310	440314
195	6571	3992	4067	4211	920644	706081	593377	444526
196	6861	3897	4664	4500	927505	713966	598040	449025
197	6912	4790	4718	4394	934417	721658	602758	453419
198	6915	4664	4624	4317	941332	729197	607382	457736
199	5765	5184	4555	4486	947097	736598	611937	462223
200	5094	6827	4287	4101	952191	744405	616224	466324
201	6058	5210	4564	4465	958249	752704	620788	470789
202	4714	6807	5239	5150	962963	760768	626027	475938
203	4571	6906	4449	4664	967534	769233	630476	480602
204	4886	6593	4653	5051	972421	777440	635130	485653
205	6410	5759	4608	4831	978831	785495	639738	490484
206	5565	6264	4812	4746	984395	793292	644550	495231
207	6521	5941	4568	4388	990917	801068	649118	499619
208	5331	6385	5497	4808	996248	809414	654615	504428
209	5253	6153	4627	4795	1001501	816803	659243	509223
210	6238	5915	4532	4536	1007739	824368	663775	513759
211	6107	5847	4687	4138	1013846	831757	668462	517897
212	5206	5510	4400	4062	1019052	839615	672862	521959
213	5129	5586	4364	4468	1024181	847375	677226	526427
214	5263	6593	5610	3432	1029444	854859	682837	529859
215	5770	6072	5346	4214	1035214	861319	688183	534073
216	5879	5238	5769	3968	1041093	869527	693952	538041
217	5162	5770	6065	4781	1046256	877615	700017	542822
218	5590	5549	5491	5046	1051846	885537	705509	547869
219	6151	5990	5322	4766	1057997	893405	710831	552635
220	5248	6307	5710	4146	1063245	899419	716541	556781
221	5996	6048	4618	3563	1069240	907706	721159	560344
222	5038	4637	5957	4844	1074279	913802	727116	565188
223	5627	6735	4318	3484	1079905	921993	731434	568672
224	5815	5762	5773	3613	1085720	929867	737207	572285
225	5257	5448	5819	3472	1090977	937636	743026	575758
226	6407	5447	5500	3736	1097384	946364	748526	579494
227	5768	4977	5667	4440	1103152	954852	754194	583934
228	6705	5821	5562	3858	1109857	963076	759756	587792
229	6093	4662	5999	3684	1115949	970361	765755	591476
230	6015	4845	5863	3778	1121964	978588	771618	595255
231	6177	4433	6088	3872	1128141	987203	777706	599127
232	6478	5361	6171	3813	1134620	995714	783877	602940
233	6172	5290	6165	4120	1140791	1004563	790041	607060
234	4822	4684	5915	4160	1145614	1012371	795957	611220
235	5696	5481	5999	4805	1151310	1018639	801955	616025
236	5478	6459	6236	4173	1156788	1024663	808191	620199

237	4755	6589	6075	3506	1161542	1033269	814266	623704
238	4630	5413	6104	3511	1166172	1039613	820370	627216
239	4757	6618	6060	3821	1170929	1047997	826430	631037
240	4988	5730	5927	3523	1175918	1055464	832357	634560
241	4630	6292	5981	3460	1180548	1061992	838337	638020
242	5354	5603	5221	4587	1185902	1069477	843559	642607
243	6718	6258	5523	3913	1192620	1076893	849082	646520
244	6486	5349	5670	4225	1199107	1083497	854752	650746
245	6654	6319	5277	4468	1205761	1091100	860029	655213
246	6677	5573	5576	4803	1212438	1099329	865605	660017
247	6906	5842	5967	4721	1219344	1106974	871572	664737
248	6906	5783	6013	4431	1226249	1115403	877585	669168
249	6900	4942	6120	5074	1233150	1122469	883705	674242
250	7554	5415	5824	4819	1240704	1129945	889529	679062
251	7587	5234	6210	4497	1248290	1136772	895739	683558
252	5336	5184	5823	4655	1253627	1141983	901561	688214
253	6219	4822	4639	4301	1259846	1148790	906200	692514
254	5310	5080	5392	5072	1265156	1155696	911592	697586
255	5017	5429	5651	4955	1270173	1162889	917243	702541
256	6173	4748	5452	5314	1276346	1168647	922695	707855
257	6209	4949	5042	5164	1282555	1174912	927738	713019
258	5384	4742	5482	5351	1287939	1180853	933220	718369
259	6733	5313	5255	4497	1294672	1187238	938474	722866
260	6539	4706	5360	4836	1301211	1193391	943835	727702
261	5457	4786	5538	4726	1306668	1199307	949373	732429
262	5130	4331	5473	4571	1311798	1205153	954845	737000
263	5256	4720	5326	4284	1317054	1210663	960171	741283
264	5910	4520	4713	4123	1322964	1216249	964884	745406
265	5810	4655	5590	4561	1328774	1223842	970474	749967
266	6087	4323	5739	4550	1334861	1231214	976214	754518
267	5634	5096	5612	4782	1340495	1236452	981826	759300
268	6087	5320	5669	4985	1346582	1242222	987495	764284
269	5786	4948	5975	5036	1352368	1247771	993471	769321
270	6440	4745	5628	4935	1358808	1254761	999098	774256
271	6717	4510	6188	5202	1365524	1261468	1005286	779458
272	6491	4849	5774	5286	1372015	1267516	1011060	784744
273	4931	5134	5896	5494	1376946	1272153	1016956	790239
274	6340	4256	4903	4551	1383287	1278887	1021859	794790
275	5888	4774	6930	5446	1389175	1284650	1028789	800236
276	5334	4387	5426	5752	1394509	1290098	1034215	805988
277	6090	4884	5665	5618	1400598	1295545	1039880	811606
278	5788	4998	6555	5451	1406386	1300522	1046435	817056
279	6090	4515	6331	5282	1412476	1306343	1052765	822338
280	5890	4298	6685	5590	1418366	1311005	1059450	827928
281	5112	5739	6282	5302	1423479	1316351	1065732	833230
282	5442	5526	6495	5652	1428921	1320784	1072228	838881
283	6654	5065	5620	5012	1435575	1327146	1077848	843894
284	6077	5734	6812	5714	1441652	1332436	1084660	849607
285	6054	4684	6336	5649	1447706	1337547	1090996	855256
286	4946	4503	6368	5711	1452652	1342050	1097364	860967

287	4949	4526	5749	4945	1457601	1346576	1103113	865912
288	5203	4807	5708	5071	1462804	1351382	1108821	870983
289	5079	4212	**6787**	5804	1467883	1356268	1115608	876787
290	5991	3973	6313	5835	1473874	1361463	1121922	882622
291	5716	3876	6345	5993	1479590	1366594	1128266	888615
292	6022	4296	6124	5769	1485611	1372089	1134390	894384
293	6201	3707	6263	5831	1491813	1379141	1140654	900215
294	5723	3897	6547	5575	1497535	1384310	1147201	905790
295	4610	4790	6254	**5925**	1502146	1388026	1153455	911715
296	5499	4664	5064	4777	1507645	1393323	1158519	916492
297	5374	4350	5813	5508	1513019	1398274	1164332	922001
298	4575	3106	5898	5691	1517595	1401380	1170230	927692
299	4841	3127	6020	5269	1522435	1404507	1176250	932961
300	5029	3654	5005	5230	1527464	1408161	1181255	938190
301	4840	3450	5553	5316	1532305	1411611	1186808	943507
302	4903	3470	5216	5182	1537208	1415081	1192024	948689
303	4566	3602	5268	4701	1541773	1418683	1197292	953389
304	5151	4430	4864	5103	1546924	1423113	1202157	958492
305	4815	3225	5544	5724	1551739	1426338	1207701	964216
306	4703	3329	5385	5684	1556442	1429666	1213086	969899
307	4295	2685	5504	5487	1560737	1432351	1218591	975386
308	4653	2568	5140	5384	1565390	1434919	1223730	980770
309	3659	2755	5396	5720	1569049	1437674	1229126	986490
310	4188	2612	4486	4962	1573237	1440286	1233612	991452
311	4030	2469	4504	4829	1577266	1442754	1238116	996281
312	4263	3257	4317	4760	1581529	1446011	1242433	1001040
313	4350	3740	4811	4969	1585879	1449751	1247244	1006010
314	3624	3848	4574	4961	1589503	1453599	1251818	1010971
315	3286	3219	4710	5510	1592789	1456818	1256528	1016481
316	3166	3382	4201	4852	1595955	1460200	1260729	1021333
317	3096	3054	4065	4783	1599051	1463254	1264794	1026116
318	2927	2917	4268	4899	1601978	1466172	1269062	1031015
319	2954	2753	4369	4922	1604931	1468925	1273431	1035937
320	2687	2616	4233	5006	1607618	1471541	1277664	1040943
321	2787	2643	4064	4784	1610405	1474184	1281728	1045727
322	3253	2779	4165	4838	1613658	1476963	1285893	1050565
323	3182	2560	4063	4677	1616841	1479523	1289956	1055242
324	3087	2451	3927	4578	1619927	1481973	1293883	1059820
325	3751	2940	3791	4540	1623678	1484914	1297674	1064360
326	3483	2586	4570	5172	1627161	1487499	1302244	1069533
327	3363	2367	4468	4982	1630524	1489867	1306711	1074514
328	3046	2258	4264	5065	1633570	1492125	1310975	1079579
329	2704	2176	4738	5147	1636275	1494301	1315713	1084726
330	2657	2312	4365	4988	1638931	1496612	1320078	1089714
331	2585	2229	4466	5372	1641516	1498842	1324544	1095087
332	2833	2419	4533	5273	1644349	1501261	1329077	1100360
333	2712	2256	4398	5325	1647061	1503517	1333474	1105686
334	2788	2391	4668	5166	1649849	1505908	1338142	1110852
335	2543	2228	4836	5128	1652391	1508136	1342979	1115980
336	2223	2254	3483	4491	1654615	1510390	1346462	1120471

337	2299	2281	3686	4574	1656914	1512671	1350148	1125045
338	2350	2226	3821	4477	1659264	1514897	1353969	1129521
339	2377	2307	3550	4708	1661641	1517204	1357519	1134229
340	2378	2388	3888	4641	1664019	1519592	1361406	1138870
341	2430	2198	3820	4514	1666449	1521790	1365226	1143384
342	2555	2251	4090	4803	1669004	1524041	1369316	1148188
343	2209	3147	3987	5034	1671213	1527188	1373303	1153221
344	2358	3340	3985	5149	1673571	1530528	1377288	1158370
345	1737	2447	3847	5114	1675308	1532975	1381135	1163484
346	1811	2560	3036	3987	1677119	1535535	1384171	1167472
347	2207	2263	2933	3748	1679326	1537798	1387104	1171219
348	2132	2457	2864	4098	1681458	1540255	1389968	1175317
349	2132	1941	2761	4182	1683590	1542196	1392729	1179499
350	1784	1341	2692	3914	1685375	1543537	1395421	1183413
351	1982	1645	2993	3881	1687357	1545182	1398414	1187294
352	2279	2223	3260	4112	1689636	1547406	1401674	1191406
353	2254	1952	3695	4196	1691889	1549357	1405370	1195602
354	2327	2037	3693	3870	1694216	1551394	1409063	1199472
355	2079	1874	3624	3808	1696296	1553268	1412687	1203280
356	1460	1573	3454	3746	1697756	1554841	1416141	1207025
357	2103	1741	3955	3596	1699858	1556582	1420095	1210621
358	2028	1605	3416	3505	1701887	1558187	1423512	1214126
359	2151	1995	3481	3443	1704038	1560182	1426993	1217570
360	2052	2025	3814	3586	1706090	1562207	1430807	1221156
361	1681	1556	3410	3379	1707770	1563763	1434218	1224534
362	1804	1613	2907	2997	1709574	1565376	1437125	1227531
363	1606	1504	2772	3285	1711180	1566881	1439897	1230817
364	1679	2092	2537	3137	1712859	1568972	1442434	1233953
365	1827	1732	2335	3337	1714686	1570704	1444769	1237290
366	1728	1650	2834	3102	1716414	1572354	1447602	1240392
367	1826	1876	2599	3476	1718240	1574230	1450201	1243868
368	1653	1766	2697	3270	1719893	1575996	1452898	1247137
369	1776	1628	2762	3064	1721669	1577625	1455661	1250202
370	1554	1715	2561	2946	1723223	1579340	1458222	1253148
371	**1479**	**1492**	**2659**	**2885**	**1724702**	**1580832**	**1460881**	**1256033**

2.2 Methane concentration

	Methane concentration %				Methane concentration %			
Time	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**
17	0.00	0.00	0.00	0.00	**7.70**	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	8.12	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	8.61	**7.40**	0.00	0.00
20	**11.70**	**9.90**	0.00	0.00	8.12	7.50	0.00	0.00
21	12.60	10.60	**11.70**	0.00	8.00	7.60	**7.75**	0.00
22	13.90	11.40	12.30	0.00	8.99	7.90	7.40	0.00

23	14.70	12.45	13.50	0.00	8.55	8.00	8.00	0.00
24	16.30	14.00	14.90	0.00	8.55	8.20	7.90	0.00
25	18.10	15.50	16.30	0.00	9.20	8.50	7.50	0.00
26	19.20	16.22	16.30	0.00	8.71	8.10	7.63	0.00
27	20.50	16.86	17.70	0.00	8.90	8.30	7.22	0.00
28	21.40	17.16	18.90	0.00	9.50	8.50	8.12	0.00
29	22.60	18.00	19.80	0.00	11.30	9.60	10.30	0.00
30	23.00	21.00	22.30	0.00	12.35	10.05	10.76	0.00
31	25.00	30.00	29.20	0.00	12.88	10.28	10.98	0.00
32	23.25	33.42	31.00	0.00	13.40	10.50	11.21	0.00
33	33.90	28.94	32.30	8.60	13.75	11.40	11.82	8.10
34	36.42	31.13	32.51	10.73	14.10	12.30	12.43	8.30
35	37.13	28.83	35.87	10.50	14.40	12.50	12.95	8.20
36	40.79	35.38	36.46	12.31	14.55	12.60	13.20	7.90
37	46.00	38.00	36.70	13.52	14.70	12.70	13.46	8.30
38	40.39	34.81	36.90	13.10	15.30	13.40	14.99	9.40
39	46.18	41.91	37.70	15.40	15.90	13.80	15.65	8.85
40	49.25	44.06	37.10	16.52	16.20	14.00	15.97	8.58
41	42.23	38.56	36.30	13.95	16.50	14.20	16.30	8.30
42	48.36	41.16	38.70	16.00	14.83	12.90	14.25	8.50
43	43.60	48.36	37.90	16.00	13.16	11.60	12.20	8.70
44	46.40	49.85	39.00	17.65	14.82	12.93	13.23	9.13
45	43.36	48.82	39.31	18.46	16.48	14.25	14.27	9.57
46	49.74	49.50	39.20	20.03	18.14	15.58	15.30	10.00
47	48.50	50.00	40.20	21.46	19.80	16.90	16.33	10.43
48	50.27	50.20	42.30	22.46	**20.16**	17.39	17.08	10.82
49	50.27	50.20	40.20	22.46	20.51	17.89	17.82	11.21
50	50.27	**50.20**	43.60	22.46	20.87	18.38	18.57	11.60
51	53.16	49.49	44.75	21.44	21.23	18.88	19.31	11.98
52	52.33	43.55	**46.40**	21.93	21.59	19.37	**20.06**	12.37
53	54.02	44.51	45.00	21.93	21.94	19.87	20.80	12.76
54	55.06	48.89	43.36	20.73	22.30	**20.36**	21.55	13.15
55	**55.20**	48.91	43.36	20.73	22.85	21.64	22.76	14.47
56	54.66	43.41	40.20	20.19	23.39	22.92	23.96	15.78
57	53.61	46.30	41.78	21.34	23.94	24.20	25.17	17.10
58	54.56	45.18	41.61	22.17	24.48	25.48	26.37	18.41
59	54.56	45.18	41.61	22.17	26.04	25.86	25.63	18.62
60	52.83	41.23	43.24	19.87	27.60	26.23	24.89	18.83
61	52.39	40.90	42.40	19.50	28.75	27.64	25.95	19.48
62	51.96	40.68	41.70	19.20	29.32	28.35	26.48	19.81
63	51.53	40.40	41.20	18.80	29.89	29.05	27.01	20.13
64	51.10	40.13	40.64	18.43	31.05	31.54	29.07	22.53
65	49.84	39.30	40.40	18.60	32.22	32.10	31.14	24.92
66	48.57	38.46	40.94	18.80	33.38	33.00	31.40	24.92
67	47.31	38.55	40.71	18.65	33.38	34.03	33.20	24.92
68	46.05	38.65	40.48	18.50	34.06	33.82	33.50	24.31
69	44.79	38.74	40.24	18.34	34.74	33.60	33.10	25.13
70	43.53	38.83	40.01	18.19	35.42	33.39	33.90	23.49
71	43.46	38.70	39.94	18.53	36.10	33.17	33.60	24.10
72	43.40	38.58	39.87	18.86	36.60	33.29	33.80	23.90

73	43.33	38.45	39.80	19.20	37.10	33.42	33.94	23.76
74	42.78	38.34	39.47	19.60	37.60	33.54	33.70	24.00
75	42.22	38.23	39.14	20.00	38.10	33.67	34.29	23.42
76	41.67	38.12	38.81	20.40	38.60	33.79	34.46	23.25
77	41.12	38.01	38.47	20.79	39.09	33.92	34.63	23.09
78	40.56	37.90	38.14	21.19	39.59	34.04	34.80	22.92
79	40.01	37.79	37.81	21.59	**40.09**	34.17	34.97	22.75
80	39.59	37.27	37.41	22.06	40.59	34.29	35.15	22.58
81	39.18	36.75	37.01	22.53	41.09	34.42	35.32	22.41
82	38.76	36.24	36.61	23.00	41.59	34.54	35.49	22.24
83	38.34	35.72	36.20	23.48	42.67	37.38	37.39	23.10
84	37.92	36.86	35.80	23.95	43.75	**40.22**	39.28	23.96
85	37.51	36.45	35.40	24.42	44.82	43.06	**41.18**	24.82
86	37.09	36.05	35.00	24.89	45.90	45.90	43.07	25.68
87	37.57	36.33	35.10	26.23	46.44	45.11	42.69	25.62
88	38.05	36.62	35.20	27.57	46.97	44.31	42.30	25.55
89	38.52	36.91	35.30	28.91	47.55	45.43	42.10	27.89
90	39.00	37.20	35.40	30.25	47.83	45.99	42.00	29.05
91	38.29	36.96	35.62	29.53	48.12	46.55	41.90	30.22
92	37.59	36.71	35.84	28.81	48.43	47.88	44.96	29.46
93	36.88	36.47	35.06	28.10	48.59	48.54	46.49	29.08
94	36.18	36.23	35.40	27.38	**48.74**	**49.20**	48.02	28.70
95	**35.47**	35.99	35.50	26.66	48.66	48.52	**47.97**	31.95
96	36.78	36.69	34.90	28.68	48.57	47.84	47.91	35.20
97	38.09	36.40	36.70	30.70	47.81	46.10	45.70	36.89
98	39.40	35.60	36.80	32.72	47.06	44.36	43.49	38.58
99	40.71	35.10	36.90	34.74	46.30	42.62	41.28	**40.27**
100	39.80	34.60	35.60	35.77	45.55	40.88	39.07	41.96
101	38.89	37.40	35.88	36.80	46.77	43.30	41.11	39.73
102	37.98	36.40	36.30	37.82	46.64	43.33	41.18	39.77
103	37.07	35.10	35.50	38.85	46.51	43.35	41.25	39.82
104	36.24	36.98	37.73	38.28	46.37	43.38	41.32	39.86
105	35.40	36.01	36.61	37.70	46.24	43.41	41.38	39.91
106	35.42	36.03	36.64	38.13	46.11	43.43	41.45	39.95
107	35.44	36.06	36.68	38.56	45.98	43.46	41.52	40.00
108	35.47	36.09	36.71	39.00	45.85	43.49	41.59	40.04
109	35.49	36.12	35.75	39.43	45.71	43.51	41.66	40.09
110	35.51	36.15	34.78	39.86	45.58	43.54	41.73	40.13
111	35.53	36.18	34.82	40.29	45.45	43.57	41.80	40.18
112	35.56	36.20	36.85	40.73	45.45	43.57	41.80	40.18
113	35.58	36.23	36.89	41.16	45.32	43.57	41.80	40.18
114	35.60	36.26	36.92	41.59	45.19	43.59	41.80	40.18
115	35.65	36.21	35.77	42.01	45.05	43.62	41.87	40.18
116	35.70	36.16	35.61	42.42	44.79	43.70	42.14	40.40
117	35.75	36.10	34.46	42.84	47.43	42.98	42.26	40.45
118	35.80	36.05	35.30	43.25	50.07	42.25	42.37	40.50
119	35.90	35.95	37.01	41.35	49.88	42.44	42.27	40.68
120	36.00	35.86	35.71	39.45	49.70	42.63	42.18	40.87
121	36.20	35.69	35.18	39.86	49.51	42.83	42.08	41.05
122	36.40	35.53	34.66	40.28	49.32	43.02	41.98	41.23

123	36.60	35.36	34.13	40.69	49.13	43.21	41.89	41.42
124	36.80	**35.20**	33.60	41.10	48.95	43.40	41.79	41.60
125	37.15	35.63	**34.10**	41.90	48.76	43.59	41.69	41.78
126	37.50	36.05	34.60	42.70	48.57	43.78	41.60	41.97
127	38.56	36.75	34.93	43.42	48.39	43.98	41.50	42.15
128	39.62	37.44	35.27	44.14	48.20	44.17	41.40	42.33
129	40.68	38.14	35.60	44.86	48.01	44.36	41.31	42.52
130	39.90	38.00	36.10	44.29	47.82	44.55	41.21	42.70
131	39.12	37.86	36.60	43.72	47.64	44.74	41.11	42.88
132	38.34	37.72	37.09	43.15	47.45	44.93	41.02	43.07
133	37.56	37.58	37.59	42.58	47.26	45.13	40.92	43.25
134	37.42	37.76	38.11	43.67	47.07	45.32	40.82	43.43
135	37.27	37.95	38.62	44.76	46.89	45.51	40.73	43.62
136	37.13	38.13	39.14	45.85	46.70	45.70	40.63	43.80
137	36.98	38.32	39.66	46.94	46.51	45.40	40.94	43.98
138	36.84	38.50	40.17	48.03	46.32	45.09	41.25	44.17
139	36.69	38.69	40.69	49.12	46.13	44.79	41.57	44.35
140	36.55	38.87	41.20	50.21	45.94	44.48	41.88	44.54
141	36.40	39.06	41.72	**51.30**	45.75	44.18	42.19	44.72
142	37.47	39.55	41.63	50.76	45.56	43.88	42.50	44.90
143	38.55	40.05	41.55	50.21	45.37	43.57	42.81	45.09
144	39.62	40.54	41.46	49.67	45.18	43.27	43.13	45.27
145	40.69	41.03	41.37	49.13	44.99	42.96	43.44	45.46
146	41.76	41.52	41.28	48.58	44.80	42.66	43.75	45.64
147	42.84	42.02	41.20	48.04	44.85	42.88	43.80	45.54
148	42.84	42.02	41.20	48.04	44.90	43.10	43.85	45.44
149	42.84	42.02	41.20	48.04	44.95	43.32	43.90	45.33
150	46.05	43.49	40.93	46.41	45.00	43.54	43.95	45.23
151	46.05	43.49	40.93	46.41	45.05	43.75	44.00	45.13
152	48.20	44.48	40.76	45.32	45.10	43.97	44.05	45.02
153	47.96	44.39	40.83	44.75	45.15	44.19	44.10	44.92
154	47.71	44.31	40.90	44.19	45.20	44.41	44.15	44.82
155	47.47	44.22	40.97	43.63	45.25	44.63	44.20	44.71
156	47.23	44.13	41.03	43.06	45.30	44.84	44.25	44.61
157	46.98	44.04	41.10	42.50	45.35	45.06	44.30	44.50
158	46.74	43.96	41.17	41.93	45.16	45.30	44.10	44.35
159	45.66	43.35	41.05	41.56	44.98	45.53	43.89	44.19
160	44.59	42.75	40.92	41.19	44.79	45.77	43.68	44.03
161	43.51	42.15	40.80	40.83	44.61	46.00	43.48	43.88
162	42.43	41.55	40.67	40.46	44.42	46.24	43.27	43.72
163	41.36	40.95	40.55	40.09	44.24	46.47	43.06	43.56
164	40.28	40.35	40.43	39.72	44.05	46.71	42.85	43.40
165	39.20	39.75	40.30	39.35	43.87	46.94	42.65	43.25
166	38.12	39.15	40.18	38.99	43.68	47.18	42.44	43.09
167	37.05	38.55	40.05	39.00	43.50	47.41	42.23	42.93
168	35.97	37.95	39.93	38.25	43.31	47.65	42.02	42.77
169	40.54	38.48	36.42	38.66	43.13	47.88	41.82	42.62
170	38.75	36.71	34.67	35.47	42.94	48.12	41.61	42.46
171	38.45	36.42	34.38	34.94	42.76	48.35	41.40	42.30
172	38.16	36.12	34.08	34.41	42.58	48.58	41.19	42.14

173	37.86	35.83	33.79	33.87	42.95	48.71	41.73	42.36
174	37.56	35.53	33.50	33.34	43.32	48.85	42.28	42.57
175	37.26	35.24	33.21	32.81	43.69	48.98	42.82	42.79
176	36.96	34.94	32.92	32.28	44.06	49.12	43.37	43.00
177	36.67	34.65	32.62	31.75	44.43	49.26	43.92	43.21
178	36.37	34.35	32.33	**31.21**	44.80	49.39	44.46	43.42
179	37.56	35.53	33.50	33.34	45.17	49.53	45.01	43.64
180	37.72	36.75	35.78	37.57	45.55	49.66	45.55	43.85
181	37.75	36.95	36.16	38.28	45.92	49.80	46.10	44.06
182	37.78	37.16	36.54	38.98	46.29	49.93	46.64	44.28
183	37.80	37.36	36.92	39.69	46.66	50.07	47.19	44.49
184	37.83	37.57	37.30	40.39	47.03	50.21	47.74	44.70
185	37.86	37.77	37.68	41.10	47.40	50.34	48.28	44.92
186	37.88	37.97	38.06	41.80	47.78	50.48	48.83	45.12
187	37.91	38.18	38.44	42.51	47.80	50.38	48.88	45.29
188	37.94	38.38	38.82	43.21	47.82	50.29	48.93	45.45
189	37.83	37.57	37.30	40.39	47.84	50.19	48.99	45.62
190	38.34	38.22	38.10	38.83	47.86	50.10	49.04	45.78
191	38.45	38.33	38.21	38.57	47.88	50.00	49.09	45.95
192	38.55	38.44	38.32	38.31	47.90	49.91	49.14	46.11
193	38.65	38.54	38.44	38.05	47.92	49.81	49.19	46.28
194	38.75	38.65	38.55	37.79	47.94	49.72	49.25	46.44
195	38.86	38.76	38.66	37.53	47.96	49.62	49.30	46.61
196	38.96	38.87	38.77	37.27	47.98	49.53	49.35	46.78
197	39.06	38.97	38.89	37.01	48.00	49.43	49.40	46.94
198	39.16	39.08	39.00	36.75	48.02	49.34	49.45	47.11
199	39.27	39.19	39.11	36.49	48.04	49.24	49.51	47.27
200	39.37	39.30	39.23	36.23	48.06	49.15	49.56	47.44
201	39.47	39.40	39.34	35.97	48.08	49.05	49.61	47.60
202	39.57	39.51	39.45	35.71	48.10	48.96	49.66	47.77
203	39.68	39.62	39.56	35.45	48.12	48.86	49.71	47.93
204	39.06	39.22	39.38	36.49	48.14	48.77	49.77	48.10
205	39.88	39.83	39.79	37.72	48.16	48.67	49.82	48.27
206	39.98	39.94	39.90	37.92	48.18	48.58	49.87	48.43
207	40.09	40.05	40.01	38.12	48.20	48.48	49.92	48.60
208	40.19	40.16	40.13	38.32	48.22	48.39	49.97	48.76
209	40.29	40.26	40.24	38.53	48.24	48.29	50.03	48.93
210	40.39	40.37	40.35	38.73	48.26	48.20	50.08	49.09
211	40.50	40.48	40.46	38.93	48.28	48.10	50.13	49.26
212	40.60	40.59	40.58	39.14	48.30	48.11	50.00	49.18
213	40.70	40.70	40.69	39.34	48.31	48.12	49.88	49.10
214	40.80	40.80	40.80	39.54	48.33	48.12	49.75	49.02
215	40.91	40.91	40.92	39.74	48.35	48.13	49.62	48.95
216	41.01	41.02	41.03	39.95	48.37	48.14	49.50	48.87
217	41.11	41.13	41.14	40.15	48.38	48.15	49.37	48.79
218	40.81	40.69	40.56	39.33	48.40	48.16	49.25	48.71
219	42.51	40.30	41.29	40.20	48.42	48.16	49.12	48.63
220	42.79	40.85	41.42	40.35	48.43	48.17	48.99	48.55
221	43.07	41.39	41.54	40.49	48.45	48.18	48.87	48.47
222	43.35	41.94	41.66	40.64	48.47	48.19	48.74	48.40

223	43.63	42.48	41.79	40.78	48.48	48.20	48.61	48.32
224	42.50	40.30	41.30	40.20	48.50	48.20	48.49	48.24
225	42.19	40.83	41.21	40.21	48.52	48.21	48.36	48.16
226	42.13	40.92	41.19	40.22	48.54	48.22	48.23	48.08
227	42.08	41.00	41.18	40.22	48.55	48.23	48.11	48.00
228	42.03	41.09	41.16	40.22	48.57	48.24	47.98	47.93
229	41.97	41.18	41.15	40.23	48.59	48.24	47.85	47.85
230	41.92	41.27	41.13	40.23	48.60	48.25	47.73	47.77
231	41.87	41.36	41.12	40.24	48.62	48.26	47.60	47.69
232	41.81	41.45	41.10	40.24	48.89	48.21	47.78	47.78
233	41.76	41.53	41.09	40.24	49.18	48.17	47.97	47.85
234	41.71	41.62	41.08	40.25	49.46	48.13	48.15	47.93
235	41.65	41.71	41.06	40.25	49.75	48.08	48.33	48.01
236	41.60	41.80	41.05	40.25	50.03	48.04	48.52	48.08
237	41.55	41.89	41.03	40.26	50.31	48.00	48.70	48.16
238	41.49	41.97	41.02	40.26	50.60	47.95	48.89	48.23
239	41.44	42.06	41.00	40.27	50.88	47.91	49.07	48.31
240	41.39	42.15	40.99	40.27	51.16	47.87	49.26	48.39
241	41.33	42.24	40.97	40.27	51.45	47.82	49.44	48.46
242	41.28	42.33	40.96	40.28	51.73	47.78	49.63	48.54
243	41.23	42.42	40.95	40.28	52.02	47.74	49.81	48.61
244	41.17	42.50	40.93	40.29	52.31	47.70	50.00	48.68
245	41.12	42.59	40.92	40.29	52.19	47.74	49.86	49.86
246	41.07	42.68	40.90	40.29	52.06	47.78	49.73	49.73
247	41.01	42.77	40.89	40.30	51.94	47.81	49.59	49.59
248	40.96	42.86	40.87	40.30	51.81	47.85	49.45	49.45
249	40.91	42.94	40.86	40.30	51.69	47.89	49.31	49.31
250	40.86	43.03	40.85	40.31	51.56	47.93	49.18	49.18
251	40.80	43.12	40.83	40.31	51.44	47.96	49.04	49.04
252	40.75	43.21	40.82	40.32	51.31	48.00	48.90	48.90
253	40.70	43.30	40.80	40.32	51.19	48.04	48.76	48.76
254	40.64	43.39	40.79	40.32	51.06	48.08	48.63	48.63
255	40.59	43.47	40.77	40.33	50.93	48.11	48.49	48.49
256	40.54	43.56	40.76	40.33	50.81	48.15	48.35	48.35
257	40.48	43.65	40.74	40.33	50.68	48.19	48.21	48.21
258	40.43	43.74	40.73	40.34	50.56	48.23	48.08	48.08
259	40.38	43.83	40.72	40.34	50.43	48.26	47.94	47.94
260	40.32	43.92	40.70	40.35	50.30	48.30	47.80	47.00
261	40.27	44.00	40.69	40.35	50.30	48.29	48.03	47.22
262	40.22	44.09	40.67	40.35	50.30	48.28	48.26	47.42
263	40.42	43.74	40.74	40.35	50.30	48.29	48.03	47.22
264	40.30	43.94	40.69	40.43	50.30	48.28	48.26	47.42
265	40.19	44.13	40.64	40.51	50.30	48.27	48.49	47.63
266	40.08	44.32	40.59	40.59	50.30	48.26	48.72	47.83
267	39.96	44.52	40.54	40.67	50.31	48.25	48.95	48.04
268	39.85	44.71	40.50	40.74	50.31	48.24	49.17	48.25
269	39.74	44.91	40.45	40.82	50.31	48.23	49.40	48.45
270	39.63	45.10	40.40	40.90	50.31	48.23	49.63	48.66
271	39.52	45.29	40.35	40.98	50.31	48.22	49.86	48.86
272	39.41	45.49	40.30	41.06	50.32	48.21	50.08	49.07

273	39.29	45.68	40.26	41.13	50.32	48.20	50.31	49.27
274	39.18	45.88	40.21	41.21	50.32	48.19	50.54	49.48
275	39.07	46.07	40.16	41.29	50.32	48.18	50.77	49.68
276	38.96	46.26	40.11	41.37	50.32	48.17	51.00	49.89
277	38.85	46.46	40.07	41.44	50.33	48.16	51.22	50.10
278	38.74	46.65	40.02	41.52	50.33	48.15	51.45	50.30
279	38.62	46.85	39.97	41.60	50.33	48.15	51.68	50.51
280	38.51	47.04	39.92	41.68	50.34	48.14	51.90	50.70
281	38.41	47.23	39.88	41.75	50.37	48.09	51.88	50.69
282	38.48	47.39	39.94	41.95	50.39	48.03	51.84	50.68
283	38.54	47.56	40.01	42.16	50.41	47.97	51.80	50.67
284	38.60	47.73	40.08	42.36	50.43	47.92	51.76	50.67
285	38.66	47.90	40.15	42.57	50.45	47.86	51.73	50.66
286	38.72	48.07	40.22	42.78	50.47	47.80	51.69	50.65
287	38.77	48.24	40.29	42.99	50.50	47.74	51.65	50.64
288	38.83	48.41	40.35	43.20	50.52	47.68	51.61	50.63
289	38.89	48.58	40.42	43.40	50.54	47.63	51.57	50.62
290	38.95	48.75	40.49	43.61	50.56	47.57	51.54	50.61
291	39.01	48.92	40.56	43.82	50.58	47.51	51.50	50.60
292	39.07	49.09	40.63	44.03	50.60	47.45	51.46	50.59
293	39.13	49.26	40.70	44.24	50.62	47.39	51.42	50.58
294	39.19	49.43	40.77	44.44	50.64	47.33	51.39	50.57
295	39.25	49.60	40.84	44.65	50.66	47.28	51.35	50.56
296	39.31	49.77	40.90	44.86	50.69	47.22	51.31	50.55
297	39.36	49.94	40.97	45.07	50.70	47.15	51.26	50.54
298	39.42	50.11	41.04	45.28	50.55	47.05	51.07	50.46
299	39.48	50.28	41.11	45.48	50.42	46.95	50.89	50.39
300	39.54	50.45	41.18	45.69	50.29	46.85	50.71	50.31
301	39.60	50.62	41.25	45.90	50.16	46.75	50.53	50.23
302	39.66	50.79	41.32	46.11	50.03	46.64	50.35	50.15
303	39.72	50.96	41.38	46.31	49.90	46.54	50.17	50.08
304	39.78	51.13	41.45	46.52	49.77	46.44	49.99	50.00
305	39.84	51.30	41.52	46.73	49.64	46.33	49.81	49.92
306	39.90	51.47	41.59	46.94	49.50	46.23	49.63	49.84
307	39.95	51.65	41.66	47.15	49.37	46.13	49.46	49.77
308	40.01	51.82	41.73	47.35	49.24	46.02	49.28	49.69
309	40.07	51.99	41.80	47.56	49.11	45.92	49.10	49.61
310	40.12	52.17	41.87	47.78	48.98	45.82	48.92	49.53
311	40.23	52.04	42.28	47.73	48.85	45.71	48.74	49.46
312	40.34	51.89	42.71	47.69	48.72	45.61	48.56	49.38
313	40.46	51.75	43.13	47.66	48.60	45.50	48.40	49.30
314	40.57	51.61	43.56	47.62	48.65	45.48	48.41	49.21
315	40.69	51.46	43.98	47.58	48.68	45.47	48.40	49.14
316	40.80	51.32	44.40	47.54	48.71	45.46	48.40	49.06
317	40.91	51.17	44.83	47.51	48.75	45.45	48.39	48.98
318	41.03	51.03	45.25	47.47	48.78	45.44	48.39	48.91
319	41.14	50.89	45.67	47.43	48.82	45.43	48.38	48.83
320	41.26	50.74	46.10	47.40	48.85	45.42	48.38	48.75
321	41.37	50.60	46.52	47.36	48.89	45.41	48.38	48.68
322	41.48	50.46	46.94	47.32	48.92	45.40	48.37	48.60

323	41.60	50.31	47.37	47.28	48.96	45.39	48.37	48.52
324	41.71	50.17	47.79	47.25	48.99	45.38	48.36	48.45
325	41.83	50.03	48.21	47.21	49.03	45.37	48.36	48.37
326	41.94	49.88	48.64	47.17	49.06	45.36	48.35	48.29
327	42.06	49.73	49.07	47.15	49.10	45.35	48.35	48.22
328	41.78	49.58	48.92	47.25	49.13	45.34	48.35	48.14
329	41.50	49.43	48.79	47.34	49.17	45.33	48.34	48.06
330	41.22	49.27	48.65	47.43	49.20	45.32	48.34	47.99
331	40.95	49.11	48.52	47.53	49.24	45.31	48.33	47.91
332	40.67	48.95	48.38	47.62	49.27	45.31	48.33	47.83
333	40.39	48.79	48.25	47.71	49.30	45.30	48.32	47.76
334	40.12	48.63	48.12	47.80	49.34	45.29	48.32	47.68
335	39.84	48.48	47.98	47.89	49.37	45.28	48.32	47.60
336	39.56	48.32	47.85	47.99	49.41	45.27	48.31	47.53
337	39.28	48.16	47.72	48.08	49.44	45.26	48.31	47.45
338	39.01	48.00	47.58	48.17	49.48	45.25	48.30	47.37
339	38.73	47.84	47.45	48.26	49.51	45.24	48.30	47.30
340	38.45	47.69	47.31	48.35	49.55	45.23	48.29	47.22
341	38.18	47.53	47.18	48.44	49.58	45.22	48.29	47.14
342	37.90	47.37	47.05	48.54	49.62	45.21	48.29	47.07
343	37.63	47.20	46.93	48.62	49.64	45.21	48.27	47.00
344	37.55	47.11	46.83	48.57	49.64	45.26	48.24	46.97
345	37.49	47.02	46.74	48.53	49.63	45.32	48.21	46.93
346	37.42	46.93	46.66	48.49	49.61	45.38	48.19	46.88
347	37.35	46.84	46.57	48.45	49.60	45.44	48.16	46.84
348	37.29	46.75	46.48	48.41	49.59	45.50	48.13	46.80
349	37.22	46.66	46.39	48.36	49.58	45.57	48.10	46.75
350	37.15	46.57	46.31	48.32	49.57	45.63	48.07	46.71
351	37.09	46.48	46.22	48.28	49.55	45.69	48.05	46.67
352	37.02	46.39	46.13	48.24	49.54	45.75	48.02	46.62
353	36.95	46.30	46.04	48.20	49.53	45.81	47.99	46.58
354	36.89	46.21	45.95	48.16	49.52	45.87	47.96	46.54
355	36.82	46.12	45.87	48.12	49.50	45.93	47.93	46.49
356	36.75	46.03	45.78	48.08	49.49	46.00	47.91	46.45
357	36.69	45.94	45.69	48.04	49.48	46.06	47.88	46.41
358	36.62	45.85	45.60	48.00	49.47	46.12	47.85	46.36
359	36.55	45.76	45.52	47.96	49.45	46.18	47.82	46.32
360	36.49	45.67	45.43	47.92	49.44	46.24	47.79	46.28
361	36.42	45.58	45.34	47.88	49.43	46.30	47.77	46.23
362	36.35	45.49	45.25	47.84	49.42	46.36	47.74	46.19
363	36.28	45.40	45.16	47.79	49.41	46.42	47.71	46.15
364	36.22	45.31	45.08	47.75	49.39	46.49	47.68	46.10
365	36.15	45.22	44.99	47.71	49.38	46.55	47.65	46.06
366	36.08	45.13	44.90	47.67	49.37	46.61	47.63	46.02
367	36.02	45.04	44.81	47.63	49.36	46.67	47.60	45.97
368	35.95	44.95	44.73	47.59	49.34	46.73	47.57	45.93
369	35.88	44.86	44.64	47.55	49.33	46.79	47.54	45.89
370	35.82	44.77	44.55	47.51	49.32	46.85	47.51	45.84
371	35.75	44.68	44.46	47.47	49.31	46.91	47.49	45.80
372	35.68	44.59	44.38	47.43				

373	35.63	44.50	44.30	47.40	
374	35.55	44.41	44.20	47.35	
375	35.48	44.32	44.11	47.31	
376	35.63	44.50	44.30	47.40	
377	35.35	44.14	43.94	47.23	
378	35.28	44.05	43.85	47.18	
379	35.63	44.50	44.30	47.40	
380	35.15	43.87	43.67	47.10	

2.3 BMP assays

2.3.1 First set

G.1	Accumulative methane (ml)				Methane concentration %			
Time	R1	R2	R3	R4	R1	R2	R3	R4
1	9.34	3.51	0.98	0.00	10.17	0.00	0.00	0.00
2	39.83	9.86	2.66	0.00	27.19	14.89	0.00	0.00
3	78.20	22.43	11.34	0.00	44.20	24.47	14.50	0.00
4	157.12	31.06	23.32	0.00	54.27	34.05	27.60	0.00
5	244.63	50.51	42.95	0.00	64.34	42.02	33.10	0.00
6	350.58	72.93	66.69	0.00	70.41	49.98	38.60	0.00
7	441.87	122.94	100.89	0.00	76.48	55.76	49.76	0.00
8	558.82	171.91	141.87	0.00	75.90	61.53	60.91	0.00
9	690.13	230.61	175.90	0.00	75.31	66.51	61.91	0.00
10	895.38	284.92	219.13	0.00	75.66	71.49	62.90	0.00
11	1072.42	358.64	295.29	0.00	76.00	73.31	66.62	8.40
12	1269.86	432.11	367.04	1.85	74.77	74.13	70.34	10.67
13	1378.39	563.72	479.32	6.40	73.54	72.77	70.87	14.62
14	1441.16	688.72	572.30	14.05	72.91	71.40	71.40	18.56
15	1491.87	831.77	704.94	25.58	72.27	71.90	71.90	22.13
16	1512.32	960.09	828.03	39.52	70.64	72.40	72.40	25.70
17	1519.30	1065.32	946.04	62.40	69.00	70.95	72.18	28.48
18	1524.58	1158.96	999.65	91.34	69.40	71.91	71.95	31.26
19	1530.29	1218.52	1048.70	126.36	68.70	72.86	72.91	33.38
20	1536.82	1247.07	1057.79	166.94	69.40	71.76	73.86	35.50
21	1545.85	1259.85	1069.62	196.22	69.32	70.65	71.11	37.13
22	1553.27	1282.73	1078.52	215.00	68.40	70.29	68.35	38.76
23	1556.68	1290.83	1086.37	231.00	67.30	69.93	67.83	40.21
24	**1562.49**	**1296.88**	**1092.21**	**241.55**	66.91	69.70	67.30	41.65

➢ First set (second group)

G.2	Accumulative methane (ml)				Methane concentration %			
Time	R5	R6	R7	R8	R5	R6	R7	R8
1	2.98	0.00	0.00	0.00	7.50	0.00	0.00	0.00
2	6.89	6.93	4.40	0.00	10.19	14.30	10.30	0.00
3	18.40	18.29	10.39	0.00	24.10	25.33	22.40	0.00
4	39.56	33.29	24.53	0.00	38.00	33.43	32.03	0.00
5	74.87	55.22	45.92	0.00	47.38	41.53	41.65	0.00
6	128.25	85.35	82.71	0.00	56.76	49.58	48.44	0.00

7	209.38	127.88	116.67	2.49	63.36	57.63	55.22	12.30
8	298.45	200.56	170.66	7.37	69.95	63.99	59.70	15.68
9	418.76	271.81	226.37	11.51	70.77	70.35	64.18	19.06
10	557.05	382.56	307.25	20.01	71.59	73.96	69.87	21.37
11	712.93	497.59	404.55	30.18	72.80	77.56	75.56	24.67
12	865.51	601.46	511.22	42.60	74.00	75.57	73.72	28.14
13	1054.07	743.57	633.42	58.84	72.00	73.57	71.88	31.61
14	1151.55	859.66	759.47	88.44	69.10	73.95	70.83	30.32
15	1254.48	1006.98	831.15	108.83	69.40	74.32	69.77	32.02
16	1397.89	1135.42	894.76	142.10	69.80	70.18	69.79	32.85
17	1573.61	1245.77	990.72	179.43	70.40	66.03	69.81	37.67
18	1720.13	1349.37	1092.39	211.51	69.84	69.52	70.62	36.35
19	1831.44	1448.66	1156.99	229.87	72.40	73.00	71.43	39.03
20	1928.88	1532.86	1198.98	248.71	73.20	71.40	72.10	42.30
21	1982.93	1601.61	1243.76	267.27	71.50	70.40	72.40	43.40
22	2017.98	1633.97	1299.72	289.35	69.21	71.00	70.00	48.50
23	2038.32	1656.40	1343.27	314.82	74.00	72.10	70.40	51.50
24	**2051.67**	**1678.77**	**1364.74**	**336.11**	75.31	71.90	73.30	49.30

2.3.2 Second set

G.1	Accumulative methane (ml)				Methane concentration %			
Time	R1	R2	R3	R4	R1	R2	R3	R4
1	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	7.55	0	0.00	0.00	10.40	0.00	0.00	0.00
3	12.72	0.64	0.00	0.00	16.88	7.80	0.00	0.00
4	24.17	2.55	1.08	0.00	23.35	12.01	7.10	0.00
5	36.39	5.58	3.56	0.00	29.84	17.36	11.35	0.00
6	53.14	10.37	6.50	0.00	36.34	22.75	15.60	0.00
7	81.07	18.58	11.31	1.52	42.83	28.14	19.40	10.50
8	117.65	26.61	17.50	4.58	49.32	33.43	23.60	14.50
9	156.71	41.97	25.52	10.20	57.30	38.92	25.56	17.12
10	220.64	63.37	34.81	18.83	61.60	44.31	29.60	19.34
11	294.56	93.99	52.74	26.78	66.27	49.76	34.50	21.76
12	360.24	131.09	67.77	40.81	69.40	52.18	36.72	28.61
13	422.39	173.53	99.47	49.55	70.50	54.60	41.17	26.61
14	483.30	227.05	132.92	59.94	71.60	57.02	45.63	29.03
15	532.87	303.33	175.16	67.27	71.80	59.44	50.08	31.45
16	591.66	389.34	231.98	71.92	72.50	61.85	54.54	33.87
17	631.15	490.17	306.38	75.32	73.50	64.27	58.99	33.82
18	641.83	598.21	398.47	79.22	73.80	66.69	60.47	33.85
19	657.75	683.54	500.92	83.37	74.00	69.11	61.94	33.87
20	669.35	777.26	611.61	85.63	74.15	71.53	64.48	35.43
21	677.40	876.87	700.36	88.80	74.10	71.86	67.01	36.99
22	681.56	962.74	787.82	92.39	73.50	72.19	69.55	38.54
23	683.53	1038.42	882.04	96.72	73.20	72.52	72.09	40.10
24	**685.50**	1097.13	972.46	108.87	73.00	72.85	72.05	42.73
25		1128.97	1047.93	115.77		73.18	72.04	45.37

26	1136.90	1115.55	127.65	73.51	72.01	48.00
27	1140.52	1164.14	143.17	73.84	71.98	50.63
28	1147.98	1189.89	170.46	74.17	71.96	53.26
29	1156.56	1204.83	194.17	74.50	71.94	55.90
30	**1161.21**	1218.41	225.45		71.93	58.53
31		1227.97	256.79		71.92	61.16
32		1235.15	292.56		71.40	66.00
33		1242.81	326.60		71.00	68.41
34		1247.33	366.73		70.86	75.08
35		1249.22	410.72		70.00	73.23
36		**1251.63**	450.59		70.30	75.64
37			487.71			78.05
38			538.99			78.63
39			573.95			78.34
40			611.65			78.06
41			645.21			77.78
42			668.39			77.49
43			698.87			77.21
44			732.63			76.92
45			782.61			76.64
46			826.79			76.35
47			874.16			76.07
48			917.45			75.79
49			967.80			75.50
50			1010.22			75.22
51			1066.35			75.07
52			1117.97			74.92
53			1168.94			74.78
54			1223.10			74.63
55			1266.74			74.48
56			1304.29			74.34
57			1341.21			74.19
58			1361.73			74.04
59			1390.90			73.90
60			1408.62			73.75
61			1432.26			73.60
62			1454.77			73.46
63			1460.67			75.12
64			1486.63			75.65
65			1494.49			78.16
66			1503.33			76.72
67			1511.10			77.26
68			1518.35			77.80
69			**1522.15**			77.49

➢ Second set (second group)

G.2	Accumulative methane (ml)				Methane concentration %			
Time	R5	R6	R7	R8	R5	R6	R7	R8
1	4.15	0.00	0.00	0.00	7.03	0.00	0.00	0.00
2	12.79	2.24	0.00	0.00	14.06	7.50	0.00	0.00
3	22.98	4.37	0.00	0.00	21.50	10.08	0.00	0.00
4	40.20	6.20	0.86	0.00	28.50	12.94	7.50	0.00
5	62.30	8.71	2.29	0.00	35.12	16.00	10.40	0.00
6	89.09	12.30	3.49	0.93	41.38	19.06	12.32	8.00
7	121.94	18.26	6.45	3.30	47.30	23.71	17.02	10.57
8	166.86	27.41	9.27	6.46	52.84	27.74	21.72	12.49
9	218.27	37.41	16.39	11.09	58.01	31.87	26.41	14.55
10	283.90	49.50	26.84	15.93	62.78	35.80	31.11	16.32
11	345.55	64.81	37.72	20.15	67.10	39.82	35.50	18.24
12	430.07	83.21	53.76	27.50	70.80	45.06	39.89	23.60
13	514.68	106.13	73.11	33.72	74.02	47.88	44.09	22.08
14	606.12	138.53	97.33	38.06	74.57	51.91	45.95	23.99
15	711.55	172.49	122.18	42.08	75.12	55.93	47.81	24.16
16	844.03	223.33	140.69	46.51	75.67	59.96	49.66	27.83
17	1000.63	283.18	178.73	51.38	76.22	63.30	55.82	29.26
18	1135.32	364.66	205.69	55.68	76.77	64.79	53.37	33.00
19	1235.14	449.53	242.52	64.43	76.87	65.92	55.23	35.56
20	1304.77	553.46	288.57	70.49	77.00	67.05	57.09	38.12
21	1342.64	679.91	349.12	81.97	76.41	68.18	58.94	40.68
22	1374.18	801.38	420.52	102.31	75.83	69.30	60.80	43.24
23	1382.89	904.24	510.81	130.52	75.24	71.10	60.70	48.14
24	1391.53	1012.54	614.67	174.95	74.65	71.56	63.19	48.36
25	1399.84	1114.84	708.38	201.47	74.06	72.69	65.24	50.92
26	1411.80	1207.55	792.36	244.81	73.48	73.82	67.29	53.48
27	1421.82	1286.42	870.23	279.67	72.89	74.95	69.35	56.04
28	**1426.52**	1360.37	961.42	323.76	72.30	76.08	71.40	58.60
29		1431.31	1052.00	348.54		77.21	73.45	61.16
30		1484.92	1139.11	369.70		78.03	76.97	62.23
31		1515.99	1216.61	383.61		77.60	77.55	66.28
32		1543.97	1284.81	401.04		77.50	79.60	68.84
33		1552.42	1352.09	434.25		76.88	80.62	71.73
34		1558.72	1403.54	476.31		76.00	79.42	71.78
35		1565.91	1438.10	516.42		73.00	78.22	72.00
36		**1572.69**	1476.99	566.05		72.00	77.01	72.21
37			1499.11	607.83			75.80	72.20
38			1510.64	660.90			75.86	72.63
39			1516.04	696.74			75.91	72.84
40			1524.59	737.44			75.97	73.05
41			1531.67	802.10			76.02	73.27
42			1539.99	878.65			76.08	73.48
43			**1543.17**	941.55			76.13	73.69
44				1037.79				73.90
45				1119.29				74.11

46	1195.10	74.32
47	1256.09	74.60
48	1332.58	74.46
49	1390.11	74.32
50	1444.85	74.18
51	1491.99	74.04
52	1517.65	73.90
53	1532.59	73.76
54	1543.78	73.62
55	1546.44	73.48
56	1549.62	73.34
57	**1550.68**	73.20

2.3.3 Third set

Third set (Normal digested anaerobic sludge)

	Accumulative methane (ml)				Methane concentration %			
Time	N0%	N1%	N2%	N3%	N0%	N1%	N2%	N3%
1	5.11	0.00	0.00	0.00	6.2	0	0	0
2	10.99	0.00	0.00	0.00	12.49	0	0	0
3	21.51	0.44	0.00	0.00	20.77	2.65	0	0
4	40.47	1.45	0.00	0.00	29.1	5.14	0	0
5	66.31	2.09	0.00	0.00	37.41	7.48	0	0
6	106.87	3.61	0.00	0.00	45.72	9.659	0	0
7	151.91	5.35	0.00	0.00	51.225	11.68	0	0
8	207.79	7.53	0.00	0.00	56.73	13.54	0	0
9	273.25	10.22	0.00	0.00	62.23	15.258	0	0
10	368.17	13.45	0.00	0.00	67.74	16.8	0	0
11	464.54	17.90	0.30	0.00	70.55	18.28	4.25	0
12	615.15	24.53	1.20	0.00	73.37	20.84	7.878	0
13	762.28	29.04	2.09	0.00	76.19	24.47	10.88	0
14	921.96	40.49	2.72	0.15	75.338	29.165	13.256	3.1
15	1068.13	53.79	3.42	0.44	74.48	34.93	15.003	5.77
16	1144.71	77.72	5.89	0.73	73.634	41.764	16.13	8.07
17	1179.57	106.18	7.07	2.11	72.78	49.66	16.63	10.07
18	1190.01	145.08	9.47	2.35	71.93	58.64	16.51	12.26
19	1198.62	191.00	10.93	2.77	70.73	58.5	18.6	13.38
20	1206.80	249.85	13.45	3.34	69.53	60.7	20.76	14.51
21	1218.81	314.84	17.58	5.56	69.54	64.43	26.95	16.2
22	1231.38	391.92	23.60	8.40	69.58	67.72	32.631	17.61
23	1235.47	465.62	30.27	10.80	69.59	70.59	37.8	19.07
24	1239.84	556.47	39.78	13.31	69.6	73.02	42.47	20.66
25	1242.30	658.93	55.88	16.40	69.61	75.01	46.64	22.45
26	1245.58	762.03	73.46	20.15	69.61	76.58	50.3	24.49
27	1254.29	860.07	95.69	28.26	69.34	76.62	53.45	26.84

28	1262.15	936.50	119.92	37.78	69.07	76.67	56.1	29.58
29	1263.77	1011.78	150.54	48.46	68.8	76.72	58.23	32.77
30	1273.46	1059.68	176.86	64.63	68.536	76.75	59.87	36.46
31	1275.07	1116.05	207.60	81.25	68.26	76.8	60.72	40.72
32	1285.74	1150.14	243.40	99.87	68	76.86	61.62	45.61
33	1287.34	1167.30	279.53	115.09	67.85	76.7	64.37	49.09
34	1295.31	1183.55	324.58	136.55	67.71	76.66	67.12	52.57
35	1300.09	1195.81	375.74	157.25	67.59	76.2	68.6	55.525
36	1301.41	1216.07	433.27	175.05	67.47	75.913	70.13	58.13
37	1306.70	1224.97	501.88	205.87	67.35	75.54	71.65	60.4
38	1310.92	1230.87	578.83	233.74	67.23	75.16	73.15	62.29
39	1317.77	1239.09	674.95	268.82	67.11	74.79	74.66	63.84
40	**1323.03**	**1243.18**	754.47	316.82	66.99	74.42	76.17	65.05
41			875.90	332.43			76.2	66.3
42			953.72	377.47			76.25	67.5
43			1010.62	382.92			76.3	69.4
44			1046.58	438.97			76.35	71.4
45			1073.57	484.56			76.4	72.6
46			1094.58	527.95			76.5	73.7
47			1112.61	571.94			76.55	74.72
48			1125.77	621.93			76.2	74.91
49			1137.64	686.78			75.6	75.1
50			1148.29	742.34			75.4	75.3
51			1157.14	793.97			75.1	75.6
52			1167.14	862.83			74.99	75.62
53			1176.53	923.99			74.7	74.91
54			1183.51	971.88			74.1	74.4
55			1189.30	1018.49			73.8	74.23
56			1195.08	1064.49			73.6	74.17
57			1202.57	1090.64			73.4	74.02
58			**1208.31**	1110.95			73.1	73.92
59				1128.34				73.85
60				1143.95				73.67
61				1157.79				73.43
62				1169.89				73.38
63				1176.21				73.29
64				**1179.09**				73.2

Third set (Acclimatized digested anaerobic sludge)

	Accumulative methane (ml)				Methane concentration %			
Time	S0%	S1%	S2%	S3%	S0%	S1%	S2%	S3%
1	4.50	2.18	0.00	0.00	7.03	3.05	0.00	0
2	13.88	4.90	0.00	0.00	14.06	7.21	0.00	0
3	24.93	9.99	2.14	0.00	21.50	13.10	6.81	0
4	43.61	17.73	5.00	0.00	28.50	18.60	13.02	0
5	67.60	27.14	11.87	0.67	35.12	23.76	18.62	9.44

6	96.67	39.13	16.42	2.49	41.38	28.55	23.63	11.91
7	132.32	51.30	25.54	4.52	47.30	32.98	28.02	14
8	181.06	65.55	35.91	6.94	52.84	37.04	31.82	15.8
9	236.84	83.62	44.71	9.05	58.01	40.75	35.01	17.3
10	308.05	108.38	56.95	11.58	62.78	44.10	37.60	18.43
11	374.95	127.90	68.83	13.03	67.10	48.76	40.90	20.5
12	466.65	151.77	82.26	17.53	70.80	52.90	43.85	22.5
13	558.46	176.67	95.57	18.78	74.02	56.64	46.45	24.55
14	657.68	214.02	110.67	23.25	74.57	59.84	48.70	26.49
15	772.08	248.36	125.75	25.26	75.12	62.50	50.56	28.4
16	915.83	286.50	144.15	29.29	75.67	64.78	52.10	30.2
17	1025.92	334.53	162.77	34.69	76.22	66.50	53.30	32
18	1143.74	378.15	181.45	37.08	76.77	67.77	54.07	33.75
19	1191.71	432.39	197.87	39.80	76.87	69.10	57.30	34.75
20	1206.82	494.65	215.23	44.72	77.00	70.50	60.59	35.75
21	1217.60	568.07	240.07	51.62	74.20	71.94	63.28	36.67
22	1221.82	668.07	267.65	58.72	71.70	73.21	65.68	37.66
23	1230.55	747.12	294.79	64.49	69.50	74.32	67.80	38.72
24	1233.74	831.65	323.48	73.26	67.70	75.30	69.60	39.86
25	1241.79	914.03	354.76	79.53	66.20	76.05	71.17	41
26	1253.27	978.73	390.58	87.01	65.00	76.67	72.43	42.33
27	1262.95	1033.82	433.44	95.56	64.88	76.70	72.80	43.6
28	1265.49	1072.08	476.25	104.59	64.80	76.75	73.20	45.07
29	1275.65	1096.80	530.42	117.00	64.70	76.80	73.40	46.5
30	1276.62	1117.91	586.17	126.44	64.67	76.83	73.60	48.1
31	1284.23	1130.27	648.45	137.36	64.60	76.80	73.80	49.7
32	1285.24	1145.66	710.85	155.32	64.56	76.90	73.95	51.4
33	1286.76	1157.09	764.16	170.59	64.32	75.44	74.63	51.9
34	1287.26	1167.83	823.87	186.88	64.20	73.98	75.31	52.51
35	1287.76	1177.92	882.72	205.00	64.00	73.40	75.72	54.2
36	1290.77	1183.63	938.31	222.10	63.80	72.76	76.14	55.85
37	1292.27	1186.46	1008.02	242.87	63.63	72.20	76.56	57.52
38	1295.75	1189.83	1062.35	260.99	63.42	71.50	76.90	59.2
39	1298.24	1198.18	1104.72	287.24	63.31	70.90	77.10	60.8
40	**1300.22**	**1207.02**	1132.21	306.39	63.22	70.40	77.82	62.54
41			1164.58	332.13			77.80	64.3
42			1192.02	353.01			77.70	66.5
43			1218.28	374.46			77.80	68.3
44			1236.61	425.93			77.80	70.5
45			1259.82	460.03			77.83	72.4
46			1264.41	503.48			77.85	73.8
47			1269.30	545.13			77.88	75.8
48			1275.38	589.62			77.50	77.64
49			1282.06	651.52			77.30	77.3
50			1285.69	701.43			77.10	76.6
51			1290.52	751.87			76.90	75.6
52			1294.74	818.51			76.87	75.13
53			1298.94	879.16			76.40	75.01

54		1303.71	936.20	76.00	74.91
55		1310.83	980.59	75.60	74.4
56		1317.91	1026.62	75.10	74.23
57		1322.02	1073.20	74.90	74.17
58		**1326.12**	1110.97	74.60	74.02
59			1142.89		73.92
60			1167.82		73.85
61			1188.63		73.67
62			1205.93		73.43
63			1223.21		73.38
64			**1228.96**		73.29

3. Leachate quality

3.1 COD

First group	COD (mg/l)			
Time	R1	R2	R3	R4
1	13600	15650	15700	20700
2	**29550**	**22950**	**25800**	29700
5	21750	14900	18650	29000
6	21533	14833	20933	**30933**
8	21700	13766	20700	30033
10	21800	13800	20050	29060
12	18900	12666	18633	26533
14	14166.6	10500	15450	21266
17	**9266.67**	**9133**	**13000**	**17600**
18	10166	9850	16266	17933
22	15933	13266	18600	19365
25	21100	14833	21900	20700
29	24800	16566	22403	27200
35	28533	16900	24060	28900
41	29900	22000	26600	32900
49	**32400**	25300	**27600**	**38800**
55	30900	**26600**	27000	38200
57	29600	24700	26400	38700
66	26066	21200	22800	37530
72	24000	**19700**	22700	37003
80	21800	19700	22000	36500
84	21000	20100	20900	35050
94	20700	20100	19700	35500
98	18900	19800	19800	34600
103	19100	20126	19700	35436

111	18700	19100	20000	33700
117	19400	20100	19800	**34800**
124	19200	20140	20450	28856
129	18765	20000	20200	27250
140	18700	20500	20200	25300
153	15200	18300	18500	22700
164	15000	16200	17800	22100
175	13030	14800	16300	20000
187	9700	11050	15800	23100
203	5300	9200	16100	19050
213	4750	7900	15750	17850
218	4250	7300	14800	18850
228	3900	6250	14000	18200
235	3400	4700	12600	17000
260	**2850**	**3550**	6100	13000
273	3225	3900	6375	11425
287	3937.5	4050	6712.5	**8812.5**
301	2925	2550	5635	8520
315	3637	3262	4300	8380
343	2850	3187.5	3375	7012.5
354	2287.5	2925	3300	6450
393	**2700**	**2725**	**3425**	**6250**

Second group	**COD (mg/l)**			
Time	**R5**	**R6**	**R7**	**R8**
1	28250	26650	33200	33100
4	**24045**	**24650**	**30650**	**34800**
7	19900	21850	25300	30250
9	18300	17900	20800	30900
11	11650	12700	19950	29400
13	9350	9550	17000	25550
15	7000	7300	14100	23700
17	**4700**	**5800**	**8550**	**15050**
19	12100	15150	7500	15500
22	14100	16100	8750	16687
26	20000	22900	10417	16271
28	22600	26900	12500	17250
30	24450	26800	12500	18530
33	28550	29850	19050	21650
42	32100	33350	**24600**	25250
48	34250	34100	25256	26900
56	32500	33300	27300	29868
60	33700	34000	28213	29900
70	35400	34500	30500	32700
73	**37685**	36200	**33200**	**33631**
79	37125	36731	29747	32500

87	34312	36563	28456	30654
94	36000	**36800**	27563	29813
101	31443	35212	27618	31162
106	29137	31894	23063	28518
116	27200	**24906**	25312	28743
129	**27112**	25987	22800	27000
140	27650	25350	23062	26437
151	26600	25500	21750	24550
163	25050	24050	20600	22850
179	21050	19400	18000	20100
189	17650	15000	16600	20350
194	13600	12900	15050	18950
204	12750	11000	13700	16500
211	8100	7520	13000	14100
236	6150	5250	8100	10050
249	**3825**	**3150**	**4500**	**7662**
263	4950	4538	5400	6788
277	3563	4200	4463	5438
291	3750	4088	4800	5250
319	3825	3975	4913	4538
330	3075	3000	3863	4125
369	3275	3525	4100	4475
388	**2925**	**3100**	**3550**	**4120**

3.2 BOD

First group	**BOD (mg/l)**			
Time	**R1**	**R2**	**R3**	**R4**
5	**14805**	**11498**	**12926**	**15880**
10	11074	7176	9023	12496
17	**4307**	**4513**	**6250**	**8568**
25	10719	7713	9855	8901
38	13560	12330	14800	15530
44	15400	14520	14800	17300
50	**16800**	**14640**	**15600**	18100
55	15720	12180	14010	19700
61	14700	11000	12000	**20100**
66	14000	11600	11400	18450
86	12500	11000	11200	16800
98	11100	10000	11900	16700
103	9900	9300	11600	17400
111	9600	9200	11200	16300
117	9700	9500	11600	16800
128	10300	9500	11100	17160
183	6200	7830	10000	11600
204	3000	4290	9720	12500

214	2940	4650	9100	13050
230	1590	3450	8100	11160
264	1360	2490	3800	8700
280	1196	2300	3200	4400
319	**960**	**1170**	**2000**	**3200**
330	880	1580	1500	3300
343	660	1050	1550	2900

Second group	**BOD (mg/l)**			
Time	**R5**	**R6**	**R7**	**R8**
5	**18363**	**16269**	**18697**	**20664**
17	**2209**	**2801**	**4138**	**8676**
20	8820	9930	9960	9960
26	10820	10920	10830	11270
31	11610	11000	11320	12900
37	12310	13380	11870	12060
42	12720	12540	12300	13100
50	15570	15360	12810	13170
67	**17820**	**17440**	**13270**	**14270**
74	15500	15900	12730	13600
79	15830	15650	11730	13400
87	15730	17060	12000	12560
93	14890	14170	11910	12600
100	14000	13700	10770	12180
152	12300	11300	11270	11350
180	11600	10910	9730	10800
190	9600	9570	8640	10550
206	6270	7070	8180	9980
240	2313	3137	4554	6331
256	2310	2310	1980	2880
291	2250	2100	2100	2790
306	1550	1630	1850	2500
319	**810**	**840**	**1220**	**1520**

3.3 VFA

First group	VFA (mg/l)			
Time	R1	R2	R3	R4
5	8171	7308	7935	10715
6	**9205**	**7960**	6915	10119
8	8817	6774	**9810**	**12425**
10	7269	6331	9510	11598
12	7498	6042	8650	11000
14	5124	7174	7660	9606
17	**3244**	**3272**	**4785**	**7372**
18	4350	4420	6677	8083
22	6554	5443	6238	8636
25	9347	6813	7052	9645
29	10730	7658	8685	11477
31	12409	8075	9437	13454
35	12177	9120	**10755**	14409
41	**13090**	**9120**	9930	15270
50	12358	8400	8970	**15779**
55	10316	8260	8630	15014
57	10060	8320	8260	14636
61	8006	7964	7776	13312
66	9016	7401	7889	13155
72	8265	7664	8227	13560
75	8265	7401	7851	13449
80	8190	7401	8791	13449
84	7889	7551	7851	12950
98	8077	7551	7401	13569
103	6612	7081	7889	12784
111	7269	7701	7401	13093
118	7025	7175	7513	11763
129	7003	7551	8507	10858
140	7213	7904	7682	10662
153	6721	6987	7175	10068
163	5687	5433	8266	9543
175	4874	5527	8534	8843
187	3286	4000	6589	9080
213	973	1870	5770	7901
228	201	989	3364	5200
235	103	848	4003	5543
260	228	1223	1295	2390
273	40	726	2218	2800
301	35	390	800	1750
319	**37**	**290**	**600**	**1350**
343	20	148	390	1012
393	1	1	1	294

Second group	VFA (mg/l)			
Time	R5	R6	R7	R8
1	8731	7659	12064	15546
4	**9389**	**8761**	**12940**	**18700**
7	8784	8933	10856	16932
9	8784	8933	8308	12600
11	4408	4107	8533	10783
13	3393	3337	7255	10507
15	2872	2556	6345	9300
17	**1853**	**1929**	**3756**	**6449**
19	3248	4701	4716	6326
22	6335	7201	8512	9395
24	8313	9044	9743	10654
26	9542	11173	9843	10659
28	11665	12861	10430	11450
30	13045	13030	9965	12540
42	13572	13464	9798	12650
48	14198	12981	9923	12700
56	14612	13318	10488	13956
67	16250	14059	11447	14507
74	**16686**	14880	**12604**	**15782**
79	16262	**15463**	11276	13736
87	13003	11896	8839	13500
94	14100	12753	9348	11512
101	13067	13381	9269	11400
106	13600	13660	9913	12186
116	9937	9005	8518	11300
129	12300	11347	9300	11017
140	11117	10805	8791	10897
151	11611	9327	10501	11641
163	9100	10100	9534	11108
189	7679	5608	7296	8356
204	2803	1182	4001	4217
211	2978	1400	4592	5055
236	1333	1360	2340	3420
249	250	200	663	1082
277	92	17	239	654
319	**59**	**80**	**201**	**819**
369	10	10	150	530
388	1	1	1	140

3.4 pH

First group	pH			
Time	R1	R2	R3	R4
5	**6.50**	**6.30**	**6.10**	**5.65**
6	6.54	6.90	6.66	6.20
8	6.91	7.03	6.43	5.82
10	6.51	7.05	6.38	5.90
12	7.40	7.15	6.81	6.70
14	7.74	7.10	7.10	6.70
17	**7.56**	**7.42**	**7.50**	**7.26**
18	7.35	7.37	7.20	7.14
22	6.91	7.02	7.14	6.78
25	6.38	6.61	6.72	6.40
29	**6.20**	**6.16**	**6.33**	**6.30**
31	6.30	6.72	6.88	6.63
35	6.60	7.18	6.90	6.55
41	7.20	7.30	7.22	6.71
48	7.57	7.77	7.73	7.01
55	7.26	7.90	7.80	7.48
57	7.32	7.90	7.76	7.41
61	7.56	7.81	7.85	7.65
66	7.60	7.91	7.90	6.80
72	7.33	7.00	7.11	6.77
75	7.44	7.15	6.76	6.92
80	7.60	7.14	7.18	7.11
84	7.34	7.00	6.80	7.00
98	7.29	6.83	6.75	7.07
103	7.32	6.85	6.92	7.31
111	7.22	6.88	6.79	7.22
117	7.38	6.91	6.72	7.34
129	7.20	6.76	6.80	7.07
140	7.00	6.82	6.71	7.00
154	7.20	6.86	6.76	7.02
164	7.15	6.81	6.85	6.92
187	7.61	7.40	6.81	7.26
213	7.66	7.03	7.41	7.34
228	7.78	7.20	7.69	7.20
260	7.40	7.30	7.43	7.35
273	7.50	7.29	7.49	7.41
301	7.72	7.73	7.53	7.50
343	7.63	7.50	7.44	7.39
393	8.03	7.92	7.94	7.83

Second group	pH			
Time	R5	R6	R7	R8
1	**6.30**	**6.72**	**6.60**	**5.72**
2	6.02	6.61	6.35	5.95
4	7.22	7.10	6.67	6.50
7	7.45	7.07	7.32	6.67
9	7.50	6.80	7.41	7.30
11	7.56	7.23	7.34	7.45
13	7.40	7.32	7.52	7.53
17	**7.45**	**7.50**	**7.66**	**7.50**
18	6.62	6.43	6.50	6.80
19	6.52	6.45	6.42	6.40
22	6.50	6.50	6.48	6.43
24	**6.20**	**6.25**	**6.38**	**6.33**
26	6.70	6.58	6.46	6.46
28	6.87	6.67	6.71	6.63
31	6.85	6.80	6.85	6.77
33	6.75	6.65	6.87	6.90
37	6.80	6.53	6.95	6.92
41	6.70	6.50	7.03	6.94
60	6.68	6.63	7.11	6.96
67	6.82	6.70	7.19	6.98
74	7.00	6.88	6.87	6.94
79	7.10	6.98	6.95	6.98
87	7.14	6.89	6.92	6.88
101	7.10	6.92	6.92	6.84
105	7.16	7.10	6.69	6.98
129	7.28	7.12	6.91	6.88
140	6.89	6.92	7.22	6.83
151	6.95	7.23	7.26	7.10
163	7.08	7.16	7.31	7.28
189	7.31	7.46	7.48	7.35
204	7.50	7.47	7.40	7.41
236	7.80	7.61	7.54	7.49
249	7.53	7.55	7.34	7.50
277	7.45	7.48	7.39	7.50
291	7.60	7.51	7.43	7.46
319	7.63	7.73	7.42	7.35
369	8.08	8.10	7.98	7.87
388	8.14	8.03	8.00	7.90

3.5 TVS

First group	TVS (mg/l)			
Time	**R1**	**R2**	**R3**	**R4**
3	10152	5972	8400	12500
5	**10088**	**7319**	**9876**	**14336**
17	**3700**	**3436**	**5260**	**8130**
22	7484	5440	5680	8520
26	9924	6804	8060	10560
28	12452	8212	10236	12884
32	13000	8800	10500	13502
36	13489	9338	11270	14236
41	**15740**	**12090**	**13707**	14648
47	15170	11871	13002	15516
57	12270	10270	10800	**17060**
68	11600	10310	10692	15360
75	11280	9741	10280	16216
84	9850	9800	10031	15948
94	9464	10080	9600	14080
104	9924	9570	9744	13920
111	10080	9552	10016	13348
117	10260	10384	9816	13730
125	10056	10540	10140	13200
131	10040	10180	10710	12800
141	10080	9676	10940	12550
159	9200	8300	10060	13333
176	8508	7484	9880	12450
191	6300	6552	9512	10400
204	5260	5532	8730	10208
211	4440	4928	8270	10472
220	4132	4846	7360	9564
228	3716	3588	7396	8560
260	3116	3484	6480	7050
280	3156	3204	5596	6576
301	2852	2552	2772	5480
315	2624	3684	2372	5256
343	2516	2468	2696	5784
354	3420	3548	3572	6860
393	**2516**	**2636**	**3520**	**5768**

Second group	TVS (mg/l)			
Time	R5	R6	R7	R8
1	10370	9830	11470	12410
2	**13652**	**12120**	**14136**	**16608**
4	9380	9372	8904	12032
8	8016	8160	7756	10748
12	5560	5532	5128	8884
17	**3028**	**3240**	**4096**	**6132**
19	3500	3644	4212	5986
23	8528	9508	4608	6215
26	10220	11516	5896	7276
29	11832	10224	7092	11870
33	12508	12364	8240	12600
37	14492	13336	9208	12300
42	14372	13468	10512	14028
44	17100	13304	11768	14616
47	17200	13720	12204	14800
48	17932	14540	12184	14596
51	17820	15952	12620	14648
60	**18028**	16400	12568	15452
66	17248	**17624**	**14460**	**16103**
70	17010	16728	11952	14870
78	17016	16976	10644	13500
85	16972	17084	10400	13110
91	15160	16068	9948	12950
99	13428	14856	10228	13260
105	13772	13796	10886	12060
116	12520	13732	10828	13212
134	12080	13100	8760	12408
151	10420	10560	9388	11268
166	10500	9400	8584	10372
179	9704	8360	8500	9868
186	8252	7436	8620	10080
204	7324	5572	8280	7756
236	4476	5300	4160	4772
256	3804	4344	3936	4700
277	3471.2	3620	3812	5140
291	3464	3852	4052	4844
319	3244	3340	3956	4264
330	4276	4520	4956	5840
369	3792	3876	4052	4663
388	**2972**	**3200**	**3372**	**4768**

3.6 TS

First group	TS (mg/l)			
Time	R1	R2	R3	R4
3	18320	12736	16436	22628
5	**23408**	**20136**	**29736**	**43288**
17	**13020**	**12756**	**20120**	**34082**
22	16268	15332	22440	36052
26	20320	18528	22712	40320
28	25096	20924	26040	44020
32	25500	20860	26828	49136
36	30732	21336	28676	50268
41	30924	22324	29532	49396
43	31012	23068	30312	49588
47	**32364**	**24568**	33752	49416
50	30980	20972	**35048**	51572
53	29152	19304	32740	49400
57	27944	19056	30152	51640
61	26508	18768	29804	51740
66	23252	20212	28512	51728
68	22900	17916	27636	50252
72	21420	17320	28324	**51824**
75	20928	19856	27892	51612
84	20328	18096	28600	50280
90	19688	19000	28356	47188
94	20144	19276	29884	44752
102	20712	18672	28952	45316
109	20828	18492	28956	44576
115	22376	19196	30308	48000
123	22112	19496	30036	45408
129	21800	17784	29424	45688
140	22272	19071	29708	45436
158	20800	18212	27760	42756
175	19916	17824	26136	41732
190	17956	17696	24688	42332
203	14944	18292	22784	40248
228	12824	15552	23100	44584
260	11892	14991	22148	39356
280	12196	15156	21568	40728
301	11688	13388	22476	41376
315	11696	13060	20060	40692
343	11712	12340	22128	40136
354	12504	12104	23364	39904
393	**11680**	**13064**	**23844**	**40528**

Second group	TVS (mg/l)			
Time	R5	R6	R7	R8
1	23540	21450	22530	23650
2	**26252**	**23516**	26184	32720
4	20000	20896	**31184**	**42720**
8	17596	18616	21516	30508
12	13668	14728	18096	27308
17	**8476**	**11716**	**17956**	**29424**
19	13292	16192	18537	30641
23	17120	21352	19879	31478
26	20572	25836	20908	34616
29	23128	27692	21716	33708
33	24764	28368	25976	36712
37	29092	32128	27220	36184
42	28980	30888	29224	37204
44	31524	35552	28220	36240
47	37240	30664	30540	36874
48	38420	31612	31615	38266
50	36184	32540	34057	39723
60	37456	35880	37924	40392
66	**40560**	38348	40304	41568
70	39948	41096	42732	43256
78	37852	**42268**	**44800**	43284
85	38196	39912	43512	42768
91	36276	37228	40236	45436
99	33980	36368	39628	48068
105	30444	34496	37096	**50868**
116	30096	32956	37840	48080
134	28128	32092	35120	46784
151	30016	32884	34208	44716
166	21784	25276	31676	42412
179	21728	23284	29996	42748
204	17332	21272	30536	44136
236	13248	18780	28260	41268
256	12844	17188	27616	41540
277	13043	18280	25956	40908
291	12104	18380	24688	39112
319	11920	17908	25352	39048
330	13840	15032	25032	38332
369	12448	13532	24812	38756
388	**10928**	**14844**	**24164**	**38060**

3.7 NH_3-N

First group	NH_3-N (mg/l)			
Time	**R1**	**R2**	**R3**	**R4**
5	**188.75**	192.62	239.70	263.10
6	159.88	**244.61**	**270.67**	432.98
8	236.81	191.06	285.30	**543.21**
10	207.18	87.09	237.77	519.54
12	178.35	45.19	188.75	339.58
14	79.99	64.00	164.47	339.58
17	**37.96**	**86.73**	**109.26**	**335.48**
18	37.81	70.55	81.95	294.70
22	28.94	61.72	79.02	300.73
25	50.82	94.05	139.31	228.33
29	91.79	146.25	226.49	292.32
31	92.54	157.31	303.17	492.90
35	101.99	222.85	410.78	1112.48
41	104.07	340.95	558.83	1112.48
55	84.31	392.88	613.39	1251.13
57	101.99	399.29	782.11	1308.12
61	103.23	454.55	876.03	2017.67
66	131.10	567.96	977.26	2421.03
70	**237.4**	631.03	949.94	2668.17
75	129.52	**657.11**	**1085.78**	**3240.72**
84	48.41	277.33	460.45	2362.32
98	25.73	169.89	380.43	2112.68
103	37.05	198.15	312.65	2012.21
111	26.91	196.56	273.98	1713.01
117	24.71	191.84	275.09	1545.43
129	34.03	170.58	335.48	1109.86
140	35.87	164.47	297.09	901.22
154	30.02	152.91	269.58	837.86
164	40.18	162.49	313.16	742.00
187	34.45	184.97	328.75	767.96
228	**36.75**	**164.47**	**303.17**	**658.83**
260	39.86	165.14	301.95	467.62

Second group	NH_3-N (mg/l)			
Time	R5	R6	R7	R8
1	303.17	436.50	488.92	532.32
2	**447.24**	**463.84**	**515.35**	**605.98**
4	248.60	265.24	528.03	452.71
7	463.84	479.12	339.58	316.98
9	159.88	221.95	135.97	142.74
11	163.15	266.32	116.57	104.50
13	149.24	139.31	104.07	88.87
15	56.01	81.29	68.30	69.98
17	**11.97**	**28.71**	**31.01**	**45.55**
19	13.79	35.01	61.72	72.58
22	15.89	53.35	77.75	131.10
24	95.98	143.32	80.61	103.23
26	139.31	171.97	122.87	205.51
28	168.63	220.69	229.26	310.41
31	184.63	279.78	232.06	487.76
33	**207.47**	**305.18**	277.33	547.52
37	164.27	286.58	399.29	605.60
42	126.92	259.31	**505.02**	**638.47**
60	73.58	146.25	281.86	535.60
67	97.15	164.47	256.79	475.63
74	128.47	123.37	255.75	426.73
79	131.06	135.97	293.51	366.74
94	80.31	198.15	193.40	306.88
101	39.06	157.31	169.89	332.77
105	19.54	121.39	168.52	262.04
116	27.68	116.57	160.52	223.75
129	84.65	114.23	157.31	171.27
140	33.76	92.17	141.58	206.34
163	43.04	87.44	115.63	135.97
195	30.51	60.73	76.81	119.92
204	18.84	30.88	46.86	71.70
236	**22.88**	**35.30**	**36.75**	**59.75**

3.8 Shortcircuiting

First analysis for shortcircuiting

3/11/2005	Initial COD (mg/l)			Mass in bioreactors (kg) $_{initial}$	Final Moisture content %	Volume of H_2O (l)	Expected COD (mg/l)	Measured COD out after 24 hr (mg/l)		
Reactors	COD_1	COD_2	Average					COD_1	COD_2	Average
R1	**9400**	**10000**	**9700**	**33.5**	**62.48**	**20.93**	**7268.98**	**5240**	**5840**	**5540**
R2	**10500**	**11600**	**11050**	**34.3**	**61.52**	**21.10**	**8297.63**	**6400**	**6700**	**6550**
R3	**16000**	**15600**	**15800**	**36.1**	**63.64**	**22.97**	**12109.94**	**9650**	**9900**	**9775**
R4	**23000**	**23200**	**23100**	**36.2**	**60.58**	**21.93**	**17510.76**	**15400**	**14100**	**14750**
R5	**26100**	**25100**	**25600**	**35.1**	**62.50**	**21.94**	**19407.60**	**14900**	**15600**	**15250**
R6	**24400**	**23700**	**24050**	**34.5**	**62.84**	**21.68**	**18179.67**	**13900**	**14000**	**13950**
R7	**21000**	**20200**	**20600**	**35.3**	**62.94**	**22.22**	**15664.64**	**12150**	**12200**	**12175**
R8	**23400**	**22300**	**22850**	**36.2**	**64.68**	**23.42**	**17591.20**	**14300**	**14600**	**14450**

Second analysis for shortcircuiting

3/11/2005	Initial COD (mg/l)			Mass in bioreactors (kg) $_{initial}$	Final Moisture content %	Volume of H_2O (l)	Expected COD (mg/l)	Measured COD out after 24 hr (mg/l)		
Reactors	COD_1	COD_2	Average					COD_1	COD_2	Average
R1	**2750**	**2650**	**2700**	**33.5**	**62.48**	**20.93**	**2023.33**	**1350**	**1670**	**1510**
R2	**2800**	**2650**	**2725**	**34.3**	**61.52**	**21.10**	**2046.25**	**1700**	**1450**	**1575**
R3	**3500**	**3350**	**3425**	**36.1**	**63.64**	**22.97**	**2625.10**	**2070**	**2100**	**2085**
R4	**6100**	**6400**	**6250**	**36.2**	**60.58**	**21.93**	**4737.76**	**3900**	**3750**	**3825**
R5	**3050**	**2800**	**2925**	**35.1**	**62.50**	**21.94**	**2217.47**	**1640**	**1790**	**1715**
R6	**3150**	**3050**	**3100**	**34.5**	**62.84**	**21.68**	**2343.33**	**1650**	**1950**	**1800**
R7	**3500**	**3600**	**3550**	**35.3**	**62.94**	**22.22**	**2699.49**	**2150**	**2140**	**2145**
R8	**4200**	**4050**	**4120**	**36.2**	**64.68**	**23.42**	**3171.81**	**2500**	**2730**	**2615**

4. Hydrolysis

4.1 First set

(Group one, with 20% normal anaerobic digested sludge)

	Accumulative methane (ml)				Methane concentration %			
Time	BR1	BR2	BR3	BR4	BR1	BR2	BR3	BR4
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	3.52	0.00	0.00	0.00	8.30	0.00	0.00	0.00
3	5.15	0.00	0.00	0.00	17.50	0.00	0.00	0.00
4	6.65	0.55	0.00	0.00	19.14	8.70	0.00	0.00
5	9.10	2.43	1.38	0.00	26.30	11.25	8.30	0.00
6	21.57	13.85	10.97	0.00	33.46	17.51	12.00	0.00
7	49.86	41.75	29.83	0.00	40.62	23.76	17.84	0.00
8	131.27	85.08	69.12	24.57	47.78	33.92	24.43	15.93
9	205.09	121.93	97.57	44.89	54.94	44.08	31.02	20.52
10	270.43	185.63	111.03	64.72	61.41	54.24	37.62	23.72
11	350.99	267.40	122.63	82.26	63.81	64.39	44.21	31.51
12	442.87	340.18	141.23	93.73	66.21	66.12	48.03	39.31
13	488.62	389.42	172.75	98.12	68.60	67.84	51.84	47.10
14	513.51	411.25	214.78	104.33	71.00	69.57	55.66	47.80
15	523.05	419.99	268.87	109.21	73.40	71.30	59.47	48.50
16	531.46	427.19	319.92	114.88	73.00	71.55	63.29	49.20
17	535.01	433.88	356.28	117.69	72.30	71.80	67.10	49.90
18	539.06	437.41	373.32	124.64	71.80	72.06	70.92	50.59
19	547.29	442.02	381.38	137.68	71.42	72.31	74.73	52.69
20	551.34	446.08	386.68	153.62	71.90	71.90	74.59	51.99
21	557.02	450.14	390.61	170.64	72.40	72.00	74.45	53.00
22	559.52	457.94	400.27	211.20	72.80	72.30	74.31	55.89
23	562.58	460.98	406.63	262.78	73.40	72.90	74.17	59.09
24	564.56	464.55	416.80	307.30	73.18	72.84	74.03	62.30
25	565.99	468.65	422.59	346.64	72.95	72.78	73.90	65.50
26	567.42	473.82	427.84	370.22	72.73	72.71	73.76	68.70
27	568.31	476.85	431.99	382.06	72.50	72.65	73.62	69.48
28	569.72	479.35	437.76	389.65	72.28	72.59	73.48	70.27
29	570.08	482.37	441.89	391.04	72.05	72.53	73.34	71.05
30	570.96	484.32	444.41	395.62	71.83	72.46	73.20	71.83
31	572.36	486.81	447.86	398.65	71.60	72.40	70.50	72.62
32	573.76	489.28	451.84	402.79	71.28	72.06	70.41	73.40
33	575.68	492.27	455.80	405.31	70.96	71.71	70.32	73.35
34	576.54	494.20	458.21	407.44	70.63	71.37	70.23	73.30
35	576.89	495.59	460.11	411.04	70.31	71.02	70.14	73.25
36	577.75	496.46	461.48	412.47	69.99	70.68	70.05	73.20
37	579.12	498.36	462.85	414.99	69.67	70.34	69.96	73.15
38	580.48	500.25	464.74	418.25	69.35	69.99	69.87	73.10
39	581.32	501.10	465.60	420.22	69.02	69.65	69.78	73.05
40	**581.66**	**501.95**	**466.46**	**423.26**	68.70	69.30	70.30	73.00

(Group two, 20% Acclimatized anaerobic digested sludge)

	Accumulative methane (ml)				Methane concentration %			
Time	BR5	BR6	BR7	BR8	BR5	BR6	BR7	BR8
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	7.17	0.00	0.00	0.00	8.50	0.00	0.00	0.00
3	15.27	5.25	0.00	0.00	14.50	7.50	0.00	0.00
4	19.06	7.21	0.00	0.00	23.00	10.40	0.00	0.00
5	28.39	9.30	4.53	0.00	37.68	13.10	10.00	0.00
6	40.44	28.20	13.69	0.00	45.93	30.00	18.40	0.00
7	90.51	58.93	31.79	3.22	54.17	38.80	32.53	9.60
8	161.90	107.38	68.50	12.37	56.88	47.50	35.73	15.60
9	243.03	172.29	107.63	18.17	59.59	53.60	38.93	20.40
10	318.49	231.76	136.03	27.01	62.30	59.60	42.13	24.70
11	391.10	275.64	172.93	50.59	65.01	62.35	45.33	30.63
12	440.24	299.94	216.36	76.77	67.72	65.22	48.53	33.70
13	460.79	321.31	232.75	114.82	70.43	68.09	49.88	36.77
14	475.68	340.96	248.07	152.18	73.14	70.95	51.23	40.11
15	487.76	363.05	269.60	182.11	75.85	73.82	52.58	43.44
16	502.04	380.82	300.80	199.20	75.64	73.98	53.93	46.78
17	517.40	398.63	328.73	220.82	75.43	74.13	57.82	50.11
18	538.79	420.85	353.54	254.45	75.23	74.29	61.72	53.37
19	547.99	444.21	377.51	287.63	75.02	74.44	65.61	56.63
20	552.76	458.84	388.08	318.76	74.81	74.60	69.50	59.89
21	556.97	463.61	400.34	348.33	74.63	74.75	70.43	63.15
22	560.08	468.81	407.51	372.20	74.72	73.10	71.36	65.33
23	561.55	472.36	411.06	390.41	74.81	72.40	72.28	67.52
24	563.55	476.43	415.67	395.36	74.18	72.26	72.42	69.70
25	564.99	480.50	426.70	404.70	73.55	72.11	72.55	71.88
26	566.42	484.56	434.01	410.90	72.92	71.97	72.68	72.18
27	567.31	488.08	442.93	414.99	72.29	71.83	72.81	72.48
28	568.19	491.07	451.88	417.48	71.66	71.68	72.95	72.79
29	570.63	493.53	459.22	423.22	71.03	71.54	73.08	73.09
30	573.05	495.46	463.35	427.36	70.40	71.40	73.21	73.39
31	575.46	497.38	470.16	432.60	70.19	71.17	73.02	73.69
32	576.83	498.77	477.48	438.95	69.98	70.94	72.83	73.99
33	578.20	500.16	480.51	445.87	69.77	70.71	72.64	74.30
34	579.57	501.54	482.46	450.08	69.56	70.48	72.45	74.60
35	581.44	503.43	484.94	453.73	69.35	70.25	72.26	74.52
36	583.30	505.32	488.48	456.84	69.14	70.02	72.06	74.44
37	583.64	506.18	492.00	460.49	68.93	69.79	71.87	74.36
38	583.98	507.03	493.93	464.67	68.72	69.56	71.68	74.28
39	584.82	507.37	495.86	467.77	68.51	69.33	71.49	74.20
40	**585.66**	**507.71**	**497.26**	**471.40**	68.30	69.10	71.30	74.12

4.2 Second set

(30% (v/v) normal digested sludge)

	Accumulative methane (ml)				Methane concentration %			
Time	BR1	BR2	BR3	BR4	BR1	BR2	BR3	BR4
1	0	0	0	0	0.00	0.00	0.00	0.00
2	5.44	0	0	0	8.50	0.00	0.00	0.00
3	12.39	2.78	0	0	14.50	7.50	0.00	0.00
4	28.84	7.61	0	0	23.00	10.40	0.00	0.00
5	56.21	16.31	0	0	37.68	13.10	10.00	0.00
6	93.89	29.42	4.29	0	45.93	30.00	18.40	0.00
7	174.84	51.64	10.66	1.86	54.17	38.80	32.53	9.60
8	259.34	85.98	23.40	7.51	56.88	47.50	35.73	15.60
9	308.65	135.77	48.35	14.63	59.59	53.60	38.93	20.40
10	335.96	202.56	85.48	26.15	62.30	59.60	42.13	24.70
11	370.08	276.57	149.14	49.93	65.01	62.35	45.33	30.63
12	402.71	320.83	207.73	76.61	67.72	65.22	48.53	33.70
13	460.02	374.88	260.14	110.63	70.43	68.09	49.88	36.77
14	543.04	423.48	307.07	162.47	73.14	70.95	51.23	40.11
15	611.16	453.13	334.61	196.54	75.85	73.82	52.58	43.44
16	635.34	465.86	371.66	241.65	75.64	73.98	53.93	46.78
17	643.52	478.43	396.85	277.16	75.43	74.13	57.82	50.11
18	654.42	489.88	411.25	298.27	75.23	74.29	61.72	53.37
19	658.64	511.29	417.55	310.60	75.02	74.44	65.61	56.63
20	660.10	528.80	428.17	320.37	74.81	74.60	69.50	59.89
21	663.18	547.41	437.70	333.33	74.63	74.75	70.43	63.15
22	664.62	556.06	447.78	346.86	74.72	73.10	71.36	65.33
23	666.06	564.15	459.47	358.33	74.81	72.40	72.28	67.52
24	670.68	574.43	469.55	373.03	74.18	72.26	72.42	69.70
25	672.62	578.66	480.16	389.92	73.55	72.11	72.55	71.88
26	675.60	581.77	496.71	409.55	72.92	71.97	72.68	72.18
27	676.48	586.54	513.80	424.95	72.29	71.83	72.81	72.48
28	678.93	590.20	529.27	433.95	71.66	71.68	72.95	72.79
29	681.37	594.40	536.64	443.51	71.03	71.54	73.08	73.09
30	682.24	599.70	542.40	451.48	70.40	71.40	73.21	73.39
31	683.63	601.16	547.62	458.40	70.19	71.17	73.02	73.69
32	685.54	602.08	551.21	468.62	69.98	70.94	72.83	73.99
33	687.45	602.99	555.35	477.78	69.77	70.71	72.64	74.30
34	688.31	604.42	558.41	487.53	69.56	70.48	72.45	74.60
35	688.66	605.33	562.54	496.70	69.35	70.25	72.26	74.52
36	689.52	606.23	565.60	509.15	69.14	70.02	72.06	74.44
37	690.88	607.67	569.20	519.93	68.93	69.79	71.87	74.36
38	691.73	608.57	571.72	531.24	68.72	69.56	71.68	74.28
39	692.58	609.47	575.85	539.24	68.51	69.33	71.49	74.20
40	**693.92**	**610.90**	**579.99**	**547.77**	68.30	69.10	71.30	74.12

Appendix B: Results of statistical analysis

Statistical methods

ANOVA

Analysis of variance (ANOVA) is a statistical procedure that is used to compare the means of parameters in different groups (e.g bioreactors). There are two types, one way and two way ANOVA.

- **One way ANOVA**

It is designed to compare the mean of one parameters in different groups (e.g compare the mean COD concentration in all bioreactors).In this method, the null hypothesis is assumed that the means COD are equal in all bioreactors and the alternatives are not equal. This table shows an example of one way ANOVA table

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	3541693830	7	505956261	5.543	**0.002**
Within Groups	32496375655	356	91281954		
Total	36038069485	363			

Since the significant or (P-value) is less than 0.05, then the null hypothesis is rejected and it is concluded that there was a significant difference in the mean COD in all bioreactors at 5% significance different.

If the significant difference is identified, then multiple comparison procedures could be used to determine where the difference is. This procedure compares all possible pairs of COD means simultaneously. There are different types of multiple comparisons such as Tukey, Bonferroni and Duncan.

- **Two way ANOVA**

The two way ANOVA introduces blocking variables which are used to associate some of the variations in the observation. It allows testing two different null hypotheses.

So, if we would like to compare the mean methane yield in two treatments (with and without sludge additions) at different salt contents (0. 0.5, 1, 3) % (w/v). The two null hypotheses could be

1) No difference in the mean methane yield at different salt contents.

2) No difference in the mean methane yield in two treatments.

This table presents an example of two way ANOVA table

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1077.817	4	269.454	402.838	.000
Intercept	35385.086	1	35385.086	52901.247	.000
Salt	610.621	3	203.540	304.296	**.000**
Group	499.320	1	499.320	367.816	**.000**
Error	4.073	3	1.358		
Total	36784.086	8			
Corrected Total	1123.539	7			

Since the P-values were less than 0.05. Then the null hypotheses were rejected and it can be concluded that there were significant differences in the mean methane yield in two treatments and at different salt contents.

References

MeBean, E. & Rovers, F. (1998). Statistical procedures for analysis environmental monitoring data and risk assessment, Prentic Hall PTR.

Hoshmand A. (1998). Statistical methods for environmental and agriculture sciences, CRC Press LLC.

1. Solid waste

1.1 Statistical analysis of moisture content

Table 1.1.1: One way ANOVA table for the mean of initial and final moisture content

	Sum of squares	df	Mean square	F	Sig.
Between groups	1857.610	1	1857.610	1070.779	**0.000**
Within groups	24.288	14	1.735		
Total	1881.898	15			

Table 1.1.2: One way ANOVA table for moisture profile in R1

	Sum of squares	df	Mean square	F	Sig.
Between groups	114.132	2	57.066	4.311	**0.069**
Within groups	79.424	6	13.237		
Total	193.557	8			

Table 1.1.3: One way ANOVA table for moisture profile in R2

	Sum of squares	df	Mean square	F	Sig.
Between Groups	64.579	2	32.290	1.092	**0.394**
Within Groups	177.367	6	29.561		
Total	241.947	8			

Table 1.1.4: One way ANOVA table for moisture profile in R3

	Sum of squares	df	Mean square	F	Sig.
Between groups	39.220	2	19.610	2.529	**0.160**
Within groups	46.526	6	7.754		
Total	85.746	8			

Table 1.1.5: One way ANOVA table for moisture profile in R4

	Sum of squares	df	Mean square	F	Sig.
Between groups	59.069	2	29.534	.577	**0.590**
Within groups	307.159	6	51.193		
Total	366.228	8			

Table 1.1.6: One way ANOVA table for moisture profile in R5

	Sum of squares	df	Mean square	F	Sig.
Between groups	18.425	2	9.212	2.902	**0.131**
Within groups	19.044	6	3.174		
Total	37.469	8			

Table 1.1.7: One way ANOVA table for moisture profile in R6

	Sum of squares	df	Mean square	F	Sig.
Between groups	4.270	2	2.135	1.665	**0.266**
Within groups	7.695	6	1.283		
Total	11.965	8			

Table 1.1.8: One way ANOVA table for moisture profile in R7

	Sum of squares	df	Mean square	F	Sig.
Between groups	10.722	2	5.361	1.113	**0.388**
Within groups	28.892	6	4.815		
Total	39.614	8			

Table 1.1.9: One way ANOVA table for moisture profile in R8

	Sum of squares	df	Mean square	F	Sig.
Between groups	22.822	2	11.411	1.100	**0.392**
Within groups	62.254	6	10.376		
Total	85.075	8			

Table 1.1.10: One way ANOVA table for mean final moisture content in all bioreactors

	Sum of squares	df	Mean square	F	Sig.
Between groups	94.835	7	13.548	1.301	**0.264**
Within groups	666.417	64	10.413		
Total	761.252	71			

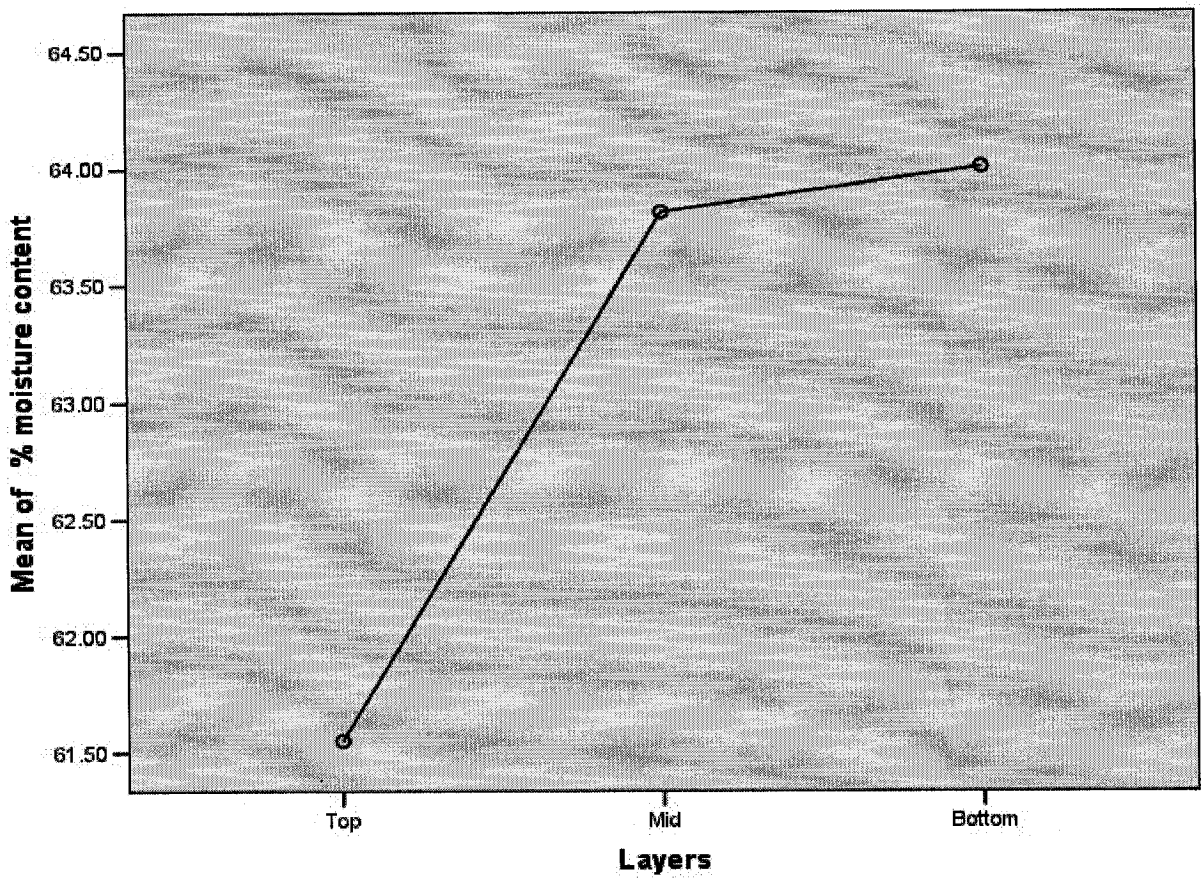

Figure 1.1: Mean moisture content in the layers in all bioreactors

1.2 Statistical analysis of Temperature

Table 1.2.1: One way ANOVA table for Temperature profile in R1

	Sum of squares	df	Mean square	F	Sig.
Between groups	20.427	2	10.214	.993	**0.381**
Within groups	360.107	35	10.289		
Total	380.534	37			

Table 1.2.2: One way ANOVA table for Temperature profile in R2

	Sum of squares	df	Mean square	F	Sig.
Between groups	9.481	2	4.740	2.032	**0.146**
Within groups	83.998	36	2.333		
Total	93.479	38			

Table 1.2.3: One way ANOVA table for Temperature profile in R3

	Sum of squares	df	Mean square	F	Sig.
Between groups	14.025	2	7.013	3.019	**0.061**
Within groups	83.618	36	2.323		
Total	97.644	38			

Table 1.2.4: One way ANOVA table for Temperature profile in R4

	Sum of squares	df	Mean square	F	Sig.
Between groups	10.552	2	5.276	1.305	**0.284**
Within groups	145.558	36	4.043		
Total	156.111	38			

Table 1.2.5: One way ANOVA table for Temperature profile in R5

	Sum of squares	df	Mean square	F	Sig.
Between groups	9.908	2	4.954	1.047	**0.361**
Within groups	170.288	36	4.730		
Total	180.196	38			

Table 1.2.6: One way ANOVA table for Temperature profile in R6

	Sum of squares	df	Mean square	F	Sig.
Between groups	5.668	2	2.834	.683	**0.511**
Within groups	149.326	36	4.148		
Total	154.994	38			

Table 1.2.7: One way ANOVA table for Temperature profile in R7

	Sum of squares	df	Mean square	F	Sig.
Between groups	21.887	2	10.943	2.433	**0.102**
Within groups	161.948	36	4.499		
Total	183.834	38			

Table 1.2.8: One way ANOVA table for Temperature profile in R8

	Sum of squares	df	Mean square	F	Sig.
Between groups	17.934	2	8.967	2.898	**0.068**
Within Groups	111.375	36	3.094		
Total	129.310	38			

Table 1.2.9: One way ANOVA table for mean Temperature in all reactors

	Sum of squares	df	Mean square	F	Sig.
Between groups	86.543	7	12.363	2.727	**0.009**
Within groups	1378.135	304	4.533		
Total	1464.679	311			

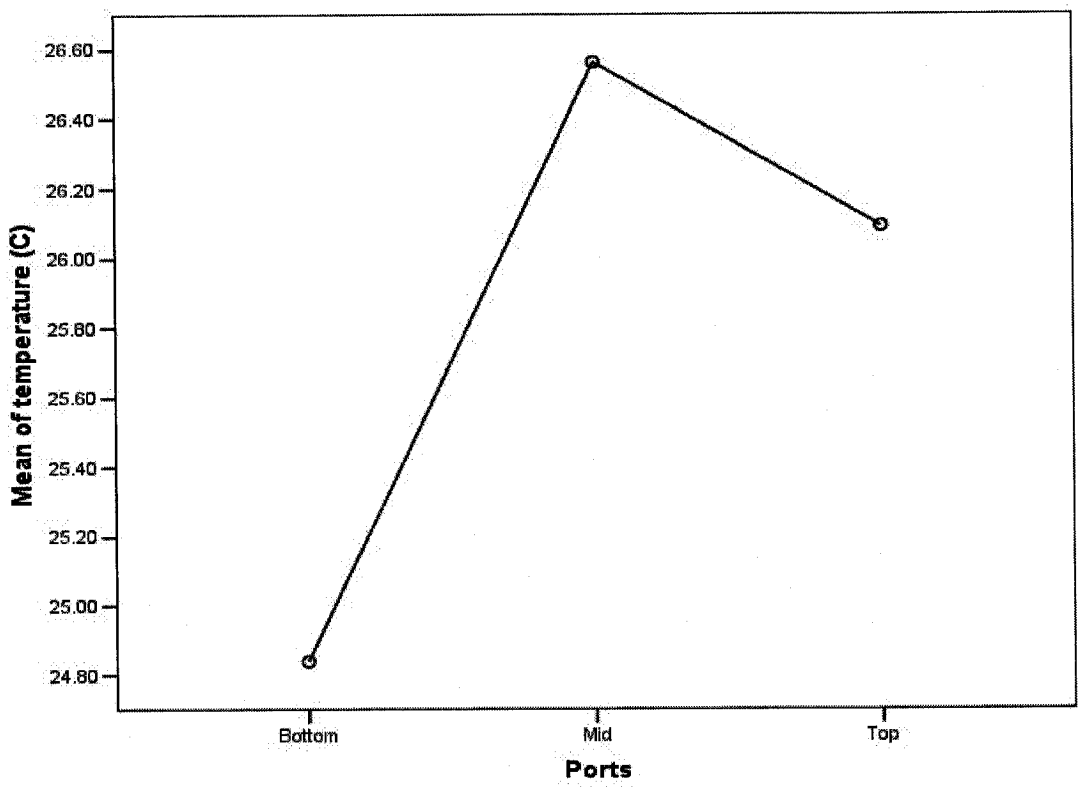

Figure 1.2: Mean temperature in layers in all bioreactors

1.3 Statistical analysis of settlement

Table 1.3.1: One way ANOVA table for mean settlement occurring during the aerobic stage in all bioreactors

	Sum of squares	df	Mean square	F	Sig.
Between groups	167.245	7	23.892	22.768	**0.000**
Within groups	25.185	24	1.049		
Total	192.430	31			

Table 1.3.2 Two way ANOVA table for settlement occurring during the aerobic stage as a function of salt content and groups

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	41.650	4	10.412	170.289	.001
Intercept	2927.273	1	2927.273	47873.624	.000
Group	.090	1	.090	1.477	**0.311**
Salt	41.560	3	13.853	226.560	**0.000**
Error	.183	3	.061		
Total	2969.106	8			
Corrected total	41.833	7			

Table 1.3.3: One way ANOVA table for mean settlement occurring during the anaerobic stage in all bioreactors

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	445.662	7	63.666	24.654	**0.000**
Within Groups	103.293	40	2.582		
Total	548.955	47			

Table 1.3.4: Two way ANOVA table for mean settlement occurring during the anaerobic stage as a function of salt content and groups

Source	Sum of squares	df	Mean square	F	Sig.
Corrected model	73.638	4	18.409	80.163	.002
Intercept	1708.786	1	1708.786	7440.826	.000
Group	52.122	1	52.122	226.963	**0.001**
Salt	21.516	3	7.172	31.230	**0.009**
Error	.689	3	.230		
Total	1783.113	8			

Table 1.3.5: Multiple comparisons of mean settlement occurred in aerobic stage as function of salt content and groups

Multiple Comparisons

Dependent Variable: Aerobic

Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	.8250	.24728	.126	-.3683	2.0183
	1.00	3.6550*	.24728	.002	2.4617	4.8483
	3.00	5.7250*	.24728	.001	4.5317	6.9183
.50	.00	-.8250	.24728	.126	-2.0183	.3683
	1.00	2.8300*	.24728	.004	1.6367	4.0233
	3.00	4.9000*	.24728	.001	3.7067	6.0933
1.00	.00	-3.6550*	.24728	.002	-4.8483	-2.4617
	.50	-2.8300*	.24728	.004	-4.0233	-1.6367
	3.00	2.0700*	.24728	.011	.8767	3.2633
3.00	.00	-5.7250*	.24728	.001	-6.9183	-4.5317
	.50	-4.9000*	.24728	.001	-6.0933	-3.7067
	1.00	-2.0700*	.24728	.011	-3.2633	-.8767

Based on observed means.

*. The mean difference is significant at the .05 level.

Table 1.3.6: Multiple comparisons of mean settlement occurred in anaerobic stage

Multiple Comparisons

Dependent Variable: Anaerobic

Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	.9400	.47922	.365	-1.3725	3.2525
	1.00	2.1800	.47922	.058	-.1325	4.4925
	3.00	4.3800*	.47922	.008	2.0675	6.6925
.50	.00	-.9400	.47922	.365	-3.2525	1.3725
	1.00	1.2400	.47922	.220	-1.0725	3.5525
	3.00	3.4400*	.47922	.017	1.1275	5.7525
1.00	.00	-2.1800	.47922	.058	-4.4925	.1325
	.50	-1.2400	.47922	.220	-3.5525	1.0725
	3.00	2.2000	.47922	.057	-.1125	4.5125
3.00	.00	-4.3800*	.47922	.008	-6.6925	-2.0675
	.50	-3.4400*	.47922	.017	-5.7525	-1.1275
	1.00	-2.2000	.47922	.057	-4.5125	.1125

Based on observed means.

*. The mean difference is significant at the .05 level.

Table 1.3.7: Two way ANOVA table for mean of total settlement occurred in the study as function of salt content and groups

Source	Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	178.284	4	44.571	141.998	.001
Intercept	9107.101	1	9107.10	29014.286	.000
Group	56.498	1	56.498	179.998	**0.001**
Salt	121.785	3	40.595	129.332	**0.001**
Error	.942	3	.314		
Total	9286.326	8			
Corrected Total	179.225	7			

Table 1.3.8: Multiple comparisons between mean of total settlement at different salt contents

Multiple Comparisons

Dependent Variable: Total

Tukey HSD

(I) Salt	(J) Salt	Mean difference (I-J)	Std. Error	Sig.	95% Confidence interval	
					Lower bound	Upper bound
.00	.50	1.7650	.56025	.144	-.9386	4.4686
	1.00	5.8300*	.56025	.006	3.1264	8.5336
	3.00	10.1050*	.56025	.001	7.4014	12.8086
.50	.00	-1.7650	.56025	.144	-4.4686	.9386
	1.00	4.0650*	.56025	.016	1.3614	6.7686
	3.00	8.3400*	.56025	.002	5.6364	11.0436
1.00	.00	-5.8300*	.56025	.006	-8.5336	-3.1264
	.50	-4.0650*	.56025	.016	-6.7686	-1.3614
	3.00	4.2750*	.56025	.014	1.5714	6.9786
3.00	.00	-10.1050*	.56025	.001	-12.8086	-7.4014
	.50	-8.3400*	.56025	.002	-11.0436	-5.6364
	1.00	-4.2750*	.56025	.014	-6.9786	-1.5714

Based on observed means.

*. The mean difference is significant at the .05 level.

2. Landfill biogas

2.1 Daily methane production

Table 2.1.1: ANOVA table for mean of methane production in all bioreactors

	Sum of squares	df	Mean square	F	Sig.
Between groups	1103832982.792	6	183972163.79	46.471	**.000**
Within groups	9901029989.023	2501	3958828.464		
Total	11004862971.815	2507			

Table 2.1.2: ANOVA table for mean of daily methane production in two groups

	Sum of squares	df	Mean square	F	Sig.
Between groups	486054062.165	1	486054062.165	115.844	**.000**
Within groups	10518808925.561	2507	4195775.399		
Total	11004862987.727	2508			

Table 2.1.3: Two way ANOVA table for mean of daily methane produced as function of salt content and groups

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1077.817	4	269.454	402.838	.000
Intercept	35385.086	1	35385.086	52901.247	.000
Group	467.196	1	467.196	698.465	**.000**
Salt	610.621	3	203.540	304.296	**.000**
Error	2.007	3	.669		
Total	36464.910	8			
Corrected Total	1079.824	7			

Table 2.1.4: Multiple comparisons of mean daily methane production in all bioreactors

Multiple Comparisons

Dependent Variable: CH4

Tukey HSD

(I) Reactors	(J) Reactors	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
R1	R2	478.29659*	147.68794	.021	42.5095	914.0837
	R4	1319.50597*	147.68794	.000	883.7189	1755.2930
	R5	-884.21940*	148.51765	.000	-1322.4547	-445.9841
	R6	-426.57149	148.51765	.062	-864.8068	11.6638
	R7	-226.31926	148.51765	.730	-664.5546	211.9161
	R8	382.79881	148.62367	.134	-55.7494	821.3470
R2	R1	-478.29659*	147.68794	.021	-914.0837	-42.5095
	R4	841.20938*	147.68794	.000	405.4223	1276.9965
	R5	-1362.5160*	148.51765	.000	-1800.7513	-924.2807
	R6	-904.86808*	148.51765	.000	-1343.1034	-466.6327
	R7	-704.61585*	148.51765	.000	-1142.8512	-266.3805
	R8	-95.49778	148.62367	.995	-534.0459	343.0504
R4	R1	-1319.5060*	147.68794	.000	-1755.2930	-883.7189
	R2	-841.20938*	147.68794	.000	-1276.9965	-405.4223
	R5	-2203.7254*	148.51765	.000	-2641.9607	-1765.4900
	R6	-1746.0775*	148.51765	.000	-2184.3128	-1307.8421
	R7	-1545.8252*	148.51765	.000	-1984.0606	-1107.5899
	R8	-936.70716*	148.62367	.000	-1375.2553	-498.1590
R5	R1	884.21940*	148.51765	.000	445.9841	1322.4547
	R2	1362.51599*	148.51765	.000	924.2807	1800.7513
	R4	2203.72537*	148.51765	.000	1765.4900	2641.9607
	R6	457.64792*	149.34276	.036	16.9779	898.3179
	R7	657.90015*	149.34276	.000	217.2302	1098.5701
	R8	1267.01821*	149.44819	.000	826.0371	1707.9993
R6	R1	426.57149	148.51765	.062	-11.6638	864.8068
	R2	904.86808*	148.51765	.000	466.6327	1343.1034
	R4	1746.07745*	148.51765	.000	1307.8421	2184.3128
	R5	-457.64792*	149.34276	.036	-898.3179	-16.9779
	R7	200.25223	149.34276	.833	-240.4178	640.9222
	R8	809.37029*	149.44819	.000	368.3892	1250.3514
R7	R1	226.31926	148.51765	.730	-211.9161	664.5546
	R2	704.61585*	148.51765	.000	266.3805	1142.8512
	R4	1545.82522*	148.51765	.000	1107.5899	1984.0606
	R5	-657.90015*	149.34276	.000	-1098.5701	-217.2302
	R6	-200.25223	149.34276	.833	-640.9222	240.4178
	R8	609.11806*	149.44819	.001	168.1370	1050.0992
R8	R1	-382.79881	148.62367	.134	-821.3470	55.7494
	R2	95.49778	148.62367	.995	-343.0504	534.0459
	R4	936.70716*	148.62367	.000	498.1590	1375.2553
	R5	-1267.0182*	149.44819	.000	-1707.9993	-826.0371
	R6	-809.37029*	149.44819	.000	-1250.3514	-368.3892
	R7	-609.11806*	149.44819	.001	-1050.0992	-168.1370

*. The mean difference is significant at the .05 level.

Table 2.1.5: Two way ANOVA table for methane yield as function of salt contents and Groups

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1051.464	4	262.866	95.693	.002
Intercept	35401.944	1	35401.944	12887.650	.000
Salt	632.123	3	210.708	76.706	**0.002**
Group	419.341	1	419.341	152.656	**0.001**
Error	8.241	3	2.747		
Total	36461.649	8			
Corrected Total	1059.705	7			

Table 2.1.6: Multiple comparisons for the mean methane yield at different salt contents.

Multiple Comparisons

Dependent Variable: Ym

Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	7.4650	1.65740	.060	-.5331	15.4631
	1.00	12.7200*	1.65740	.014	4.7219	20.7181
	3.00	24.4050*	1.65740	.002	16.4069	32.4031
.50	.00	-7.4650	1.65740	.060	-15.4631	.5331
	1.00	5.2550	1.65740	.142	-2.7431	13.2531
	3.00	16.9400*	1.65740	.006	8.9419	24.9381
1.00	.00	-12.7200*	1.65740	.014	-20.7181	-4.7219
	.50	-5.2550	1.65740	.142	-13.2531	2.7431
	3.00	11.6850*	1.65740	.018	3.6869	19.6831
3.00	.00	-24.4050*	1.65740	.002	-32.4031	-16.4069
	.50	-16.9400*	1.65740	.006	-24.9381	-8.9419
	1.00	-11.6850*	1.65740	.018	-19.6831	-3.6869

Based on observed means.

*. The mean difference is significant at the .05 level.

2.2 Methane concentration

Table 2.2.1: One way ANOVA table for mean methane concentration in all bioreactors

	Sum of squares	df	Mean square	F	Sig.
Between groups	10159.304	7	1452.218	13.065	**0.000**
Within groups	318330.393	2864	111.151		
Total	328489.698	2871			

Table 2.2.2: One way ANOVA table for mean methane concentration in two groups

	Sum of squares	df	Mean square	F	Sig.
Between groups	3768.090	1	3768.090	33.302	**0.000**
Within groups	324734.161	2870	113.148		
Total	328502.251	2871			

Table 2.2.3: One way ANOVA table for mean methane concentration at different salt contents

	Sum of squares	df	Mean square	F	Sig.
Between groups	5030.513	3	1676.838	14.867	**0.000**
Within groups	323471.738	2868	112.787		
Total	328502.251	2871			

Table 2.2.4: Multiple comparisons for mean methane concentration in all bioreactors

Multiple Comparisons

Dependent Variable: CH4

Tukey HSD

(I) Reactors	(J) Reactors	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
R1	R2	2.08047	.78269	.136	-.2935	4.4545
	R3	1.83939	.78269	.267	-.5346	4.2134
	R4	4.33523*	.78269	.000	1.9612	6.7092
	R5	-2.09039	.78709	.137	-4.4777	.2970
	R6	-.27301	.78709	1.000	-2.6604	2.1143
	R7	-.50619	.78709	.998	-2.8935	1.8811
	R8	1.95358	.78765	.204	-.4355	4.3426
R2	R1	-2.08047	.78269	.136	-4.4545	.2935
	R3	-.24107	.78269	1.000	-2.6151	2.1329
	R4	2.25477	.78269	.077	-.1192	4.6288
	R5	-4.17086*	.78709	.000	-6.5582	-1.7835
	R6	-2.35348	.78709	.057	-4.7408	.0339
	R7	-2.58666*	.78709	.023	-4.9740	-.1993
	R8	-.12689	.78765	1.000	-2.5159	2.2622
R3	R1	-1.83939	.78269	.267	-4.2134	.5346
	R2	.24107	.78269	1.000	-2.1329	2.6151
	R4	2.49584*	.78269	.031	.1218	4.8698
	R5	-3.92978*	.78709	.000	-6.3171	-1.5424
	R6	-2.11240	.78709	.128	-4.4997	.2749
	R7	-2.34559	.78709	.058	-4.7329	.0418
	R8	.11419	.78765	1.000	-2.2749	2.5032
R4	R1	-4.33523*	.78269	.000	-6.7092	-1.9612
	R2	-2.25477	.78269	.077	-4.6288	.1192
	R3	-2.49584*	.78269	.031	-4.8698	-.1218
	R5	-6.42562*	.78709	.000	-8.8130	-4.0383
	R6	-4.60824*	.78709	.000	-6.9956	-2.2209
	R7	-4.84143*	.78709	.000	-7.2288	-2.4541
	R8	-2.38165	.78765	.051	-4.7707	.0074
R5	R1	2.09039	.78709	.137	-.2970	4.4777
	R2	4.17086*	.78709	.000	1.7835	6.5582
	R3	3.92978*	.78709	.000	1.5424	6.3171
	R4	6.42562*	.78709	.000	4.0383	8.8130
	R6	1.81738	.79146	.296	-.5832	4.2180
	R7	1.58420	.79146	.481	-.8164	3.9848
	R8	4.04397*	.79202	.000	1.6417	6.4463
R6	R1	.27301	.78709	1.000	-2.1143	2.6604
	R2	2.35348	.78709	.057	-.0339	4.7408
	R3	2.11240	.78709	.128	-.2749	4.4997
	R4	4.60824*	.78709	.000	2.2209	6.9956
	R5	-1.81738	.79146	.296	-4.2180	.5832
	R7	-.23318	.79146	1.000	-2.6338	2.1674
	R8	2.22659	.79202	.093	-.1757	4.6289
R7	R1	.50619	.78709	.998	-1.8811	2.8935
	R2	2.58666*	.78709	.023	.1993	4.9740
	R3	2.34559	.78709	.058	-.0418	4.7329
	R4	4.84143*	.78709	.000	2.4541	7.2288
	R5	-1.58420	.79146	.481	-3.9848	.8164
	R6	.23318	.79146	1.000	-2.1674	2.6338
	R8	2.45977*	.79202	.040	.0575	4.8621
R8	R1	-1.95358	.78765	.204	-4.3426	.4355
	R2	.12689	.78765	1.000	-2.2622	2.5159
	R3	-.11419	.78765	1.000	-2.5032	2.2749
	R4	2.38165	.78765	.051	-.0074	4.7707
	R5	-4.04397*	.79202	.000	-6.4463	-1.6417
	R6	-2.22659	.79202	.093	-4.6289	.1757
	R7	-2.45977*	.79202	.040	-4.8621	-.0575

*. The mean difference is significant at the .05 level.

2.3 BMP assays using leachate produced from bioreactors as substrate

2.3.1 First set of BMP assays (in growth phase)

Hint: group one refers to use the leachate produced form group one of 1D bioreactors (R1, R2, R3, and R4), whereas, the group two to leachate produced from group two of 1D bioreactors (R5, R6, R7 and R8).

Table 2.3.1: One way ANOVA for mean daily methane production from all BMP assysas

	Sum of squares	df	Mean square	F	Sig.
Between groups	134819.170	7	19259.881	9.061	**0.000**
Within groups	391125.429	184	2125.682		
Total	525944.599	191			

Table 2.3.2: One way ANOVA for mean daily methane production from two groups of BMP assyas

	Sum of squares	df	Mean square	F	Sig.
Between groups	5482.260	1	5482.260	2.072	**0.152**
Within groups	502626.417	190	2645.402		
Total	508108.677	191			

Table 2.3.3: Two way ANOVA table for lag time to production methane in two groups of BMP assays and at different salt contents.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	82.500	4	20.625	11.512	.036
Intercept	55.125	1	55.125	30.767	.012
Group	3.125	1	3.125	1.744	**0.278**
Salt	79.375	3	26.458	14.767	**0.027**
Error	5.375	3	1.792		
Total	143.000	8			
Corrected total	87.875	7			

Table 2.3.4: Multiple comparisons for mean daily methane production from all BMP assays

Multiple Comparisons

Dependent Variable: CH4

Tukey HSD

(I) Reactor	(J) Reactor	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
R1	R2	9.70042	13.30940	.996	-31.1081	50.5089
	R3	19.00292	13.30940	.843	-21.8056	59.8114
	R4	62.59875*	13.30940	.000	21.7902	103.4073
	R5	-17.60917	13.30940	.889	-58.4177	23.1994
	R6	-2.07125	13.30940	1.000	-42.8798	38.7373
	R7	11.01208	13.30940	.991	-29.7964	51.8206
	R8	56.95208*	13.30940	.001	16.1436	97.7606
R2	R1	-9.70042	13.30940	.996	-50.5089	31.1081
	R3	9.30250	13.30940	.997	-31.5060	50.1110
	R4	52.89833*	13.30940	.003	12.0898	93.7069
	R5	-27.30958	13.30940	.450	-68.1181	13.4989
	R6	-11.77167	13.30940	.987	-52.5802	29.0369
	R7	1.31167	13.30940	1.000	-39.4969	42.1202
	R8	47.25167*	13.30940	.011	6.4431	88.0602
R3	R1	-19.00292	13.30940	.843	-59.8114	21.8056
	R2	-9.30250	13.30940	.997	-50.1110	31.5060
	R4	43.59583*	13.30940	.027	2.7873	84.4044
	R5	-36.61208	13.30940	.114	-77.4206	4.1964
	R6	-21.07417	13.30940	.760	-61.8827	19.7344
	R7	-7.99083	13.30940	.999	-48.7994	32.8177
	R8	37.94917	13.30940	.089	-2.8594	78.7577
R4	R1	-62.59875*	13.30940	.000	-103.4073	-21.7902
	R2	-52.89833*	13.30940	.003	-93.7069	-12.0898
	R3	-43.59583*	13.30940	.027	-84.4044	-2.7873
	R5	-80.20792*	13.30940	.000	-121.0164	-39.3994
	R6	-64.67000*	13.30940	.000	-105.4785	-23.8615
	R7	-51.58667*	13.30940	.004	-92.3952	-10.7781
	R8	-5.64667	13.30940	1.000	-46.4552	35.1619
R5	R1	17.60917	13.30940	.889	-23.1994	58.4177
	R2	27.30958	13.30940	.450	-13.4989	68.1181
	R3	36.61208	13.30940	.114	-4.1964	77.4206
	R4	80.20792*	13.30940	.000	39.3994	121.0164
	R6	15.53792	13.30940	.940	-25.2706	56.3464
	R7	28.62125	13.30940	.387	-12.1873	69.4298
	R8	74.56125*	13.30940	.000	33.7527	115.3698
R6	R1	2.07125	13.30940	1.000	-38.7373	42.8798
	R2	11.77167	13.30940	.987	-29.0369	52.5802
	R3	21.07417	13.30940	.760	-19.7344	61.8827
	R4	64.67000*	13.30940	.000	23.8615	105.4785
	R5	-15.53792	13.30940	.940	-56.3464	25.2706
	R7	13.08333	13.30940	.976	-27.7252	53.8919
	R8	59.02333*	13.30940	.000	18.2148	99.8319
R7	R1	-11.01208	13.30940	.991	-51.8206	29.7964
	R2	-1.31167	13.30940	1.000	-42.1202	39.4969
	R3	7.99083	13.30940	.999	-32.8177	48.7994
	R4	51.58667*	13.30940	.004	10.7781	92.3952
	R5	-28.62125	13.30940	.387	-69.4298	12.1873
	R6	-13.08333	13.30940	.976	-53.8919	27.7252
	R8	45.94000*	13.30940	.016	5.1315	86.7485
R8	R1	-56.95208*	13.30940	.001	-97.7606	-16.1436
	R2	-47.25167*	13.30940	.011	-88.0602	-6.4431
	R3	-37.94917	13.30940	.089	-78.7577	2.8594
	R4	5.64667	13.30940	1.000	-35.1619	46.4552
	R5	-74.56125*	13.30940	.000	-115.3698	-33.7527
	R6	-59.02333*	13.30940	.000	-99.8319	-18.2148
	R7	-45.94000*	13.30940	.016	-86.7485	-5.1315

*. The mean difference is significant at the .05 level.

Table 2.3.5: Multiple comparisons for mean lag time of methane production in two groups at different salt contents

Multiple Comparisons

Dependent Variable: Lag

Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	-1.0000	1.33853	.873	-7.4593	5.4593
	1.00	-1.5000	1.33853	.705	-7.9593	4.9593
	3.00	-8.0000*	1.33853	.028	-14.4593	-1.5407
.50	.00	1.0000	1.33853	.873	-5.4593	7.4593
	1.00	-.5000	1.33853	.979	-6.9593	5.9593
	3.00	-7.0000*	1.33853	.040	-13.4593	-.5407
1.00	.00	1.5000	1.33853	.705	-4.9593	7.9593
	.50	.5000	1.33853	.979	-5.9593	6.9593
	3.00	-6.5000*	1.33853	.049	-12.9593	-.0407
3.00	.00	8.0000*	1.33853	.028	1.5407	14.4593
	.50	7.0000*	1.33853	.040	.5407	13.4593
	1.00	6.5000*	1.33853	.049	.0407	12.9593

Based on observed means.

*. The mean difference is significant at the .05 level.

Table 2.3.6: Two way ANOVA table for time required to reach the peak methane production in two groups and at different salt contents.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	99.000	4	24.750	8.735	.053
Intercept	1860.500	1	1860.500	656.647	.000
Group	.500	1	.500	.176	**0.703**
Salt	98.500	3	32.833	11.588	**0.037**
Error	8.500	3	2.833		
Total	1968.000	8			
Corrected Total	107.500	7			

Table 2.3.7: Multiple comparisons for mean time required to reach the peak methane production in two groups at different salt contents

Multiple Comparisons

Dependent Variable: TimePeak

Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	-2.5000	1.68325	.538	-10.6228	5.6228
	1.00	-3.0000	1.68325	.423	-11.1228	5.1228
	3.00	-9.5000*	1.68325	.033	-17.6228	-1.3772
.50	.00	2.5000	1.68325	.538	-5.6228	10.6228
	1.00	-.5000	1.68325	.989	-8.6228	7.6228
	3.00	-7.0000	1.68325	.074	-15.1228	1.1228
1.00	.00	3.0000	1.68325	.423	-5.1228	11.1228
	.50	.5000	1.68325	.989	-7.6228	8.6228
	3.00	-6.5000	1.68325	.089	-14.6228	1.6228
3.00	.00	9.5000*	1.68325	.033	1.3772	17.6228
	.50	7.0000	1.68325	.074	-1.1228	15.1228
	1.00	6.5000	1.68325	.089	-1.6228	14.6228

Based on observed means.

*. The mean difference is significant at the .05 level.

Table 2.3.8: Two way ANOVA table for methane yield production from BMP assays in two groups and at different salt contents.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	175438.000	4	43859.500	246.633	.000
Intercept	800112.500	1	800112.500	4499.227	.000
Group	420.500	1	420.500	2.365	**0.222**
Salt	175017.500	3	58339.167	328.055	**0.000**
Error	533.500	3	177.833		
Total	976084.000	8			
Corrected Total	175971.500	7			

Table 2.3.9: Multiple comparisons for mean methane yield in two groups at different salt contents

Multiple Comparisons

Dependent Variable: Ym

Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	17.0000	13.33542	.632	-47.3523	81.3523
	1.00	74.0000*	13.33542	.034	9.6477	138.3523
	3.00	366.0000*	13.33542	.000	301.6477	430.3523
.50	.00	-17.0000	13.33542	.632	-81.3523	47.3523
	1.00	57.0000	13.33542	.069	-7.3523	121.3523
	3.00	349.0000*	13.33542	.000	284.6477	413.3523
1.00	.00	-74.0000*	13.33542	.034	-138.3523	-9.6477
	.50	-57.0000	13.33542	.069	-121.3523	7.3523
	3.00	292.0000*	13.33542	.001	227.6477	356.3523
3.00	.00	-366.0000*	13.33542	.000	-430.3523	-301.6477
	.50	-349.0000*	13.33542	.000	-413.3523	-284.6477
	1.00	-292.0000*	13.33542	.001	-356.3523	-227.6477

Based on observed means.

*. The mean difference is significant at the .05 level.

2.3.2 Second set of BMP assays (in decline phase)

Table 2.3.10: One way ANOVA for mean daily methane production from all BMP assysas

	Sum of squares	df	Mean square	F	Sig.
Between groups	25423.495	7	3631.928	3.526	**0.001**
Within groups	322420.503	313	1030.097		
Total	347843.997	320			

Table 2.3.11: One way ANOVA for mean daily methane production from two groups of BMP assyas

	Sum of squares	df	Mean square	F	Sig.
Between groups	4756.314	1	4756.314	4.410	**0.037**
Within groups	338688.828	314	1078.627		
Total	343445.142	315			

Table 2.3.12: Multiple comparisons for mean daily methane production from all BMP Assays in second set

Multiple Comparisons

Dependent Variable: CH4
Tukey HSD

(I) Reactor	(J) Reactor	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
R1	R2	-12.84011	9.54139	.880	-41.9595	16.2792
	R3	-6.30138	9.10274	.997	-34.0820	21.4792
	R4	6.40617	8.31685	.994	-18.9760	31.7883
	R5	-22.48083	9.54139	.267	-51.6002	6.6385
	R6	-15.21952	9.10274	.705	-43.0001	12.5611
	R7	-7.52764	8.84308	.990	-34.5158	19.4605
	R8	1.26088	8.50376	1.000	-24.6917	27.2135
R2	R1	12.84011	9.54139	.880	-16.2792	41.9595
	R3	6.53873	8.08869	.993	-18.1471	31.2246
	R4	19.24628	7.19285	.134	-2.7056	41.1981
	R5	-9.64071	8.57936	.951	-35.8240	16.5426
	R6	-2.37940	8.08869	1.000	-27.0653	22.3065
	R7	5.31248	7.79533	.997	-18.4781	29.1030
	R8	14.10099	7.40818	.550	-8.5080	36.7100
R3	R1	6.30138	9.10274	.997	-21.4792	34.0820
	R2	-6.53873	8.08869	.993	-31.2246	18.1471
	R4	12.70755	6.59990	.534	-7.4347	32.8498
	R5	-16.17945	8.08869	.483	-40.8653	8.5064
	R6	-8.91814	7.56628	.938	-32.0096	14.1734
	R7	-1.22626	7.25182	1.000	-23.3580	20.9055
	R8	7.56226	6.83394	.955	-13.2942	28.4188
R4	R1	-6.40617	8.31685	.994	-31.7883	18.9760
	R2	-19.24628	7.19285	.134	-41.1981	2.7056
	R3	-12.70755	6.59990	.534	-32.8498	7.4347
	R5	-28.88700*	7.19285	.002	-50.8388	-6.9352
	R6	-21.62569*	6.59990	.026	-41.7679	-1.4835
	R7	-13.93381	6.23690	.334	-32.9682	5.1006
	R8	-5.14529	5.74569	.986	-22.6805	12.3900
R5	R1	22.48083	9.54139	.267	-6.6385	51.6002
	R2	9.64071	8.57936	.951	-16.5426	35.8240
	R3	16.17945	8.08869	.483	-8.5064	40.8653
	R4	28.88700*	7.19285	.002	6.9352	50.8388
	R6	7.26131	8.08869	.986	-17.4245	31.9472
	R7	14.95319	7.79533	.539	-8.8374	38.7437
	R8	23.74170*	7.40818	.032	1.1327	46.3507
R6	R1	15.21952	9.10274	.705	-12.5611	43.0001
	R2	2.37940	8.08869	1.000	-22.3065	27.0653
	R3	8.91814	7.56628	.938	-14.1734	32.0096
	R4	21.62569*	6.59990	.026	1.4835	41.7679
	R5	-7.26131	8.08869	.986	-31.9472	17.4245
	R7	7.69188	7.25182	.964	-14.4399	29.8237
	R8	16.48039	6.83394	.239	-4.3761	37.3369
R7	R1	7.52764	8.84308	.990	-19.4605	34.5158
	R2	-5.31248	7.79533	.997	-29.1030	18.4781
	R3	1.22626	7.25182	1.000	-20.9055	23.3580
	R4	13.93381	6.23690	.334	-5.1006	32.9682
	R5	-14.95319	7.79533	.539	-38.7437	8.8374
	R6	-7.69188	7.25182	.964	-29.8237	14.4399
	R8	8.78851	6.48406	.876	-11.0002	28.5772
R8	R1	-1.26088	8.50376	1.000	-27.2135	24.6917
	R2	-14.10099	7.40818	.550	-36.7100	8.5080
	R3	-7.56226	6.83394	.955	-28.4188	13.2942
	R4	5.14529	5.74569	.986	-12.3900	22.6805
	R5	-23.74170*	7.40818	.032	-46.3507	-1.1327
	R6	-16.48039	6.83394	.239	-37.3369	4.3761
	R7	-8.78851	6.48406	.876	-28.5772	11.0002

*. The mean difference is significant at the .05 level.

Table 2.3.13: One way ANOVA table for mean lag time of methane production in two groups

	Sum of squares	df	Mean square	F	Sig.
Between groups	2.000	1	2.000	.429	**0.537**
Within groups	28.000	6	4.667		
Total	30.000	7			

Table 2.3.14: One way ANOVA table for mean lag time of methane production at different salt contents

	Sum of squares	df	Mean square	F	Sig.
Between groups	28.000	3	9.333	18.667	**0.008**
Within groups	2.000	4	.500		
Total	30.000	7			

Table 2.3.15: Multiple comparisons for mean lag time of methane production in two groups at different salt contents

Multiple Comparisons

Dependent Variable: Lag

Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	-1.00000	.70711	.553	-3.8785	1.8785
	1.00	-2.00000	.70711	.146	-4.8785	.8785
	3.00	-5.00000*	.70711	.007	-7.8785	-2.1215
.50	.00	1.00000	.70711	.553	-1.8785	3.8785
	1.00	-1.00000	.70711	.553	-3.8785	1.8785
	3.00	-4.00000*	.70711	.016	-6.8785	-1.1215
1.00	.00	2.00000	.70711	.146	-.8785	4.8785
	.50	1.00000	.70711	.553	-1.8785	3.8785
	3.00	-3.00000*	.70711	.044	-5.8785	-.1215
3.00	.00	5.00000*	.70711	.007	2.1215	7.8785
	.50	4.00000*	.70711	.016	1.1215	6.8785
	1.00	3.00000*	.70711	.044	.1215	5.8785

*. The mean difference is significant at the .05 level.

Table 2.3.16: Two way ANOVA table for time required to reach the peak methane production in two groups and at different salt contents.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	1429.500	4	357.375	14.015	0.028
Intercept	5202.000	1	5202.000	204.000	0.001
Group	12.500	1	12.500	.490	**0.534**
Salt	1417.000	3	472.333	18.523	**0.019**
Error	76.500	3	25.500		
Total	6708.000	8			
Corrected total	1506.000	7			

Table 2.3.17: Multiple comparisons for mean time required to reach the peak methane production in two groups at different salt contents

Multiple Comparisons

Dependent Variable: TimePeak

Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	-5.5000	5.04975	.720	-29.8684	18.8684
	1.00	-8.0000	5.04975	.497	-32.3684	16.3684
	3.00	-34.5000*	5.04975	.019	-58.8684	-10.1316
.50	.00	5.5000	5.04975	.720	-18.8684	29.8684
	1.00	-2.5000	5.04975	.955	-26.8684	21.8684
	3.00	-29.0000*	5.04975	.031	-53.3684	-4.6316
1.00	.00	8.0000	5.04975	.497	-16.3684	32.3684
	.50	2.5000	5.04975	.955	-21.8684	26.8684
	3.00	-26.5000*	5.04975	.040	-50.8684	-2.1316
3.00	.00	34.5000*	5.04975	.019	10.1316	58.8684
	.50	29.0000*	5.04975	.031	4.6316	53.3684
	1.00	26.5000*	5.04975	.040	2.1316	50.8684

Based on observed means.

*. The mean difference is significant at the .05 level.

Table 2.3.18: Two way ANOVA table of stabilization time for methane production in two groups and at different salt contents.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected nodel	1581.000	4	395.250	9.680	.046
Intercept	12960.500	1	12960.500	317.400	.000
Group	4.500	1	4.500	.110	**0.762**
Salt	1576.500	3	525.500	12.869	**0.032**
Error	122.500	3	40.833		
Total	14664.000	8			
Corrected total	1703.500	7			

Table 2.3.19: Multiple comparisons for stabilization time of methane production in two groups at different salt contents

Multiple Comparisons

Dependent Variable: Stabilization

Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	-8.0000	6.49038	.651	-39.3204	23.3204
	1.00	-14.5000	6.49038	.292	-45.8204	16.8204
	3.00	-38.0000*	6.49038	.030	-69.3204	-6.6796
.50	.00	8.0000	6.49038	.651	-23.3204	39.3204
	1.00	-6.5000	6.49038	.761	-37.8204	24.8204
	3.00	-30.0000	6.49038	.056	-61.3204	1.3204
1.00	.00	14.5000	6.49038	.292	-16.8204	45.8204
	.50	6.5000	6.49038	.761	-24.8204	37.8204
	3.00	-23.5000	6.49038	.104	-54.8204	7.8204
3.00	.00	38.0000*	6.49038	.030	6.6796	69.3204
	.50	30.0000	6.49038	.056	-1.3204	61.3204
	1.00	23.5000	6.49038	.104	-7.8204	54.8204

Based on observed means.

*. The mean difference is significant at the .05 level.

Table 2.3.20: Two way ANOVA table of methane yield in two groups and at different salt contents.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	2923.500	4	730.875	3.341	.175
Intercept	1483503.125	1	1483503.125	6780.437	.000
Group	120.125	1	120.125	.549	**0.512**
Salt	2803.375	3	934.458	4.271	**0.132**
Error	656.375	3	218.792		
Total	1487083.000	8			
Corrected total	3579.875	7			

2.3.3 Third set of BMP (Comparison between two types of inoculums)

In this set, leachate from R1 used as substrate for the BMP assays and operated at 0, 1, 2, and 3% (w/v) salt content. Two types of inoculums (normal and acclimatized digested sludge) were used in this set.
Group one (N) refer to the BMP using normal digested sludge as inoculums, whereas, the group two (S) using acclimatized digested sludge as inoculums.

Table 2.3.21: One way ANOVA for mean daily methane production from all BMP assysas

	Sum of squares	df	Mean square	F	Sig.
Between Groups	12974.424	7	1853.489	2.156	**0.037**
Within Groups	340466.804	396	859.765		
Total	353441.229	403			

Table 2.3.22: One way ANOVA for mean daily methane production from two groups of BMP assyas

	Sum of squares	df	Mean square	F	Sig.
Between Groups	10.383	1	10.383	.012	**0.914**
Within Groups	353430.845	402	879.181		
Total	353441.229	403			

Table 2.3.23: Two way ANOVA table for lag time of methane production in two groups of BMP assays and at different salt contents.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	158.000	4	39.500	3.485	0.167
Intercept	128.000	1	128.000	11.294	0.044
Group	50.000	1	50.000	4.412	**0.127**
Salt	108.000	3	36.000	3.176	**0.184**
Error	34.000	3	11.333		
Total	320.000	8			
Corrected total	192.000	7			

Table 2.3.24: Multiple comparisons for mean daily methane production from all BMP assays

Multiple Comparisons

Dependent Variable: CH4
Tukey HSD

(I) Reactor	(J) Reactor	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
N0%	N1%	1.99650	6.55654	1.000	-17.9827	21.9757
	N2%	12.24280	6.02641	.462	-6.1210	30.6066
	N3%	14.40641	5.92800	.230	-3.6575	32.4703
	S0%	1.29405	6.51644	1.000	-18.5629	21.1510
	S1%	2.90125	6.55654	1.000	-17.0779	22.8804
	S2%	10.21228	6.02641	.691	-8.1515	28.5761
	S3%	13.87391	5.90999	.271	-4.1351	31.8829
N1%	N0%	-1.99650	6.55654	1.000	-21.9757	17.9827
	N2%	10.24630	6.02641	.687	-8.1175	28.6101
	N3%	12.40991	5.92800	.421	-5.6540	30.4738
	S0%	-.70245	6.51644	1.000	-20.5594	19.1545
	S1%	.90475	6.55654	1.000	-19.0744	20.8839
	S2%	8.21578	6.02641	.873	-10.1480	26.5796
	S3%	11.87741	5.90999	.477	-6.1316	29.8864
N2%	N0%	-12.24280	6.02641	.462	-30.6066	6.1210
	N1%	-10.24630	6.02641	.687	-28.6101	8.1175
	N3%	2.16361	5.33578	1.000	-14.0957	18.4229
	S0%	-10.94875	5.98276	.600	-29.1795	7.2820
	S1%	-9.34155	6.02641	.780	-27.7053	9.0222
	S2%	-2.03052	5.44491	1.000	-18.6223	14.5613
	S3%	1.63110	5.31576	1.000	-14.5672	17.8294
N3%	N0%	-14.40641	5.92800	.230	-32.4703	3.6575
	N1%	-12.40991	5.92800	.421	-30.4738	5.6540
	N2%	-2.16361	5.33578	1.000	-18.4229	14.0957
	S0%	-13.11235	5.88362	.337	-31.0410	4.8163
	S1%	-11.50516	5.92800	.524	-29.5690	6.5587
	S2%	-4.19412	5.33578	.994	-20.4534	12.0651
	S3%	-.53250	5.20393	1.000	-16.3900	15.3250
S0%	N0%	-1.29405	6.51644	1.000	-21.1510	18.5629
	N1%	.70245	6.51644	1.000	-19.1545	20.5594
	N2%	10.94875	5.98276	.600	-7.2820	29.1795
	N3%	13.11235	5.88362	.337	-4.8163	31.0410
	S1%	1.60720	6.51644	1.000	-18.2498	21.4642
	S2%	8.91823	5.98276	.812	-9.3125	27.1490
	S3%	12.57985	5.86547	.388	-5.2935	30.4532
S1%	N0%	-2.90125	6.55654	1.000	-22.8804	17.0779
	N1%	-.90475	6.55654	1.000	-20.8839	19.0744
	N2%	9.34155	6.02641	.780	-9.0222	27.7053
	N3%	11.50516	5.92800	.524	-6.5587	29.5690
	S0%	-1.60720	6.51644	1.000	-21.4642	18.2498
	S2%	7.31103	6.02641	.928	-11.0527	25.6748
	S3%	10.97266	5.90999	.582	-7.0363	28.9816
S2%	N0%	-10.21228	6.02641	.691	-28.5761	8.1515
	N1%	-8.21578	6.02641	.873	-26.5796	10.1480
	N2%	2.03052	5.44491	1.000	-14.5613	18.6223
	N3%	4.19412	5.33578	.994	-12.0651	20.4534
	S0%	-8.91823	5.98276	.812	-27.1490	9.3125
	S1%	-7.31103	6.02641	.928	-25.6748	11.0527
	S3%	3.66162	5.31576	.997	-12.5366	19.8599
S3%	N0%	-13.87391	5.90999	.271	-31.8829	4.1351
	N1%	-11.87741	5.90999	.477	-29.8864	6.1316
	N2%	-1.63110	5.31576	1.000	-17.8294	14.5672
	N3%	.53250	5.20393	1.000	-15.3250	16.3900
	S0%	-12.57985	5.86547	.388	-30.4532	5.2935
	S1%	-10.97266	5.90999	.582	-28.9816	7.0363
	S2%	-3.66162	5.31576	.997	-19.8599	12.5366

Table 2.3.25: Two way ANOVA table for time required to reach the peak methane production in two groups and at different salt contents.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	1468.500	4	367.125	106.157	0.001
Intercept	8128.125	1	8128.125	2350.301	0.000
Group	6.125	1	6.125	1.771	**0.275**
Salt	1462.375	3	487.458	140.952	**0.001**
Error	10.375	3	3.458		
Total	9607.000	8			
Corrected total	1478.875	7			

Table 2.3.26: Multiple comparisons for mean time required to reach the peak methane production in two groups at different salt contents

Multiple Comparisons

Dependent Variable: TimePeak

Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	1.00	-9.0000*	1.85966	.050	-17.9741	-.0259
	2.00	-23.0000*	1.85966	.003	-31.9741	-14.0259
	3.00	-35.5000*	1.85966	.001	-44.4741	-26.5259
1.00	.00	9.0000*	1.85966	.050	.0259	17.9741
	2.00	-14.0000*	1.85966	.015	-22.9741	-5.0259
	3.00	-26.5000*	1.85966	.002	-35.4741	-17.5259
2.00	.00	23.0000*	1.85966	.003	14.0259	31.9741
	1.00	14.0000*	1.85966	.015	5.0259	22.9741
	3.00	-12.5000*	1.85966	.020	-21.4741	-3.5259
3.00	.00	35.5000*	1.85966	.001	26.5259	44.4741
	1.00	26.5000*	1.85966	.002	17.5259	35.4741
	2.00	12.5000*	1.85966	.020	3.5259	21.4741

Based on observed means.

*. The mean difference is significant at the .05 level.

Table 2.3.27: Two way ANOVA for mean total methane production in two groups at different salt contents

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	15081.500	4	3770.375	1.481	.389
Intercept	12537528.125	1	12537528.1	4923.5	.000
Group	1485.125	1	1485.125	.583	**0.501**
Salt	13596.375	3	4532.125	1.780	**0.324**
Error	7639.375	3	2546.458		
Total	12560249.000	8			
Corrected Total	22720.875	7			

Table 2.3.28: Two way ANOVA table of stabilization time of methane production in two groups and at different salt contents.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	1809.000	4	452.250	193.821	.001
Intercept	15842.000	1	15842.000	6789.429	.000
Group	8.000	1	8.000	3.429	**0.161**
Salt	1801.000	3	600.333	257.286	**0.000**
Error	7.000	3	2.333		
Total	17658.000	8			
Corrected total	1816.000	7			

Table 2.3.29: Multiple comparisons for stabilization time of methane production in two groups at different salt contents

Multiple Comparisons

Dependent Variable: Stabilization

Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	1.00	-14.0000*	1.56791	.009	-21.5662	-6.4338
	2.00	-28.0000*	1.56791	.001	-35.5662	-20.4338
	3.00	-40.5000*	1.56791	.000	-48.0662	-32.9338
1.00	.00	14.0000*	1.56791	.009	6.4338	21.5662
	2.00	-14.0000*	1.56791	.009	-21.5662	-6.4338
	3.00	-26.5000*	1.56791	.001	-34.0662	-18.9338
2.00	.00	28.0000*	1.56791	.001	20.4338	35.5662
	1.00	14.0000*	1.56791	.009	6.4338	21.5662
	3.00	-12.5000*	1.56791	.012	-20.0662	-4.9338
3.00	.00	40.5000*	1.56791	.000	32.9338	48.0662
	1.00	26.5000*	1.56791	.001	18.9338	34.0662
	2.00	12.5000*	1.56791	.012	4.9338	20.0662

Based on observed means.

*. The mean difference is significant at the .05 level.

Table 2.3.30: Two way ANOVA table for average methane production in two groups and at different salt contents.

Source	Type III sum of squares	df	Mean suare	F	Sig.
Corrected model	274.150	4	68.537	74.922	0.002
Intercept	5417.885	1	5417.885	5922.615	0.000
Group	.221	1	.221	.242	**0.657**
Salt	273.929	3	91.310	99.816	**0.002**
Error	2.744	3	.915		
Total	5694.779	8			
Corrected total	276.894	7			

Table 2.3.31: Multiple comparisons for average methane production in two groups at different salt contents

Multiple Comparisons

Dependent Variable: Average
Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	1.00	2.1500	.95644	.289	-2.4655	6.7655
	2.00	10.9550*	.95644	.004	6.3395	15.5705
	3.00	14.0000*	.95644	.002	9.3845	18.6155
1.00	.00	-2.1500	.95644	.289	-6.7655	2.4655
	2.00	8.8050*	.95644	.008	4.1895	13.4205
	3.00	11.8500*	.95644	.003	7.2345	16.4655
2.00	.00	-10.9550*	.95644	.004	-15.5705	-6.3395
	1.00	-8.8050*	.95644	.008	-13.4205	-4.1895
	3.00	3.0450	.95644	.140	-1.5705	7.6605
3.00	.00	-14.0000*	.95644	.002	-18.6155	-9.3845
	1.00	-11.8500*	.95644	.003	-16.4655	-7.2345
	2.00	-3.0450	.95644	.140	-7.6605	1.5705

Based on observed means.

*. The mean difference is significant at the .05 level.

3. Leachate quality

3.1 COD

Table 3.1.1: One way ANOVA table for the mean of COD in all bioreactors

	Sum of squares	df	Mean square	F	Sig.
Between groups	3541693830	7	505956261	5.543	**0.000**
Within groups	32496375655	356	91281954		
Total	36038069485	363			

Table 3.1.2: One way ANOVA table for the mean of COD in two groups

	Sum of squares	df	Mean square	F	Sig.
Between groups	245244160.885	1	245244160.885	2.480	**0.116**
Within groups	35792825324.266	362	98875208.078		
Total	36038069485.151	363			

Table 3.1.3: Two way ANOVA table for COD reduction in aerobic stage function of salt content and groups.

Source	Type III Sum of squares	df	Mean square	F	Sig.
Corrected Model	1188.925	4	297.231	27.819	.010
Intercept	32133.660	1	32133.660	3007.549	.000
Salt	671.792	3	223.931	20.959	**0.016**
Group	517.133	1	517.133	48.401	**0.006**
Error	32.053	3	10.684		
Total	33354.638	8			
Corrected Total	1220.978	7			

Table 3.1.4: Two way ANOVA table for COD reduction in anaerobic stage function of salt content and groups.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected model	49.450	4	12.363	10.370	0.042
Intercept	63724.500	1	63724.500	53455.666	0.000
Group	9.159	1	9.159	7.683	**0.069**
Salt	40.291	3	13.430	11.266	**0.039**
Error	3.576	3	1.192		
Total	63777.527	8			
Corrected total	53.027	7			

Table 3.1.5: Multiple comparisons for mean COD concentration in all bioreactors

Multiple Comparisons

Dependent Variable: COD
Tukey HSD

(I) Reactors	(J) Reactors	Mean difference (I-J)	Std. Error	Sig.	95% Confidence interval	
					Lower bound	Upper bound
R1	R2	1810.84766	1970.873	.984	-4198.4500	7820.1453
	R3	-1526.7268	1970.873	.994	-7536.0245	4482.5709
	R4	-8721.5885*	1970.873	.000	-14730.8862	-2712.2908
	R5	-3791.7430	2004.185	.557	-9902.6135	2319.1275
	R6	-4051.7601	2004.185	.469	-10162.6305	2059.1104
	R7	-1774.2498	2004.185	.987	-7885.1203	4336.6206
	R8	-5389.8569	2004.185	.129	-11500.7273	721.0136
R2	R1	-1810.8477	1970.873	.984	-7820.1453	4198.4500
	R3	-3337.5745	1970.873	.692	-9346.8721	2671.7232
	R4	-10532.436*	1970.873	.000	-16541.7338	-4523.1385
	R5	-5602.5907	2004.185	.099	-11713.4611	508.2798
	R6	-5862.6077	2004.185	.071	-11973.4782	248.2628
	R7	-3585.0975	2004.185	.628	-9695.9680	2525.7730
	R8	-7200.7045*	2004.185	.009	-13311.5750	-1089.8341
R3	R1	1526.72681	1970.873	.994	-4482.5709	7536.0245
	R2	3337.57447	1970.873	.692	-2671.7232	9346.8721
	R4	-7194.8617*	1970.873	.007	-13204.1594	-1185.5640
	R5	-2265.0162	2004.185	.950	-8375.8867	3845.8543
	R6	-2525.0332	2004.185	.913	-8635.9037	3585.8372
	R7	-247.52302	2004.185	1.000	-6358.3935	5863.3474
	R8	-3863.1301	2004.185	.533	-9974.0005	2247.7404
R4	R1	8721.58851*	1970.873	.000	2712.2908	14730.8862
	R2	10532.436*	1970.873	.000	4523.1385	16541.7338
	R3	7194.86170*	1970.873	.007	1185.5640	13204.1594
	R5	4929.84550	2004.185	.216	-1181.0250	11040.7160
	R6	4669.82846	2004.185	.280	-1441.0420	10780.6989
	R7	6947.33868*	2004.185	.014	836.4682	13058.2091
	R8	3331.73164	2004.185	.712	-2779.1388	9442.6021
R5	R1	3791.74301	2004.185	.557	-2319.1275	9902.6135
	R2	5602.59067	2004.185	.099	-508.2798	11713.4611
	R3	2265.01620	2004.185	.950	-3845.8543	8375.8867
	R4	-4929.8455	2004.185	.216	-11040.7160	1181.0250
	R6	-260.01705	2036.954	1.000	-6470.7994	5950.7653
	R7	2017.49318	2036.954	.976	-4193.2891	8228.2755
	R8	-1598.1139	2036.954	.994	-7808.8962	4612.6685
R6	R1	4051.76005	2004.185	.469	-2059.1104	10162.6305
	R2	5862.60771	2004.185	.071	-248.2628	11973.4782
	R3	2525.03324	2004.185	.913	-3585.8372	8635.9037
	R4	-4669.8285	2004.185	.280	-10780.6989	1441.0420
	R5	260.01705	2036.954	1.000	-5950.7653	6470.7994
	R7	2277.51023	2036.954	.953	-3933.2721	8488.2926
	R8	-1338.0968	2036.954	.998	-7548.8791	4872.6855
R7	R1	1774.24983	2004.185	.987	-4336.6206	7885.1203
	R2	3585.09749	2004.185	.628	-2525.7730	9695.9680
	R3	247.52302	2004.185	1.000	-5863.3474	6358.3935
	R4	-6947.3387*	2004.185	.014	-13058.2091	-836.4682
	R5	-2017.4932	2036.954	.976	-8228.2755	4193.2891
	R6	-2277.5102	2036.954	.953	-8488.2926	3933.2721
	R8	-3615.6070	2036.954	.637	-9826.3894	2595.1753
R8	R1	5389.85687	2004.185	.129	-721.0136	11500.7273
	R2	7200.70453*	2004.185	.009	1089.8341	13311.5750
	R3	3863.13006	2004.185	.533	-2247.7404	9974.0005
	R4	-3331.7316	2004.185	.712	-9442.6021	2779.1388
	R5	1598.11386	2036.954	.994	-4612.6685	7808.8962
	R6	1338.09682	2036.954	.998	-4872.6855	7548.8791
	R7	3615.60705	2036.954	.637	-2595.1753	9826.3894

*. The mean difference is significant at the .05 level.

Table 3.1.6: Multiple comparisons for mean COD reduction in aerobic stage at different salt contents

Multiple Comparisons

Dependent Variable: Aerobic
Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	6.3100	3.26869	.375	-9.4636	22.0836
	1.00	13.7400	3.26869	.072	-2.0336	29.5136
	3.00	24.6200*	3.26869	.015	8.8464	40.3936
.50	.00	-6.3100	3.26869	.375	-22.0836	9.4636
	1.00	7.4300	3.26869	.283	-8.3436	23.2036
	3.00	18.3100*	3.26869	.033	2.5364	34.0836
1.00	.00	-13.7400	3.26869	.072	-29.5136	2.0336
	.50	-7.4300	3.26869	.283	-23.2036	8.3436
	3.00	10.8800	3.26869	.127	-4.8936	26.6536
3.00	.00	-24.6200*	3.26869	.015	-40.3936	-8.8464
	.50	-18.3100*	3.26869	.033	-34.0836	-2.5364
	1.00	-10.8800	3.26869	.127	-26.6536	4.8936

Based on observed means.

*. The mean difference is significant at the .05 level.

Table 3.1.7: Multiple comparisons for mean COD reduction in anaerobic stage at different salt contents

Multiple Comparisons

Dependent Variable: Anaerobic
Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	1.3800	1.09183	.637	-3.8888	6.6488
	1.00	3.5050	1.09183	.138	-1.7638	8.7738
	3.00	5.9350*	1.09183	.036	.6662	11.2038
.50	.00	-1.3800	1.09183	.637	-6.6488	3.8888
	1.00	2.1250	1.09183	.370	-3.1438	7.3938
	3.00	4.5550	1.09183	.073	-.7138	9.8238
1.00	.00	-3.5050	1.09183	.138	-8.7738	1.7638
	.50	-2.1250	1.09183	.370	-7.3938	3.1438
	3.00	2.4300	1.09183	.294	-2.8388	7.6988
3.00	.00	-5.9350*	1.09183	.036	-11.2038	-.6662
	.50	-4.5550	1.09183	.073	-9.8238	.7138
	1.00	-2.4300	1.09183	.294	-7.6988	2.8388

Based on observed means.

*. The mean difference is significant at the .05 level.

3.2 BOD

Table 3.2.1: One way ANOVA table for mean BOD in all bioreactors

	Sum of squares	df	Mean square	F	Sig.
Between groups	443202311.282	7	63314615.897	2.464	**0.019**
Within Groups	4728617892.74	184	25699010.287		
Total	5171820204.02	191			

Table 3.2.2: One way ANOVA table for mean BOD in two groups

	Sum of squares	df	Mean square	F	Sig.
Between groups	3662906.317	1	3662906.317	.137	**0.712**
Within groups	5094496420.78	190	26813139.057		
Total	5098159327.10	191			

Table 3.2.3: Two way ANOVA table for BOD reduction in aerobic stage function of salt content and groups.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	1561.500	4	390.375	21.149	.016
Intercept	36046.125	1	36046.125	1952.837	.000
Group	741.125	1	741.125	40.151	**0.008**
Salt	820.375	3	273.458	14.815	**0.026**
Error	55.375	3	18.458		
Total	37663.000	8			
Corrected total	1616.875	7			

Table 3.2.4: Two way ANOVA table for BOD reduction in anaerobic stage function of salt content and groups.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	106.500	4	26.625	18.257	.019
Intercept	66066.125	1	66066.125	45302.486	.000
Group	21.125	1	21.125	14.486	**0.032**
Salt	85.375	3	28.458	19.514	**0.018**
Error	4.375	3	1.458		
Total	66177.000	8			
Corrected Total	110.875	7			

Table 3.2.5: Multiple comparisons between the mean of BOD in all bioreactors

Multiple Comparisons

Dependent Variable: BOD
Tukey HSD

(I) Reactors	(J) Reactors	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.00	2.00	743.63793	1433.848	1.000	-3652.7455	5140.0214
	3.00	-964.88327	1433.848	.998	-5361.2667	3431.5002
	4.00	-4594.9313*	1433.848	.034	-8991.3147	-198.5478
	5.00	-1682.9991	1464.687	.945	-6173.9393	2807.9411
	6.00	-1673.9947	1464.687	.946	-6164.9349	2816.9454
	7.00	-755.33605	1464.687	1.000	-5246.2762	3735.6041
	8.00	-1940.2165	1464.687	.888	-6431.1566	2550.7237
2.00	1.00	-743.63793	1433.848	1.000	-5140.0214	3652.7455
	3.00	-1708.5212	1433.848	.933	-6104.9047	2687.8623
	4.00	-5338.5692*	1433.848	.006	-9734.9527	-942.1857
	5.00	-2426.6370	1464.687	.715	-6917.5772	2064.3031
	6.00	-2417.6327	1464.687	.719	-6908.5728	2073.3075
	7.00	-1498.9740	1464.687	.970	-5989.9141	2991.9662
	8.00	-2683.8544	1464.687	.599	-7174.7946	1807.0857
3.00	1.00	964.88327	1433.848	.998	-3431.5002	5361.2667
	2.00	1708.52120	1433.848	.933	-2687.8623	6104.9047
	4.00	-3630.0480	1433.848	.189	-8026.4315	766.3355
	5.00	-718.11583	1464.687	1.000	-5209.0560	3772.8243
	6.00	-709.11148	1464.687	1.000	-5200.0516	3781.8287
	7.00	209.54722	1464.687	1.000	-4281.3929	4700.4874
	8.00	-975.33322	1464.687	.998	-5466.2734	3515.6069
4.00	1.00	4594.93127*	1433.848	.034	198.5478	8991.3147
	2.00	5338.56920*	1433.848	.006	942.1857	9734.9527
	3.00	3630.04800	1433.848	.189	-766.3355	8026.4315
	5.00	2911.93217	1464.687	.493	-1579.0080	7402.8723
	6.00	2920.93652	1464.687	.489	-1570.0036	7411.8767
	7.00	3839.59522	1464.687	.155	-651.3449	8330.5354
	8.00	2654.71478	1464.687	.612	-1836.2254	7145.6549
5.00	1.00	1682.99909	1464.687	.945	-2807.9411	6173.9393
	2.00	2426.63703	1464.687	.715	-2064.3031	6917.5772
	3.00	718.11583	1464.687	1.000	-3772.8243	5209.0560
	4.00	-2911.9322	1464.687	.493	-7402.8723	1579.0080
	6.00	9.00435	1494.890	1.000	-4574.5423	4592.5510
	7.00	927.66304	1494.890	.999	-3655.8836	5511.2097
	8.00	-257.21739	1494.890	1.000	-4840.7640	4326.3292
6.00	1.00	1673.99474	1464.687	.946	-2816.9454	6164.9349
	2.00	2417.63268	1464.687	.719	-2073.3075	6908.5728
	3.00	709.11148	1464.687	1.000	-3781.8287	5200.0516
	4.00	-2920.9365	1464.687	.489	-7411.8767	1570.0036
	5.00	-9.00435	1494.890	1.000	-4592.5510	4574.5423
	7.00	918.65870	1494.890	.999	-3664.8879	5502.2053
	8.00	-266.22174	1494.890	1.000	-4849.7684	4317.3249
7.00	1.00	755.33605	1464.687	1.000	-3735.6041	5246.2762
	2.00	1498.97398	1464.687	.970	-2991.9662	5989.9141
	3.00	-209.54722	1464.687	1.000	-4700.4874	4281.3929
	4.00	-3839.5952	1464.687	.155	-8330.5354	651.3449
	5.00	-927.66304	1494.890	.999	-5511.2097	3655.8836
	6.00	-918.65870	1494.890	.999	-5502.2053	3664.8879
	8.00	-1184.8804	1494.890	.993	-5768.4270	3398.6662
8.00	1.00	1940.21648	1464.687	.888	-2550.7237	6431.1566
	2.00	2683.85442	1464.687	.599	-1807.0857	7174.7946
	3.00	975.33322	1464.687	.998	-3515.6069	5466.2734
	4.00	-2654.7148	1464.687	.612	-7145.6549	1836.2254
	5.00	257.21739	1494.890	1.000	-4326.3292	4840.7640
	6.00	266.22174	1494.890	1.000	-4317.3249	4849.7684
	7.00	1184.88043	1494.890	.993	-3398.6662	5768.4270

*. The mean difference is significant at the .05 level.

Table 3.2.6: Multiple comparisons of mean BOD percentage reduction in aerobic stage at different salt contents

Multiple Comparisons

Dependent Variable: Aerobic
Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	7.5000	4.29632	.436	-13.2326	28.2326
	1.00	14.5000	4.29632	.123	-6.2326	35.2326
	3.00	27.5000*	4.29632	.023	6.7674	48.2326
.50	.00	-7.5000	4.29632	.436	-28.2326	13.2326
	1.00	7.0000	4.29632	.479	-13.7326	27.7326
	3.00	20.0000	4.29632	.055	-.7326	40.7326
1.00	.00	-14.5000	4.29632	.123	-35.2326	6.2326
	.50	-7.0000	4.29632	.479	-27.7326	13.7326
	3.00	13.0000	4.29632	.158	-7.7326	33.7326
3.00	.00	-27.5000*	4.29632	.023	-48.2326	-6.7674
	.50	-20.0000	4.29632	.055	-40.7326	.7326
	1.00	-13.0000	4.29632	.158	-33.7326	7.7326

Based on observed means.

*. The mean difference is significant at the .05 level.

Table 3.2.7: Multiple comparisons of mean BOD percentage reduction in anaerobic stage at different salt contents

Multiple Comparisons

Dependent Variable: Anaerobic
Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	1.0000	1.20761	.840	-4.8275	6.8275
	1.00	5.5000	1.20761	.058	-.3275	11.3275
	3.00	8.0000*	1.20761	.021	2.1725	13.8275
.50	.00	-1.0000	1.20761	.840	-6.8275	4.8275
	1.00	4.5000	1.20761	.097	-1.3275	10.3275
	3.00	7.0000*	1.20761	.030	1.1725	12.8275
1.00	.00	-5.5000	1.20761	.058	-11.3275	.3275
	.50	-4.5000	1.20761	.097	-10.3275	1.3275
	3.00	2.5000	1.20761	.334	-3.3275	8.3275
3.00	.00	-8.0000*	1.20761	.021	-13.8275	-2.1725
	.50	-7.0000*	1.20761	.030	-12.8275	-1.1725
	1.00	-2.5000	1.20761	.334	-8.3275	3.3275

Based on observed means.

*. The mean difference is significant at the .05 level.

3.3 VFA

Table 3.3.1: One way ANOVA table for the mean of VFA in all bioreactors

	Sum of squares	df	Mean square	F	Sig.
Between groups	603247849.933	7	86178264.276	5.061	**0.000**
Within groups	5244251311.188	308	17026789.971		
Total	5847499161.121	315			

Table 3.3.2: One way ANOVA table for mean of VFA in two groups

	Sum of squares	df	Mean square	F	Sig.
Between groups	54917442.638	1	54917442.638	2.977	**0.085**
Within groups	5792581718.483	314	18447712.479		
Total	5847499161.121	315			

Table 3.3.3: Two way ANOVA table for VFA reduction in aerobic stage function of salt content and groups.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	1205.000	4	301.250	44.085	.005
Intercept	32512.500	1	32512.500	4757.927	.000
Group	760.500	1	760.500	111.293	**0.002**
Salt	444.500	3	148.167	21.683	**0.016**
Error	20.500	3	6.833		
Total	33738.000	8			
Corrected total	1225.500	7			

Table 3.3.4: Multiple comparisons between the mean of VFA concentration in all bioreactors

Multiple Comparisons

Dependent Variable: VFA
Tukey HSD

(I) Reactors	(J) Reactors	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
R1	R2	654.47262	911.35894	.996	-2126.9008	3435.8461
	R3	-488.97652	911.35894	.999	-3270.3500	2292.3969
	R4	-3794.1081*	911.35894	.001	-6575.4816	-1012.7346
	R5	-1731.1574	929.17220	.577	-4566.8951	1104.5803
	R6	-1377.0071	929.17220	.817	-4212.7448	1458.7305
	R7	-1055.3820	929.17220	.948	-3891.1197	1780.3557
	R8	-2802.5170	929.17220	.055	-5638.2547	33.2207
R2	R1	-654.47262	911.35894	.996	-3435.8461	2126.9008
	R3	-1143.4491	911.35894	.914	-3924.8226	1637.9243
	R4	-4448.5807*	911.35894	.000	-7229.9542	-1667.2073
	R5	-2385.6300	929.17220	.172	-5221.3677	450.1077
	R6	-2031.4798	929.17220	.363	-4867.2174	804.2579
	R7	-1709.8546	929.17220	.593	-4545.5923	1125.8831
	R8	-3456.9896*	929.17220	.006	-6292.7273	-621.2519
R3	R1	488.97652	911.35894	.999	-2292.3969	3270.3500
	R2	1143.44913	911.35894	.914	-1637.9243	3924.8226
	R4	-3305.1316*	911.35894	.008	-6086.5050	-523.7581
	R5	-1242.1809	929.17220	.884	-4077.9185	1593.5568
	R6	-888.03062	929.17220	.980	-3723.7683	1947.7071
	R7	-566.40549	929.17220	.999	-3402.1432	2269.3322
	R8	-2313.5405	929.17220	.204	-5149.2782	522.1972
R4	R1	3794.10810*	911.35894	.001	1012.7346	6575.4816
	R2	4448.58072*	911.35894	.000	1667.2073	7229.9542
	R3	3305.13159*	911.35894	.008	523.7581	6086.5050
	R5	2062.95073	929.17220	.343	-772.7870	4898.6884
	R6	2417.10096	929.17220	.159	-418.6367	5252.8387
	R7	2738.72609	929.17220	.067	-97.0116	5574.4638
	R8	991.59109	929.17220	.963	-1844.1466	3827.3288
R5	R1	1731.15738	929.17220	.577	-1104.5803	4566.8951
	R2	2385.62999	929.17220	.172	-450.1077	5221.3677
	R3	1242.18086	929.17220	.884	-1593.5568	4077.9185
	R4	-2062.9507	929.17220	.343	-4898.6884	772.7870
	R6	354.15024	946.65033	1.000	-2534.9289	3243.2294
	R7	675.77537	946.65033	.997	-2213.3038	3564.8545
	R8	-1071.3596	946.65033	.949	-3960.4388	1817.7195
R6	R1	1377.00714	929.17220	.817	-1458.7305	4212.7448
	R2	2031.47976	929.17220	.363	-804.2579	4867.2174
	R3	888.03062	929.17220	.980	-1947.7071	3723.7683
	R4	-2417.1010	929.17220	.159	-5252.8387	418.6367
	R5	-354.15024	946.65033	1.000	-3243.2294	2534.9289
	R7	321.62513	946.65033	1.000	-2567.4540	3210.7043
	R8	-1425.5099	946.65033	.804	-4314.5890	1463.5693
R7	R1	1055.38201	929.17220	.948	-1780.3557	3891.1197
	R2	1709.85462	929.17220	.593	-1125.8831	4545.5923
	R3	566.40549	929.17220	.999	-2269.3322	3402.1432
	R4	-2738.7261	929.17220	.067	-5574.4638	97.0116
	R5	-675.77537	946.65033	.997	-3564.8545	2213.3038
	R6	-321.62513	946.65033	1.000	-3210.7043	2567.4540
	R8	-1747.1350	946.65033	.589	-4636.2141	1141.9441
R8	R1	2802.51701	929.17220	.055	-33.2207	5638.2547
	R2	3456.98962*	929.17220	.006	621.2519	6292.7273
	R3	2313.54049	929.17220	.204	-522.1972	5149.2782
	R4	-991.59109	929.17220	.963	-3827.3288	1844.1466
	R5	1071.35963	946.65033	.949	-1817.7195	3960.4388
	R6	1425.50987	946.65033	.804	-1463.5693	4314.5890
	R7	1747.13500	946.65033	.589	-1141.9441	4636.2141

*. The mean difference is significant at the .05 level.

Table 3.3.5: Multiple comparisons for mean VFA reduction in aerobic stage at different salt contents

Multiple Comparisons

Dependent Variable: Aerobic

Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
0	0.5	4.0000	2.61406	.519	-8.6146	16.6146
	1	11.5000	2.61406	.064	-1.1146	24.1146
	3	19.5000*	2.61406	.015	6.8854	32.1146
0.5	0	-4.0000	2.61406	.519	-16.6146	8.6146
	1	7.5000	2.61406	.177	-5.1146	20.1146
	3	15.5000*	2.61406	.029	2.8854	28.1146
1	0	-11.5000	2.61406	.064	-24.1146	1.1146
	0.5	-7.5000	2.61406	.177	-20.1146	5.1146
	3	8.0000	2.61406	.154	-4.6146	20.6146
3	0	-19.5000*	2.61406	.015	-32.1146	-6.8854
	0.5	-15.5000*	2.61406	.029	-28.1146	-2.8854
	1	-8.0000	2.61406	.154	-20.6146	4.6146

Based on observed means.

*. The mean difference is significant at the .05 level.

Table 3.3.6: Two way ANOVA table for mean VFA reduction in anaerobic stage function of salt content and groups.

Source	Type III sum of Squares	df	Mean square	F	Sig.
Corrected model	55.457	4	13.864	6.751	0.074
Intercept	75237.084	1	75237.084	36637.57	0.000
Group	15.180	1	15.180	7.392	**0.073**
Salt	40.277	3	13.426	6.538	**0.079**
Error	6.161	3	2.054		
Total	75298.702	8			
Corrected total	61.618	7			

3.4. pH

Table 3.4.1: One way ANOVA table for mean of pH values in all bioreactors

	Sum of squares	df	Mean square	F	Sig.
Between groups	2.056	7	.294	1.357	**0.223**
Within groups	64.949	300	.216		
Total	67.005	307			

Table 3.4.2: One way ANOVA table for mean of pH values in two groups

	Sum of squares	df	Mean square	F	Sig.
Between groups	.183	1	.183	.837	**0.361**
Within groups	66.822	306	.218		
Total	67.005	307			

3.5. TVS

Table 3.5.1: One way ANOVA table for the mean of TVS concentration in all bioreactors

	Sum of squares	df	Mean square	F	Sig.
Between Groups	567754846.6	7	81107835.2	5.330	**0.000**
Within Groups	4443580388.1	292	15217741.05		
Total	5011335234.7	299			

Table 3.5.2: One way ANOVA table for mean of TVS concentration in two groups

	Sum of squares	df	Mean square	F	Sig.
Between groups	88465907.234	1	88465907.23	5.355	**0.021**
Within groups	4922869327.5	298	16519695.73		
Total	5011335234.7	299			

Table 3.5.3: Two way ANOVA table for mean TVS reduction in aerobic stage function of salt content and groups.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	1092.461	4	273.115	34.030	.008
Intercept	30159.236	1	30159.236	3757.832	.000
Group	770.134	1	770.134	95.958	**0.002**
Salt	322.328	3	107.443	13.387	**0.030**
Error	24.077	3	8.026		
Total	31275.775	8			
Corrected total	1116.539	7			

Table 3.5.4: Two way ANOVA table for TVS reduction in anaerobic stage function of salt content and groups.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	283.452	4	70.863	35.342	.007
Intercept	47290.264	1	47290.264	23585.461	.000
Group	11.607	1	11.607	5.789	**0.095**
Salt	271.846	3	90.615	45.193	**0.005**
Error	6.015	3	2.005		
Total	47579.731	8			
Corrected Total	289.467	7			

Table 3.5.5: Multiple comparisons for mean TVS concentration in all bioreactors.

Multiple Comparisons

Dependent Variable: TVS
Tukey HSD

(I) Reactors	(J) Reactors	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
R1	R2	1033.45714	932.51552	.955	-1813.5619	3880.4762
	R3	-251.91429	932.51552	1.000	-3098.9333	2595.1047
	R4	-3216.5600*	932.51552	.015	-6063.5790	-369.5410
	R5	-2384.7571	902.90427	.146	-5141.3715	371.8572
	R6	-2026.2071	902.90427	.329	-4782.8215	730.4072
	R7	-154.90714	902.90427	1.000	-2911.5215	2601.7072
	R8	-2223.1071	902.90427	.216	-4979.7215	533.5072
R2	R1	-1033.4571	932.51552	.955	-3880.4762	1813.5619
	R3	-1285.3714	932.51552	.867	-4132.3904	1561.6476
	R4	-4250.0171*	932.51552	.000	-7097.0362	-1402.9981
	R5	-3418.2143*	902.90427	.005	-6174.8286	-661.6000
	R6	-3059.6643*	902.90427	.018	-5816.2786	-303.0500
	R7	-1188.3643	902.90427	.892	-3944.9786	1568.2500
	R8	-3256.5643*	902.90427	.009	-6013.1786	-499.9500
R3	R1	251.91429	932.51552	1.000	-2595.1047	3098.9333
	R2	1285.37143	932.51552	.867	-1561.6476	4132.3904
	R4	-2964.6457*	932.51552	.035	-5811.6647	-117.6267
	R5	-2132.8429	902.90427	.264	-4889.4572	623.7715
	R6	-1774.2929	902.90427	.507	-4530.9072	982.3215
	R7	97.00714	902.90427	1.000	-2659.6072	2853.6215
	R8	-1971.1929	902.90427	.365	-4727.8072	785.4215
R4	R1	3216.56000*	932.51552	.015	369.5410	6063.5790
	R2	4250.01714*	932.51552	.000	1402.9981	7097.0362
	R3	2964.64571*	932.51552	.035	117.6267	5811.6647
	R5	831.80286	902.90427	.984	-1924.8115	3588.4172
	R6	1190.35286	902.90427	.891	-1566.2615	3946.9672
	R7	3061.65286*	902.90427	.018	305.0385	5818.2672
	R8	993.45286	902.90427	.956	-1763.1615	3750.0672
R5	R1	2384.75714	902.90427	.146	-371.8572	5141.3715
	R2	3418.21429*	902.90427	.005	661.6000	6174.8286
	R3	2132.84286	902.90427	.264	-623.7715	4889.4572
	R4	-831.80286	902.90427	.984	-3588.4172	1924.8115
	R6	358.55000	872.28840	1.000	-2304.5924	3021.6924
	R7	2229.85000	872.28840	.177	-433.2924	4892.9924
	R8	161.65000	872.28840	1.000	-2501.4924	2824.7924
R6	R1	2026.20714	902.90427	.329	-730.4072	4782.8215
	R2	3059.66429*	902.90427	.018	303.0500	5816.2786
	R3	1774.29286	902.90427	.507	-982.3215	4530.9072
	R4	-1190.3529	902.90427	.891	-3946.9672	1566.2615
	R5	-358.55000	872.28840	1.000	-3021.6924	2304.5924
	R7	1871.30000	872.28840	.388	-791.8424	4534.4424
	R8	-196.90000	872.28840	1.000	-2860.0424	2466.2424
R7	R1	154.90714	902.90427	1.000	-2601.7072	2911.5215
	R2	1188.36429	902.90427	.892	-1568.2500	3944.9786
	R3	-97.00714	902.90427	1.000	-2853.6215	2659.6072
	R4	-3061.6529*	902.90427	.018	-5818.2672	-305.0385
	R5	-2229.8500	872.28840	.177	-4892.9924	433.2924
	R6	-1871.3000	872.28840	.388	-4534.4424	791.8424
	R8	-2068.2000	872.28840	.260	-4731.3424	594.9424
R8	R1	2223.10714	902.90427	.216	-533.5072	4979.7215
	R2	3256.56429*	902.90427	.009	499.9500	6013.1786
	R3	1971.19286	902.90427	.365	-785.4215	4727.8072
	R4	-993.45286	902.90427	.956	-3750.0672	1763.1615
	R5	-161.65000	872.28840	1.000	-2824.7924	2501.4924
	R6	196.90000	872.28840	1.000	-2466.2424	2860.0424
	R7	2068.20000	872.28840	.260	-594.9424	4731.3424

*. The mean difference is significant at the .05 level.

Table 3.5.6: Multiple comparisons for mean TVS percentage reduction in aerobic stage at different salt contents

Multiple Comparisons

Dependent Variable: Aerobic
Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	7.5714	2.83297	.206	-6.0995	21.2424
	1.00	11.6895	2.83297	.075	-1.9815	25.3604
	3.00	17.4266*	2.83297	.026	3.7557	31.0976
.50	.00	-7.5714	2.83297	.206	-21.2424	6.0995
	1.00	4.1180	2.83297	.551	-9.5529	17.7890
	3.00	9.8552	2.83297	.114	-3.8158	23.5261
1.00	.00	-11.6895	2.83297	.075	-25.3604	1.9815
	.50	-4.1180	2.83297	.551	-17.7890	9.5529
	3.00	5.7371	2.83297	.346	-7.9338	19.4081
3.00	.00	-17.4266*	2.83297	.026	-31.0976	-3.7557
	.50	-9.8552	2.83297	.114	-23.5261	3.8158
	1.00	-5.7371	2.83297	.346	-19.4081	7.9338

Based on observed means.

*. The mean difference is significant at the .05 level.

Table 3.5.7: Multiple comparisons for mean TVS percentage reduction in anaerobic stage at different salt contents

Multiple Comparisons

Dependent Variable: Anaerobic
Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	3.7447	1.41600	.210	-3.0884	10.5779
	1.00	8.1047*	1.41600	.032	1.2715	14.9378
	3.00	15.6697*	1.41600	.005	8.8365	22.5028
.50	.00	-3.7447	1.41600	.210	-10.5779	3.0884
	1.00	4.3600	1.41600	.152	-2.4732	11.1931
	3.00	11.9250*	1.41600	.011	5.0918	18.7581
1.00	.00	-8.1047*	1.41600	.032	-14.9378	-1.2715
	.50	-4.3600	1.41600	.152	-11.1931	2.4732
	3.00	7.5650*	1.41600	.038	.7318	14.3981
3.00	.00	-15.6697*	1.41600	.005	-22.5028	-8.8365
	.50	-11.9250*	1.41600	.011	-18.7581	-5.0918
	1.00	-7.5650*	1.41600	.038	-14.3981	-.7318

Based on observed means.

*. The mean difference is significant at the .05 level.

3.6. TS

Table 3.6.1: One way ANOVA table for mean of TS concentration in all bioreactors

	Sum of squares	df	Mean square	F	Sig.
Between groups	22155266765	7	3165038109.221	71.258	**0.000**
Within groups	13680366617	308	44416774.732		
Total	35835633381	315			

Table 3.6.2: One way ANOVA table for mean of TS concentration in two groups

	Sum of squares	df	Mean square	F	Sig.
Between groups	164785482.023	1	164785482.023	1.451	**0.229**
Within groups	35670847899.88	314	113601426.433		
Total	35835633381.90	315			

Table 3.6.3: Two way ANOVA table for mean TS percentage reduction in the aerobic stage function of salt content and groups.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	1349.500	4	337.375	15.249	.025
Intercept	13203.125	1	13203.125	596.751	.000
Group	406.125	1	406.125	18.356	**0.023**
Salt	943.375	3	314.458	14.213	**0.028**
Error	66.375	3	22.125		
Total	14619.000	8			
Corrected total	1415.875	7			

Table 3.6.4: Two way ANOVA table for TS percentage reduction in the anaerobic stage function of salt content and groups.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	2560.500	4	640.125	30.482	.009
Intercept	17484.500	1	17484.500	832.595	.000
Group	242.000	1	242.000	11.524	**0.043**
Salt	2318.500	3	772.833	36.802	**0.007**
Error	63.000	3	21.000		
Total	20108.000	8			
Corrected total	2623.500	7			

Table 3.6.5: Multiple comparisons for mean TS concentration in all bioreactors

Multiple Comparisons

Dependent Variable: Ts

Tukey HSD

(I) Reactors	(J) Reactors	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.00	2.00	2877.05500	1490.248	.531	-1671.0278	7425.1378
	3.00	-6021.4000*	1490.248	.002	-10569.4828	-1473.3172
	4.00	-23971.550*	1490.248	.000	-28519.6328	-19423.4672
	5.00	-3709.1308	1499.770	.211	-8286.2751	868.0135
	6.00	-5427.8692*	1499.770	.008	-10005.0135	-850.7249
	7.00	-6290.9462*	1499.770	.001	-10868.0904	-1713.8019
	8.00	-17465.459*	1499.770	.000	-22042.6033	-12888.3147
2.00	1.00	-2877.0550	1490.248	.531	-7425.1378	1671.0278
	3.00	-8898.4550*	1490.248	.000	-13446.5378	-4350.3722
	4.00	-26848.605*	1490.248	.000	-31396.6878	-22300.5222
	5.00	-6586.1858*	1499.770	.000	-11163.3301	-2009.0415
	6.00	-8304.9242*	1499.770	.000	-12882.0685	-3727.7799
	7.00	-9168.0012*	1499.770	.000	-13745.1454	-4590.8569
	8.00	-20342.514*	1499.770	.000	-24919.6583	-15765.3697
3.00	1.00	6021.40000*	1490.248	.002	1473.3172	10569.4828
	2.00	8898.45500*	1490.248	.000	4350.3722	13446.5378
	4.00	-17950.150*	1490.248	.000	-22498.2328	-13402.0672
	5.00	2312.26923	1499.770	.784	-2264.8751	6889.4135
	6.00	593.53077	1499.770	1.000	-3983.6135	5170.6751
	7.00	-269.54615	1499.770	1.000	-4846.6904	4307.5981
	8.00	-11444.059*	1499.770	.000	-16021.2033	-6866.9147
4.00	1.00	23971.550*	1490.248	.000	19423.4672	28519.6328
	2.00	26848.605*	1490.248	.000	22300.5222	31396.6878
	3.00	17950.150*	1490.248	.000	13402.0672	22498.2328
	5.00	20262.419*	1499.770	.000	15685.2749	24839.5635
	6.00	18543.681*	1499.770	.000	13966.5365	23120.8251
	7.00	17680.604*	1499.770	.000	13103.4596	22257.7481
	8.00	6506.09103*	1499.770	.001	1928.9467	11083.2353
5.00	1.00	3709.13077	1499.770	.211	-868.0135	8286.2751
	2.00	6586.18577*	1499.770	.000	2009.0415	11163.3301
	3.00	-2312.2692	1499.770	.784	-6889.4135	2264.8751
	4.00	-20262.419*	1499.770	.000	-24839.5635	-15685.2749
	6.00	-1718.7385	1509.233	.948	-6324.7609	2887.2840
	7.00	-2581.8154	1509.233	.680	-7187.8378	2024.2071
	8.00	-13756.328*	1509.233	.000	-18362.3507	-9150.3057
6.00	1.00	5427.86923*	1499.770	.008	850.7249	10005.0135
	2.00	8304.92423*	1499.770	.000	3727.7799	12882.0685
	3.00	-593.53077	1499.770	1.000	-5170.6751	3983.6135
	4.00	-18543.681*	1499.770	.000	-23120.8251	-13966.5365
	5.00	1718.73846	1509.233	.948	-2887.2840	6324.7609
	7.00	-863.07692	1509.233	.999	-5469.0994	3742.9455
	8.00	-12037.590*	1509.233	.000	-16643.6122	-7431.5673
7.00	1.00	6290.94615*	1499.770	.001	1713.8019	10868.0904
	2.00	9168.00115*	1499.770	.000	4590.8569	13745.1454
	3.00	269.54615	1499.770	1.000	-4307.5981	4846.6904
	4.00	-17680.604*	1499.770	.000	-22257.7481	-13103.4596
	5.00	2581.81538	1509.233	.680	-2024.2071	7187.8378
	6.00	863.07692	1509.233	.999	-3742.9455	5469.0994
	8.00	-11174.513*	1509.233	.000	-15780.5353	-6568.4904
8.00	1.00	17465.459*	1499.770	.000	12888.3147	22042.6033
	2.00	20342.514*	1499.770	.000	15765.3697	24919.6583
	3.00	11444.059*	1499.770	.000	6866.9147	16021.2033
	4.00	-6506.0910*	1499.770	.001	-11083.2353	-1928.9467
	5.00	13756.328*	1509.233	.000	9150.3057	18362.3507
	6.00	12037.590*	1509.233	.000	7431.5673	16643.6122
	7.00	11174.513*	1509.233	.000	6568.4904	15780.5353

*. The mean difference is significant at the .05 level.

Table 3.6.6: Multiple comparisons for mean TS percentage reduction in the aerobic stage at different salt contents

Multiple Comparisons

Dependent Variable: Aerobic
Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	12.5000	4.70372	.208	-10.1986	35.1986
	1.00	19.0000	4.70372	.079	-3.6986	41.6986
	3.00	30.0000*	4.70372	.023	7.3014	52.6986
.50	.00	-12.5000	4.70372	.208	-35.1986	10.1986
	1.00	6.5000	4.70372	.583	-16.1986	29.1986
	3.00	17.5000	4.70372	.097	-5.1986	40.1986
1.00	.00	-19.0000	4.70372	.079	-41.6986	3.6986
	.50	-6.5000	4.70372	.583	-29.1986	16.1986
	3.00	11.0000	4.70372	.268	-11.6986	33.6986
3.00	.00	-30.0000*	4.70372	.023	-52.6986	-7.3014
	.50	-17.5000	4.70372	.097	-40.1986	5.1986
	1.00	-11.0000	4.70372	.268	-33.6986	11.6986

Based on observed means.

*. The mean difference is significant at the .05 level.

Table 3.6.7: Multiple comparisons for mean TS percentage reduction in the anaerobic stage at different salt contents

Multiple Comparisons

Dependent Variable: Anaerobic
Tukey HSD

(I) Salt	(J) Salt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	.50	12.5000	4.58258	.197	-9.6140	34.6140
	1.00	29.5000*	4.58258	.023	7.3860	51.6140
	3.00	45.0000*	4.58258	.007	22.8860	67.1140
.50	.00	-12.5000	4.58258	.197	-34.6140	9.6140
	1.00	17.0000	4.58258	.098	-5.1140	39.1140
	3.00	32.5000*	4.58258	.017	10.3860	54.6140
1.00	.00	-29.5000*	4.58258	.023	-51.6140	-7.3860
	.50	-17.0000	4.58258	.098	-39.1140	5.1140
	3.00	15.5000	4.58258	.122	-6.6140	37.6140
3.00	.00	-45.0000*	4.58258	.007	-67.1140	-22.8860
	.50	-32.5000*	4.58258	.017	-54.6140	-10.3860
	1.00	-15.5000	4.58258	.122	-37.6140	6.6140

Based on observed means.

*. The mean difference is significant at the .05 level.

3.7 NH_3-N

Table 3.7.1: One way ANOVA table for mean NH_3-N concentration in all bioreactors

	Sum of squares	df	Mean square	F	Sig.
Between groups	22791547.976	7	3255935.425	29.532	**0.000**
Within groups	27342170.720	248	110250.688		
Total	50133718.697	255			

Table 3.7.2: One way ANOVA table for mean NH_3-N concentration in the two groups

	Sum of squares	df	Mean square	F	Sig.
Between groups	3859150.840	1	3859150.840	21.183	**0.000**
Within groups	46274567.857	254	182183.338		
Total	50133718.697	255			

Table 3.7.3: Two way ANOVA table for mean NH_3-N percentage reduction in the aerobic stage function of salt content and groups.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	2837.062	4	709.265	6.016	0.086
Intercept	48029.852	1	48029.852	407.373	0.000
Group	2288.600	1	2288.600	19.411	**0.022**
Salt	548.462	3	182.821	1.551	**0.364**
Error	353.704	3	117.901		
Total	51220.618	8			
Corrected total	3190.766	7			

Table 3.7.4: Two way ANOVA table for mean NH_3-N percentage reduction in the anaerobic stage function of salt content and groups.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	519.500	4	129.875	10.153	.043
Intercept	58311.125	1	58311.125	4558.52	.000
Group	465.125	1	465.125	36.362	**0.009**
Salt	54.375	3	18.125	1.417	**0.391**
Error	38.375	3	12.792		
Total	58869.000	8			
Corrected total	557.875	7			

Table 3.7.5: Multiple comparisons for mean NH3-N concentration in all bioreactors

Multiple Comparisons

Dependent Variable: NH3

Tukey HSD

(I) Reactors	(J) Reactors	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
R1	R2	-142.51969	83.01005	.676	-396.2817	111.2423
	R3	-302.68094*	83.01005	.008	-556.4429	-48.9189
	R4	-990.60250*	83.01005	.000	-1244.3645	-736.8405
	R5	-37.64211	83.01005	1.000	-291.4041	216.1199
	R6	-92.99166	83.01005	.952	-346.7537	160.7704
	R7	-122.59134	83.01005	.819	-376.3534	131.1707
	R8	-200.34194	83.01005	.239	-454.1040	53.4201
R2	R1	142.51969	83.01005	.676	-111.2423	396.2817
	R3	-160.16125	83.01005	.532	-413.9233	93.6008
	R4	-848.08281*	83.01005	.000	-1101.8448	-594.3208
	R5	104.87758	83.01005	.911	-148.8844	358.6396
	R6	49.52803	83.01005	.999	-204.2340	303.2900
	R7	19.92835	83.01005	1.000	-233.8337	273.6904
	R8	-57.82225	83.01005	.997	-311.5843	195.9398
R3	R1	302.68094*	83.01005	.008	48.9189	556.4429
	R2	160.16125	83.01005	.532	-93.6008	413.9233
	R4	-687.92156*	83.01005	.000	-941.6836	-434.1596
	R5	265.03883*	83.01005	.034	11.2768	518.8008
	R6	209.68928	83.01005	.189	-44.0727	463.4513
	R7	180.08960	83.01005	.374	-73.6724	433.8516
	R8	102.33900	83.01005	.921	-151.4230	356.1010
R4	R1	990.60250*	83.01005	.000	736.8405	1244.3645
	R2	848.08281*	83.01005	.000	594.3208	1101.8448
	R3	687.92156*	83.01005	.000	434.1596	941.6836
	R5	952.96039*	83.01005	.000	699.1984	1206.7224
	R6	897.61084*	83.01005	.000	643.8488	1151.3729
	R7	868.01116*	83.01005	.000	614.2491	1121.7732
	R8	790.26056*	83.01005	.000	536.4985	1044.0226
R5	R1	37.64211	83.01005	1.000	-216.1199	291.4041
	R2	-104.87758	83.01005	.911	-358.6396	148.8844
	R3	-265.03883*	83.01005	.034	-518.8008	-11.2768
	R4	-952.96039*	83.01005	.000	-1206.7224	-699.1984
	R6	-55.34955	83.01005	.998	-309.1116	198.4125
	R7	-84.94923	83.01005	.971	-338.7112	168.8128
	R8	-162.69983	83.01005	.511	-416.4618	91.0622
R6	R1	92.99166	83.01005	.952	-160.7704	346.7537
	R2	-49.52803	83.01005	.999	-303.2900	204.2340
	R3	-209.68928	83.01005	.189	-463.4513	44.0727
	R4	-897.61084*	83.01005	.000	-1151.3729	-643.8488
	R5	55.34955	83.01005	.998	-198.4125	309.1116
	R7	-29.59968	83.01005	1.000	-283.3617	224.1623
	R8	-107.35028	83.01005	.901	-361.1123	146.4117
R7	R1	122.59134	83.01005	.819	-131.1707	376.3534
	R2	-19.92835	83.01005	1.000	-273.6904	233.8337
	R3	-180.08960	83.01005	.374	-433.8516	73.6724
	R4	-868.01116*	83.01005	.000	-1121.7732	-614.2491
	R5	84.94923	83.01005	.971	-168.8128	338.7112
	R6	29.59968	83.01005	1.000	-224.1623	283.3617
	R8	-77.75060	83.01005	.982	-331.5126	176.0114
R8	R1	200.34194	83.01005	.239	-53.4201	454.1040
	R2	57.82225	83.01005	.997	-195.9398	311.5843
	R3	-102.33900	83.01005	.921	-356.1010	151.4230
	R4	-790.26056*	83.01005	.000	-1044.0226	-536.4985
	R5	162.69983	83.01005	.511	-91.0622	416.4618
	R6	107.35028	83.01005	.901	-146.4117	361.1123
	R7	77.75060	83.01005	.982	-176.0114	331.5126

*. The mean difference is significant at the .05 level.

3.8. Vertical Concentration profile in bioreactors

Table 3.8.1: One way ANOVA for mean COD concentation in all ports at R1 (first analysis)

	Sum of squares	df	Mean square	F	Sig.
Between Groups	326666.667	2	163333.333	3.128	**0.117**
Within Groups	313333.333	6	52222.222		
Total	640000.000	8			

Table 3.8.2: One way ANOVA for mean COD concentation in all ports at R1 (Second analysis)

	Sum of squares	df	Mean square	F	Sig.
Between groups	275555.556	2	137777.778	.663	**0.549**
Within groups	1246666.667	6	207777.778		
Total	1522222.222	8			

Table 3.8.3: One way ANOVA for mean COD concentation in all ports at R1 (Third analysis)

	Sum of squares	df	Mean square	F	Sig.
Between groups	46250.000	2	23125.000	.881	**0.462**
Within groups	157500.000	6	26250.000		
Total	203750.000	8			

Table 3.8.4: One way ANOVA for mean COD concentation in all ports at R5 (Second analysis)

	Sum of squares	df	Mean square	F	Sig.
Between groups	98750.000	2	49375.000	1.026	**0.414**
Within groups	288750.000	6	48125.000		
Total	387500.000	8			

4. Hydrolysis rate constant

4.1 First set

Table 4.1: Nonlinear regression analysis for 0% (w/v) salt content with 20% (v/v) normal anaerobic digested sludge

Iteration number(a)	Residual sum of squares	Parameter (k_h)
1.0	5328661.077	.010
1.1	941358.141	.044
2.0	941358.141	.044
2.1	337690.333	.075
3.0	337690.333	.075
3.1	315101.912	.087
4.0	315101.912	.087
4.1	314845.744	.085
5.0	314845.744	.085
5.1	314825.031	**0.085**

Parameter estimates

Parameter	Estimate	Std. Error	95% Confidence interval	
			Lower bound	Upper bound
k_h	**0.085**	.008	.070	.101

ANOVA(a)

Source	Sum of squares	df	Mean squares
Regression	8914053.895	1	8914053.895
Residual	314823.578	39	8072.399
Uncorrected total	9228877.473	40	
Corrected total	1869330.844	39	

(a) R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = 0.855.

Table 4.2: Nonlinear regression analysis for 1 % (w/v) salt content with 20% (v/v) normal anaerobic digested sludge

Iteration Number	Residual sum of Squares	Parameter (kh)
1.0	3563044.032	.010
1.1	584895.321	.042
2.0	584895.321	.042
2.1	225209.649	.069
3.0	225209.649	.069
3.1	215976.739	.076
4.0	215976.739	.076
4.1	215851.370	.075
5.0	215851.370	.075
5.1	215844.368	**0.076**

Parameter estimates

Parameter	Estimate	Std. Error	95% Confidence interval	
			Lower bound	Upper bound
K_h	**0.076**	.006	.063	.088

ANOVA(a)

Source	Sum of squares	df	Mean squares
Regression	6149375.696	1	6149375.696
Residual	215844.019	39	5534.462
Uncorrected total	6365219.714	40	
Corrected total	1379955.993	39	

(a) R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = 0.869.

Table 4.3: Nonlinear regression analysis for 2 % (w/v) salt content with 20% (v/v) normal anaerobic digested sludge

Iteration number	Residual sum of squares	Parameter (k_h)
1.0	2509659.118	.010
1.1	373629.857	.039
2.0	373629.857	.039
2.1	193239.442	.058
3.0	193239.442	.058
3.1	192510.234	.060
4.0	192510.234	.060
4.1	192483.264	**0.060**

Parameter estimates

Parameter	Estimate	Std. Error	95% Confidence interval	
			Lower bound	Upper bound
k_h	**.060**	.005	.051	.069

ANOVA(a)

Source	Sum of squares	df	Mean squares
Regression	4578230.453	1	4578230.453
Residual	192481.780	39	4935.430
Uncorrected total	4770712.233	40	
Corrected total	1246224.050	39	

(a) R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = 0.885

Table 4.4: Nonlinear regression analysis for 3 % (w/v) salt content with 20% (v/v) normal anaerobic digested sludge

Iteration number	Residual sum of squares	Parameter (k_h)
1.0	1411018.020	.010
1.1	305733.089	.034
2.0	305733.089	.034
2.1	265174.077	.043
3.0	265174.077	.043
3.1	264967.551	.042
4.0	264967.551	.042
4.1	264955.838	.042
5.0	264955.838	.042
5.1	264955.273	**0.042**

Parameter estimates

Parameter	Estimate	Std. Error	95% Confidence interval	
			Lower bound	Upper bound
k_h	**0.042**	.004	.034	.051

ANOVA(a)

Source	Sum of squares	df	Mean squares
Regression	2670052.542	1	2670052.542
Residual	264955.243	39	6793.724
Uncorrected total	2935007.786	40	
Corrected total	1080882.939	39	

(a) R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = 0.841

Table 4.5: Nonlinear regression analysis for 0 % (w/v) salt content with 20% (v/v) acclimatized anaerobic digested sludge

Iteration number	Residual sum of squares	Parameter (k_h)
1.0	5276966.767	.010
1.1	869468.283	.044
2.0	869468.283	.044
2.1	256841.545	.074
3.0	256841.545	.074
3.1	230816.589	.087
4.0	230816.589	.087
4.1	230668.395	.085
5.0	230668.395	.085
5.1	230659.519	**0.086**

Parameter estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
k_h	**0.086**	.007	.072	.099

ANOVA(a)

Source	Sum of squares	df	Mean squares
Regression	8981149.082	1	8981149.082
Residual	230659.043	39	5914.334
Uncorrected total	9211808.125	40	
Corrected total	1725708.380	39	

(a) R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = 0.887

Table 4.6: Nonlinear regression analysis for 1 % (w/v) salt content with 20% (v/v) acclimatized anaerobic digested sludge

Iteration number	Residual sum of Squares	Parameter (k_h)
1.0	3508143.725	.010
1.1	514239.056	.042
2.0	514239.056	.042
2.1	168625.938	.067
3.0	168625.938	.067
3.1	161121.329	.074
4.0	161121.329	.074
4.1	161003.240	.073
5.0	161003.240	.073
5.1	160996.943	**0.073**

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence interval	
			Lower bound	Upper bound
K_h	**0.073**	.005	.063	.084

ANOVA(a)

Source	Sum of squares	df	Mean squares
Regression	6198577.809	1	6198577.809
Residual	160996.640	39	4128.119
Uncorrected total	6359574.449	40	
Corrected total	1337109.679	39	

(a) R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = 0.914.

Table 4.7: Nonlinear regression analysis for 2 % (w/v) salt content with 20% (v/v) acclimatized anaerobic digested sludge

Iteration number	Residual sum of squares	Parameter (k_h)
1.0	2643404.579	.010
1.1	345844.595	.039
2.0	345844.595	.039
2.1	156662.740	.056
3.0	156662.740	.056
3.1	155734.036	.058
4.0	155734.036	.058
4.1	155710.095	.058
5.0	155710.095	.058
5.1	155709.190	**0.058**

Parameter estimates

Parameter	Estimate	Std. Error	95% Confidence interval	
			Lower bound	Upper bound
k_h	**0.058**	.004	.050	.066

ANOVA(a)

Source	Sum of squares	df	Mean squares
Regression	4992191.167	1	4992191.167
Residual	155709.157	39	3992.542
Uncorrected total	5147900.324	40	
Corrected total	1287583.245	39	

(a) R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = 0.904

Table 4.8: Nonlinear regression analysis for 3 % (w/v) salt content with 20% (v/v) acclimatized anaerobic digested sludge

Iteration number	Residual sum of squares	Parameter (k_h)
1.0	2050198.202	.010
1.1	369020.822	.036
2.0	369020.822	.036
2.1	278469.710	.049
3.0	278469.710	.049
3.1	278407.700	.049
4.0	278407.700	.049
4.1	278403.995	**0.049**

Parameter estimates

Parameter	Estimate	Std. Error	95% Confidence interval	
			Lower bound	Upper bound
k_h	**0.049**	.004	.040	.058

ANOVA(a)

Source	Sum of squares	df	Mean squares
Regression	3812541.202	1	3812541.202
Residual	278403.780	39	7138.558
Uncorrected total	4090944.983	40	
Corrected total	1352803.890	39	

(a) R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = 0.861

4.2 Second set

Table 4.9: Nonlinear regression analysis for 0 % (w/v) salt content with 30% (v/v) normal anaerobic digested sludge

Iteration number	Residual sum of squares	Parameter (k_h)
1.0	5276966.767	.010
1.1	869468.283	.044
2.0	869468.283	.044
2.1	256841.545	.074
3.0	256841.545	.074
3.1	230816.589	.087
4.0	230816.589	.087
4.1	230668.395	.085
5.0	230668.395	.085
5.1	230659.519	.086
6.0	230659.519	**0.086**

Parameter estimates

Parameter	Estimate	Std. Error	95% Confidence interval	
			Lower bound	Upper bound
k_h	**0.086**	.007	.072	.099

ANOVA(a)

Source	Sum of squares	df	Mean squares
Regression	8981149.082	1	8981149.082
Residual	230659.043	39	5914.334
Uncorrected total	9211808.125	40	
Corrected total	1725708.380	39	

(a) R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = 0.906

Table 4.10: Nonlinear regression analysis for 1 % (w/v) salt content with 30% (v/v) normal anaerobic digested sludge

Iteration number	Residual sum of squares	Parameter (k_h)
1.0	3508143.725	.010
1.1	514239.056	.042
2.0	514239.056	.042
2.1	168625.938	.067
3.0	168625.938	.067
3.1	161121.329	.074
4.0	161121.329	.074
4.1	161003.240	.073
5.0	161003.240	.073
5.1	160996.943	**0.073**

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence interval	
			Lower bound	Upper bound
k_h	**0.073**	.005	.063	.084

ANOVA(a)

Source	Sum of squares	df	Mean squares
Regression	6198577.809	1	6198577.809
Residual	160996.640	39	4128.119
Uncorrected total	6359574.449	40	
Corrected total	1337109.679	39	

(a) R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = 0.898

Table 4.11: Nonlinear regression analysis for 2 % (w/v) salt content with 30% (v/v) normal anaerobic digested sludge

Iteration number	Residual sum of squares	Parameter (k_h)
1.0	2643404.579	.010
1.1	345844.595	.039
2.0	345844.595	.039
2.1	156662.740	.056
3.0	156662.740	.056
3.1	155734.036	.058
4.0	155734.036	.058
4.1	155710.095	.058
5.0	155710.095	.058
5.1	155709.190	**0.058**

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence interval	
			Lower bound	Upper bound
k_h	**0.058**	.004	.050	.066

ANOVA(a)

Source	Sum of squares	df	Mean squares
Regression	4992191.167	1	4992191.167
Residual	155709.157	39	3992.542
Uncorrected total	5147900.324	40	
Corrected total	1287583.245	39	

(a) R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = 0.884

Table 4.12: Nonlinear regression analysis for 3 % (w/v) salt content with 30% (v/v) normal anaerobic digested sludge

Iteration Number	Residual Sum of Squares	Parameter
1.0	2050198.202	.010
1.1	369020.822	.036
2.0	369020.822	.036
2.1	278469.710	.049
3.0	278469.710	.049
3.1	278407.700	.049
4.0	278407.700	.049
4.1	278403.995	.049
5.0	278403.995	.049
5.1	278403.792	.049
6.0	278403.792	.049
6.1	278403.781	**0.049**

Parameter estimates

Parameter	Estimate	Std. Error	95% Confidence interval	
			Lower bound	Upper bound
k_h	**0.049**	.004	.040	.058

ANOVA(a)

Source	Sum of squares	df	Mean squares
Regression	4446247.754	1	4446247.754
Residual	196807.952	39	5046.358
Uncorrected total	4643055.705	40	
Corrected total	1565219.482	39	

(a) R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .874

Table 4.13: One way ANOVA for the mean k_h in two types of inoculum

	Sum of squares	df	Mean square	F	Sig.
Between groups	.000	1	.000	.050	**0.830**
Within group	.001	6	.000		
Total	.001	7			

Table 4.14: One way ANOVA for the mean Y in two types of inoculum

	Sum of squares	df	Mean square	F	Sig.
Between groups	351.920	1	351.920	.243	**0.640**
Within groups	8699.278	6	1449.880		
Total	9051.198	7			

Table 4.14: One way ANOVA for the mean k_h of G.1 in the first set and the second set.

	Sum of squares	df	Mean square	F	Sig.
Between groups	.000	1	.000	.004	**0.954**
Within groups	.002	6	.000		
Total	.002	7			

Table 4.14: One way ANOVA for the mean Y of G.1 in the first set and the second set.

	Sum of squares	df	Mean square	F	Sig.
Between groups	1055.012	1	1055.012	.682	**0.440**
Within groups	9281.068	6	1546.845		
Total	10336.080	7			

The inhibition terms are (Lehninger, 1975):

1. Competitive

$$\mu = \frac{\mu_m C_S}{K_s\left(1+\frac{I}{K_I}\right)+C_S}$$

2. Uncompetitive

$$\mu = \frac{\mu_m C_S}{K_s + C_S\left(1+\frac{I}{K_I}\right)}$$

3. Noncompetitive

$$\mu = \frac{\mu_m C_S}{\left(K_s + C_S\right)\left(1+\frac{I}{K_I}\right)}$$