

**THE EFFECT OF HYDRAULIC RETENTION TIME (HRT)
AND TEMPERATURE ON THE ACID-PHASE
ANAEROBIC DIGESTION OF PRIMARY SLUDGE AND
INDUSTRIAL WASTEWATER**

by

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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

Environmental Engineering Division
Department of Civil and Geological Engineering
University of Manitoba
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ABSTRACT

Acid-phase fermentation of municipal primary sludge as well as industrial wastewater from a potato processing plant (which is rich in starch) was investigated under different operational and environmental parameters. The operational parameter investigated was hydraulic retention time (HRT) and the environmental one was temperature. Moreover, the effect of addition of the industrial wastewater to the primary sludge on acidogenesis was also examined.

The study was carried out using two 2-liter completely mixed reactors, each with a clarifier and a recycle facility. One of the reactors was fed with a 1:1 ratio (by volume) mixture of municipal primary sludge and industrial wastewater, while the other was fed with primary sludge alone. HRT was selected at 18 and 30 hours, while three different temperatures of 22°C, 30°C and 35°C were used. The addition of the industrial wastewater and the operational and environmental parameters investigated had profound consequences on the acid-phase digestion process.

A favorable environment for the activities of the acidogenic bacteria was established. Acidogenesis was feasible under all conditions, as indicated by low pH, high volatile fatty acid (VFA) production, and negligible gas generation.

Net VFA and COD production as well as the specific production rates (expressed as mg VFA(or COD)/mgVSS*day) increased with the introduction of the starch-rich wastewater into one of the reactors.

HRT also had a profound effect on the net VFA production. Increase in HRT from 18 hours to 30 hours at 22°C increased the VFA production by 37% in the mixture of industrial wastewater and primary sludge and 14 % for the primary sludge alone.

Variation in temperature, at a constant HRT of 30 hours, had mixed effects on acidogenesis. For the mixture of industrial wastewater and primary sludge, the net VFA production went up by 15% when temperature was increased from 22°C to 30°C, but decreased by 23% when temperature was further increased from 30°C to 35°C, indicating that 30°C might be the optimum for the biomass present in this particular kind of wastewater. For the primary sludge alone, increase in temperature decreased the production due to poor clarifier performance at high temperatures.

For the mixture of industrial wastewater and primary sludge, acetic acid was the most prevalent VFA, with the average values ranging between 57 and 75% , followed by propionic and n-butyric acids which were nearly the same of around 15 to 17%. For the primary sludge alone, acetic acid was the predominant VFA constituting 65% of the total VFAs, while propionic acid followed with 20%. The addition of industrial wastewater had a remarkable impact on the VFA speciation where the percentage of n-butyric acid was increased, while HRT did not have much of an impact. Increase in temperature led to the reduction in the percentage of the n-butyric acid present.

The percent solubilization of organic matter (measured as VSS or TSS destruction) increased with the introduction with the industrial wastewater. Variation in HRT did not have significant effect on organic matter solubilization, but an increase in

temperature had an adverse effect on it, due to poor settling of the biomass in the clarifier at an elevated temperature.

Considering the nitrogen transformation processes, it was observed that the extent of protein degradation was more pronounced in the municipal primary sludge than in the mixture. Mass balance calculations showed a good recovery of TKN in both systems. The amount of net ammonia production per unit protein in the influent was higher in the municipal primary sludge than the mixture, and also it increased with increasing temperature in both reactors.

It was also observed that the steady state operation of an acid phase digester can be replicated and the performance of the system was controlled by the operating conditions and not the type of biomass initially present.

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GLOSSARY OF TERMS

BOD:	biochemical oxygen demand
BNR:	biological nutrient removal
Bio-P:	biological phosphorus
CMR:	completely mixed reactor
CoA:	coenzyme A
COD:	chemical oxygen demand
CoV:	coefficient of variation
EMP:	Embden-Meyerhof-Parnas pathway
GC:	gas chromatograph
HAc:	acetic acid
HRT:	hydraulic retention time
NH₃-N:	ammonia nitrogen
PHA:	poly hydroxyalkonates
PHB:	poly-β-hydroxybutyrate
SRT:	solids retention time
SOC:	soluble organic carbon
std. dev:	standard deviation
TCA:	tricarboxylic acid
TKN:	total Kjeldahl nitrogen
TOC:	total organic carbon
TS:	total solids
TSS:	total suspended solids
VFAs:	volatile fatty acids
VS:	volatile solids
VSS:	volatile suspended solids

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This thesis is dedicated to my uncle

(Late) Bhabesh Ch. Banerjee

for his efforts to teach me the values of knowledge and wisdom

CHAPTER 1

INTRODUCTION

The world population is increasing at a geometric rate. At the rate at which population is growing, it has been predicted that by the year 2050, the world population would be 9.36 billion, compared to 5.85 billion at present (McDevitt, 1996). With this growth, the concern for the quality of the environment is essential. With an increase in urbanization and industrialization, it is quite natural that there would be a lot more production of waste in the years to come.

Waste is generated everywhere in the form of solid, liquid or gas. The liquid waste i.e. wastewater, is the water supply to the communities which is drained out either not used or polluted by different sources. Liquid effluents from residences and industries along with the groundwater and storm water all combine into wastewater.

This wastewater has to be treated prior to disposal. Decomposition of organic matter in untreated wastewater would produce foul odors, which would result in poorer quality of the environment and lower its aesthetic value. There are a lot of microorganisms present in the wastewater, many of which are pathogenic, contributing to a health hazard. There is always a possibility of some toxic substances present in the wastewater. Wastewater also contains nutrients which might enhance aquatic plant growth, resulting in oxygen depletion and eutrophication. Hence, liquid waste management, involving the collection, treatment, disposal and reuse of wastewater is necessary to maintain the quality of the environment.

Concentrated liquid waste (i.e. sludge) is the result of settling of wastewater in the primary or secondary sedimentation tanks, after pretreatment. The sludge has to be stabilized before it can be disposed of and this can be accomplished by physical, chemical or biological means. Biologically, the sludge can be stabilized aerobically or anaerobically. Anaerobic digestion has been one of the oldest and most common treatment methods due to its capabilities of stabilizing a large volume of sludge, low biomass production, a high destruction rate of pathogens, and production of methane as an energy source (Ghosh et al., 1975).

Anaerobic digestion is a multistage process. In brief, it can be described as a two stage process. In the first stage (the acid phase), the complex organic material is converted into intermediate compounds, mainly fatty acids and alcohols. Then in the second stage (the methane phase) these compounds are converted into a variety of end-products, mainly methane (CH_4) and carbon dioxide (CO_2). Since methane is a source of energy, most of the research has been focused on the methane production phase. Little attention has been paid to the acid phase, the process by which waste particulates are solubilised and fermented to fatty acids (Eastman and Ferguson, 1981). A detailed knowledge of acid phase fermentation is important in a variety of situations ranging from improving other treatment processes to achieving optimum design for the performance of fermenters. Typical applications of acid phase digestion include improvement of digester stability resulting from physical separation of the acid and the methane phases; and increase in the concentration of soluble organics which may be used to enhance subsequent treatment processes such as Biological Nutrient Removal (BNR) processes.

With the modern era of industrialization, there is bound to be an increase in the production of liquid waste. Many of the industrial effluents are discharged to public sewers and treated along with domestic sewage (Matthews, 1994). Hence it is necessary to study the effects of different kinds of industrial wastewater in combination with municipal wastewater on the overall performance of anaerobic digestion.

CHAPTER 2

LITERATURE REVIEW

2.1 BIOLOGICAL TREATMENT PROCESSES

In most cases, wastewater can be treated biologically, if proper conditions are provided. The contaminants are removed by the biological activity of microorganisms in the system. Biological processes are used primarily to remove biodegradable organic substances (colloidal or dissolved) in the wastewater. Basically, these substances are converted into gases that can escape to the atmosphere, and into biological cell tissue that can be removed by secondary settling, since the specific gravity of cell tissue is greater than that of water. Biological processes are also used to remove nutrients from the wastewater which are present in the form of nitrogen and phosphorus. Removal of certain toxic organic compounds can also be achieved by providing appropriate conditions.

Biological treatment processes are used during secondary treatment to remove the soluble organic matter that escaped the primary treatment. Secondary treatment involves bringing the active microbial population in contact with the wastewater, so that it can consume the organic matter as food. A great variety of microorganisms come into play that include bacteria, protozoa, rotifers, nematodes, fungi, algae etc. (Metcalf and Eddy, 1991). These microorganisms can be aerobic (requiring free oxygen), anaerobic (requiring an oxygen-free environment) and facultative (growing with or without oxygen).

2.2 WASTEWATER COMPOSITION

Wastewater composition refers to the actual amounts of physical, chemical and biological constituents present in the wastewater. Physical constituents include colour, turbidity and odour. Chemical components include total solids (TS), total suspended solids (TSS), 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total organic carbon (TOC), soluble organic carbon (SOC), different forms of nitrogen and phosphorus, chlorides, sulphates, grease etc. The microbial population is referred to as the biological constituent (Metcalf and Eddy, 1991).

Municipal wastewater is the principal source of organic matter entering into the aquatic environment. Most of these organic compounds are in the form of carbohydrates, proteins and lipids. These three forms constitute 80 to 100% of the volatile solids (VS) of the primary sludge (Elefsiniotis, 1993). There is also some urea present in the wastewater, but as urea decomposes rapidly, it is seldom observed. Other organic compounds found in small fractions are synthetic detergents, phenolic compounds, pesticides and herbicides (Qasim, 1994).

2.2.1 CARBOHYDRATES

Carbohydrates are found in all animal, plant and microbial cells. They have a general formula of $(CH_2O)_n$, where $n \geq 3$. The short molecules are called monosaccharides which contain 3 to 9 carbon atoms. Polysaccharides are mainly derivatives of simple sugars linked by glycosidic bonds. Municipal wastewater contains different kinds of carbohydrates which include sugar, starch, cellulose, pectin, lignin and wood fiber. Most

of these except sugars are insoluble in water. As starch is of interest in this study, a brief description of its properties is given below.

Starch: Starch has the general formula $(C_6H_{10}O_5)_x$ and is mainly of two types - amylose and amylopectin. Amylose is composed of short chain polymers of glucose linked by 1,4-glycosidic bonds, whose molecular weight varies from several thousands to half a million. Amylose constitutes only 20% of starch. The remaining is amylopectin, which is distinguished by substantial branching from the ends of amylose segments averaging 25 glucose units in length. The molecular weight varies from 1 to 2 million (Foster, 1965; Bailey and Ollis, 1977). Starch is found in municipal wastewater in small amounts.

2.2.2 PROTEINS

Proteins are polymers of α -amino acids joined together by peptide bonds. They contain carbon, hydrogen, oxygen and nitrogen and in most cases sulphur and phosphorus. The molecular weight varies from 6000 to over 1 million. They are an essential part of all living matter. Proteins are of two major types - fibrous, which are tough and insoluble in water; and globular, which are soluble in water. Many amino acids have been identified in untreated sewage. Most of the organic nitrogen in wastewater is in the form of proteins.

2.2.3 LIPIDS

Lipids are biological compounds which are soluble in non-polar solvents and practically insoluble in water. They are diverse in chemical structure and biological function. They range from simple molecules of fat to complex molecules of triglycerols,

lipoproteins, liposaccharides and phospholipids, which are predominant building materials for the cell wall of various microorganisms (Bailey and Ollis, 1977). Most lipids contain fatty acids which contain 16 to 18 carbons atoms (Prescott et al., 1990).

Lipids are contributed to the domestic wastewater from butter, lard, margarine, vegetable fats and oils (Metcalf and Eddy, 1991). Animal fats and fats from certain fruits and seeds also contribute to the lipid content of the wastewater.

2.3 INDUSTRIAL WASTEWATER

Most industrial processes produce liquid wastes which are generally high in organic loading. Effluents from many industries are discharged to public sewers and are treated along with domestic sewage. Therefore a municipal treatment facility also provides a service to the industry (Matthews, 1994). In a study of anaerobic co-digestion of sewage sludge and concentrated wastewaters, Carrieri et al. (1993) mixed primary sludge from an anaerobic digester with concentrated wastewaters from olive oil effluents, cheese whey and landfill lechate. They concluded that the volumetric loading can be increased more than twofold than that in conventional digesters when using the mixed wastewater, and also that the conversion rates of soluble substrates were better than those obtained in high-rate digesters.

The industrial wastewater used in this study was from a potato processing plant. Potato processing industry is one of the most common food industries in the world. Slicing and grinding of the potatoes results in the production of starch. The wastewater generated from these operations has a high concentration of starch. This wastewater is

generally with high concentrations of BOD₅, COD and suspended solids (Abeling and Seyfield, 1993).

As potato processing wastewaters contain high concentrations of readily biodegradable compounds, they are most often treated by biological processes. Methods used include conventional and modified activated sludge systems, trickling filters with conventional and synthetic media, aerated lagoons and waste stabilization ponds (Fisheries and Environment Canada, 1977). Most of the related research has been conducted using combined effluents of a potato processing plant. Landine et al. (1986) studied a pilot-scale experiment of a low rate anaerobic treatment of potato processing plant effluents. They obtained more than 80% removal of BOD₅, COD and suspended solids under different conditions of hydraulic retention time (HRT) and temperature. In an attempt to treat potato processing wastewater, Lin (1986) employed an aerated lagoon following anaerobic filters and reported satisfactory removal of COD and suspended solids at different temperatures and loading conditions. The system performed well even at temperatures as low as 4°C. In another study, Landine et al. (1983) used a bulk volume fermenter which provided 90% removal of BOD₅, COD and suspended solids under anaerobic conditions, while operating under higher loads than it had been designed for and at temperatures below 20°C.

2.4 OVERVIEW OF ANAEROBIC DIGESTION

Anaerobic digestion is a multistage process in which organic matter is converted into a variety of end-products including methane and carbon dioxide, in the absence of molecular oxygen. In general, it can be considered as the following three-step process accomplished by a large consortium of microorganisms (Wang, 1994).

- 1. Hydrolysis: This involves the production of extracellular enzymes, by microorganisms, for the transformation of higher molecular mass complex organic compounds such as proteins, carbohydrates and lipids into compounds suitable for use as a source of energy and cell carbon.**
- 2. Acidogenesis: This involves the bacterial conversion of compounds produced by hydrolysis into lower molecular weight intermediate compounds such as VFAs and alcohols; and hydrogen.**
- 3. Acetogenesis and Methanogenesis: This involves the bacterial conversion of lower molecular weight intermediate compounds into methane and carbon dioxide. Methane is produced mainly via acetic acid or via hydrogen and carbon dioxide.**

Parkin and Owen (1986) also defined anaerobic digestion as a three-step process. The first step is a combination of hydrolysis, liquefaction and fermentation, followed by the next step of hydrogen and acetic acid formation. The last step is methane formation.

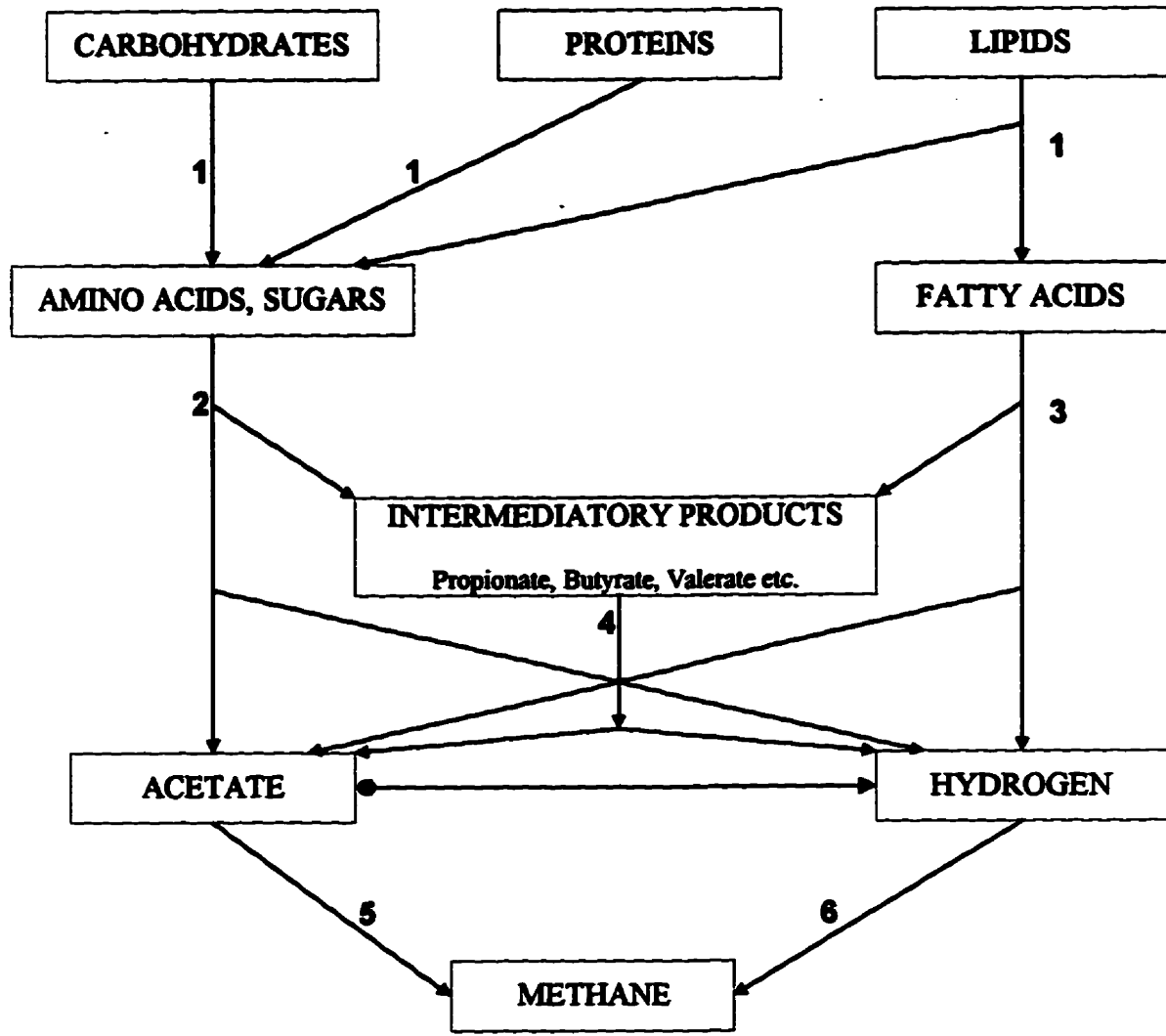
Gujer and Zehnder (1983) presented a more detailed six-step process for anaerobic digestion, as follows:

- 1. Hydrolysis of biopolymers (carbohydrates, proteins and lipids).**

2. Fermentation of amino acids and sugars.
3. Anaerobic oxidation of long chain fatty acids and alcohol.
4. Anaerobic oxidation of intermediary products such as VFAs (except acetate).
5. Conversion of acetate to methane.
6. Conversion of hydrogen to methane.

A schematic representation of the above reactions is shown in Figure 2.1. The first three steps are considered as acidogenesis, while the last three are considered as methanogenesis. Ghosh (1975) defined the acid-phase as a combination of hydrolysis and fermentation. For better operation and understanding of the overall process of anaerobic digestion, it has been suggested that the two phases be separated. This is because of the differences in physiology, growth and nutritional requirements between the two groups of bacterial population in the two phases (Gil-Pena et al., 1986). Ghosh (1987) and Fongastitkul et al. (1994) have shown the feasibility of separation of the two phases with different reactor configurations. Moreover, the two phase anaerobic digestion provided better results when production and yield were taken into consideration, compared to the single-phase anaerobic digestion. In a study conducted to compare the solids reduction in a conventional and a two-phase digester, Bhattacharya et al. (1996) showed that the two phase systems produced 2 to 6% increase in VS reduction over conventional digesters.

The main objective of an anaerobic digester is to turn an objectionable, polluting, sewage sludge into a stabilized, much less polluting, digested sludge. Gas production is a secondary feature and varies with input solids concentration and digester efficiency (Hobson, 1980).



1. HYDROLYSIS
2. FERMENTATION
3. ANAEROBIC OXIDATION OF FATTY ACIDS
4. ANAEROBIC OXIDATION OF INTERMEDIATE PRODUCTS
5. ACETOCLASTIC METHANOGENESIS
6. REDUCTIVE METHANOGENESIS

Figure 2.1: Pathways of anaerobic metabolism
 (Adapted from Gujer and Zehnder, 1983)

2.5 ACIDOGENESIS

A group of anaerobic bacteria in nature are able to ferment and break down the products of hydrolysis to simple organic acids like acetic, propionic, butyric and valeric. This group of microorganisms is known as acidogens or acid-formers.

2.5.1 MICROBIOLOGY AND BIOCHEMISTRY

In acidogenesis, carbohydrates, proteins and lipids are the principal compounds used. A large number of microorganisms utilize them as substrates and convert them into VFAs via anaerobic metabolic pathways. Since complex bio-polymers cannot penetrate the cell membrane, bacteria excrete enzymes that hydrolyze the particulate substrates to small transportable molecules (Elefsiniotis, 1993).

There are several groups of bacteria carrying out specific reactions in the overall process of anaerobic digestion. The fermentative bacteria (also known as acidogens) are responsible for hydrolysis and fermentation. They produce enzymes which are released into the medium to hydrolyze the complex organic compounds into smaller molecular weight material which is transported into the interior of the cells and fermented into a variety of end products such as ethanol, acetate, propionate etc. (Novaes, 1986).

2.5.2 PATHWAYS OF VFA FORMATION

The production of VFAs under anaerobic conditions is the effect of the activities of the microbial population. A large number of microorganisms is responsible for the breakdown of complex organic matter (carbohydrates, proteins and lipids) into VFAs and other soluble carbon compounds through different anaerobic metabolic pathways (Elefsiniotis and Oldham, 1994b). The rate of hydrolysis depends upon pH, temperature, type of substrate, size of particles and the concentration of the remaining biodegradable particulate organics (Eastman and Ferguson, 1981). The hydrolysis products are fermented via different metabolic pathways to VFAs and other soluble organic compounds.

2.5.2.1 CARBOHYDRATE METABOLISM.

a. Hydrolysis:

Carbohydrates like cellulose, pectin and starch are hydrolyzed in to simple sugars, mainly glucose, along with some galactose, arabinose and mannose. Microorganisms responsible for the hydrolysis include *Acetovibrio celluliticus*, several species of clostridia and some fungi (Gujer and Zehnder, 1983). Starch is a storage material and as such is structured to be biodegradable. Starch is converted to glucose by action of four types of enzymes (Gottschalk, 1986).

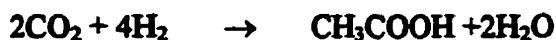
b. Fermentation of Sugars:

Glucose, the main product of the hydrolysis of polysaccharides is fermented by microorganisms using it as a main source of carbon and energy for the synthesis of cell constituents. Glucose is converted into pyruvate by the Embden-Meyerhof-Parnas (EMP) pathway, which is the main intermediate product. From pyruvate different products like VFAs, alcohols etc. are formed depending on the species of microorganisms present. The EMP pathway is shown in Figure 2.2, while the different reactions from pyruvate to various end products are shown in Figure 2.3. The volatile acids, gases (hydrogen and carbon dioxide), and alcohols formed are utilized as substrates by methanogenic bacteria, although it has been shown that alcohols are of minor importance in the digestion of sewage sludge (Andrews and Pearson, 1965).

Acetic acid is formed by fermentation of glucose according to the following reaction due to activities of microorganisms like *Clostridia* and *Acetobacteria* (Gottschalk, 1986).



It is also formed from inorganic compounds like hydrogen and carbon dioxide by *Clostridium Aceticum* (Andrews and Pearson, 1965).



Propionic acid is formed by fermentation of pyruvate by anaerobes of the *Propionibacterium* genus via the succinate-propionate pathway, according to the following reaction (Elefsiniotis, 1993).



A preferred substrate of propionate-forming bacteria is lactate, which enhances the growth of the relevant microorganisms. There are two mechanisms in which propionate is formed from lactate; in the acrylate pathway lactate is reduced stepwise to propionate and in the succinate-propionate pathway lactate is converted to propionate via pyruvate and succinate. An overall general equation for the formation of propionate from lactate is as follows (Gottschalk, 1986).



Butyric acid is formed as the fermentation product of obligate anaerobes of the genera *Clostridium*, *Butyrivibrio*, *Eubacterium* and *Fusobacterium*. In the pathway, the pyruvate is converted to acetyl CoA, which is then converted to butyrate via butyryl CoA and butyryl phosphate, under the action of different enzymes (Gottschalk, 1986).

2.5.2.2 PROTEIN METABOLISM

a. Hydrolysis:

Some bacteria use protein as a source of carbon and energy. They secrete proteolytic enzymes that hydrolyze the proteins and polypeptides to amino acids, which are transported in to the cell to be used as building blocks or fermentation substrates. Proteins are hydrolyzed in a reverse manner to which they are synthesized. The main microorganisms responsible for the production of amino acids is *Proteus vulgaris* and those belonging to the species *Clostridia clostridia* (Gujer and Zehnder, 1983).

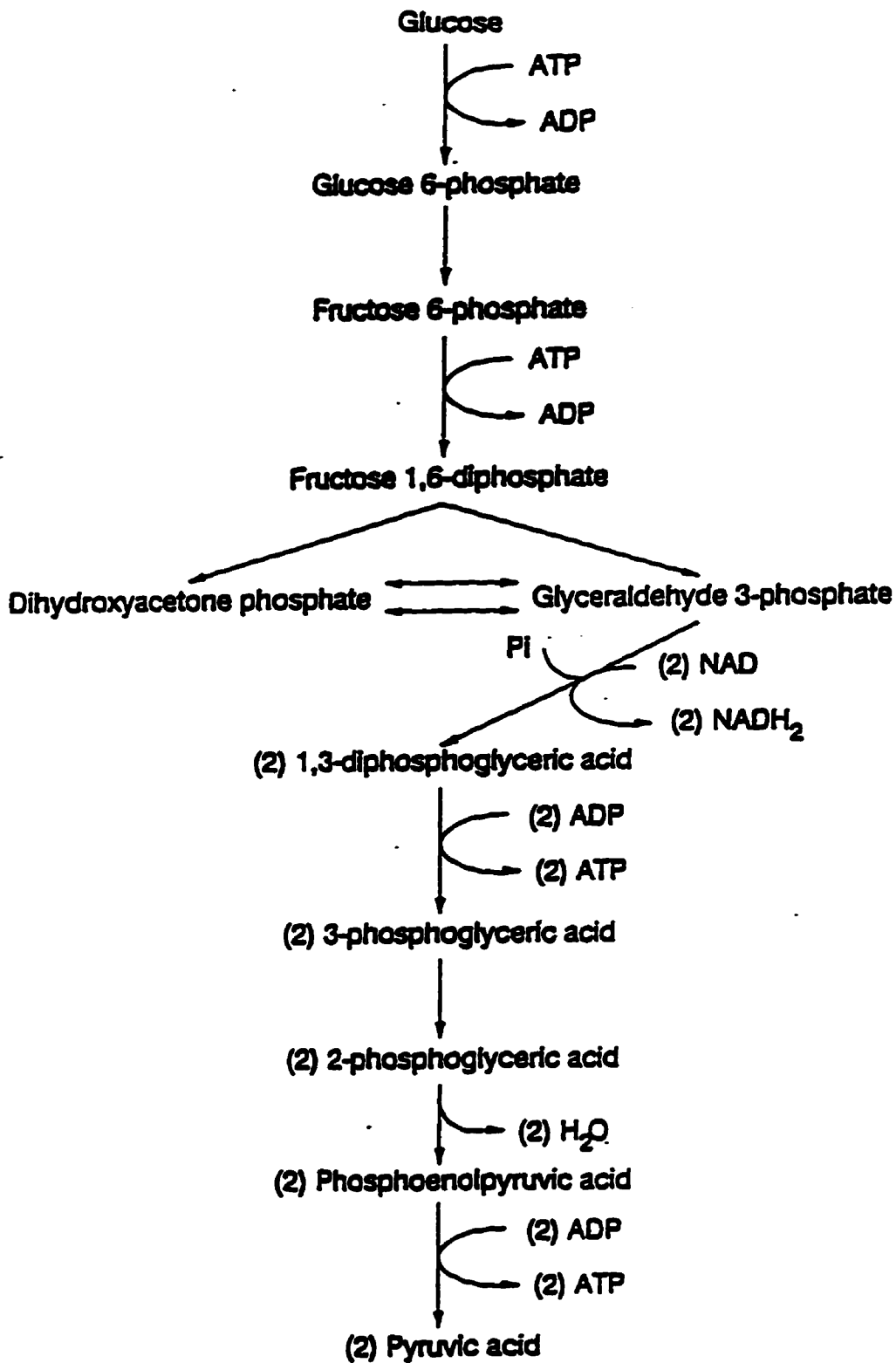
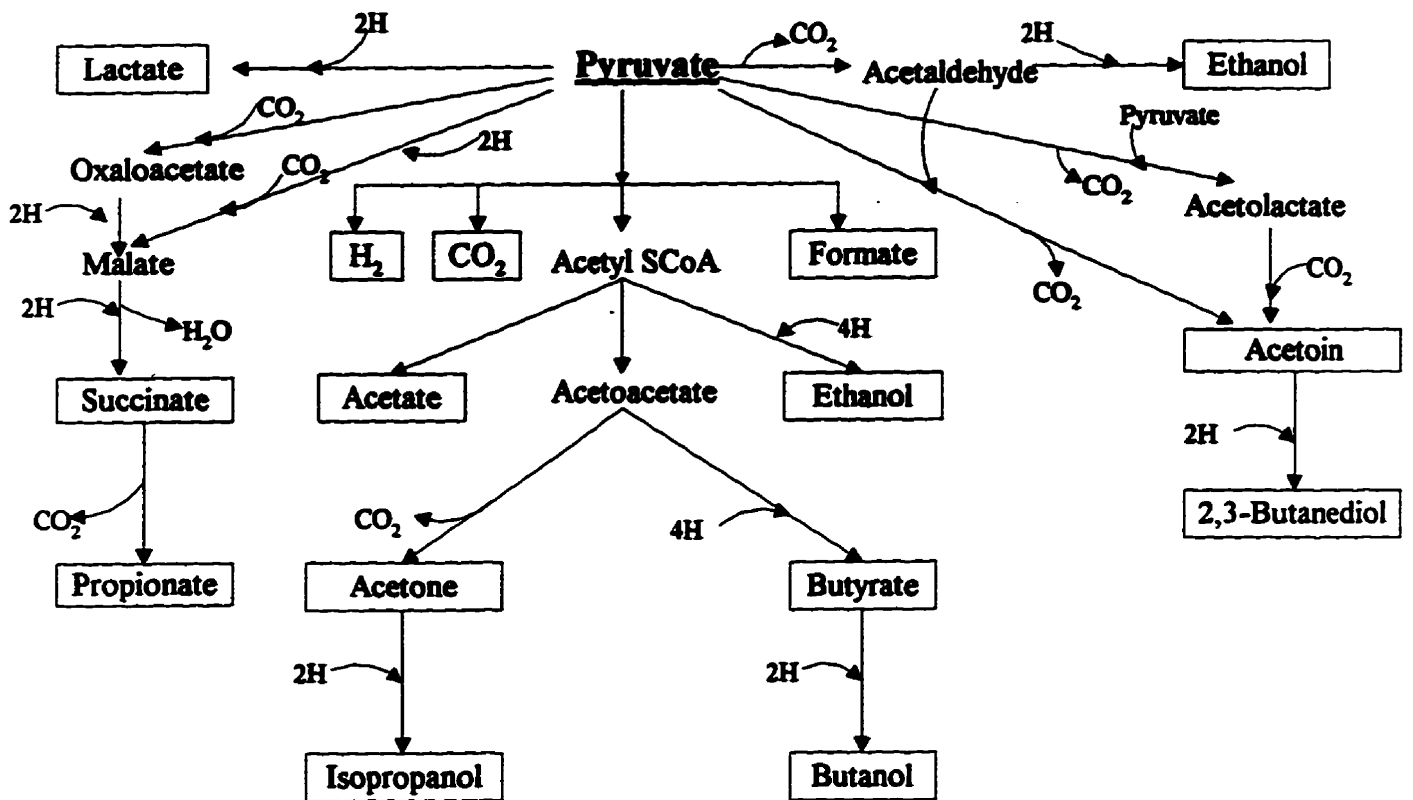


Figure 2.2: The Embden-Meyerhof-Parnas pathway for the conversion of glucose to pyruvate. (From Gaudy and Gaudy, 1980)



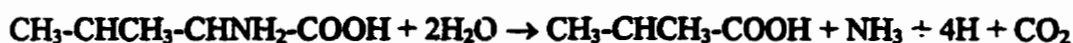
* Boxed compounds are possible end products

Figure 2.3 : Fermentation products formed from pyruvate
(Adapted from Andrews and Pearson, 1965)

b. Fermentation of Amino acids:

The first step of amino acid utilization is deamination (i.e. removal of the amino group(s) from an amino acid). This is often accomplished by transamination, where the amino group is transferred from amino acids to an α - keto acid acceptor. The organic acid resulting from the deamination can be converted to pyruvate, acetyl CoA or a TCA cycle intermediate and eventually oxidized in the TCA cycle to release energy. It can also be used as a source of carbon for synthesis of cell constituents (Prescott et al., 1990).

VFAs are also formed in the fermentation of some amino acids without passing through pyruvic acid as an intermediate compound. Some amino acids like leucine and valine are oxidized through the Stickland reaction giving branched chain VFAs like iso butyric and iso valeric acids, as shown in the following equations; while other amino acids like glycine and proline serve as acceptors of the hydrogen produced (Andrews and Pearson, 1965).



Valine

Iso butyric



Leucine



Iso valeric

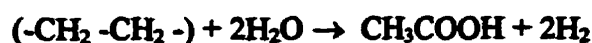
2.5.2.3 LIPID METABOLISM

a. Hydrolysis:

Lipids are first hydrolyzed to glycerol and long chain fatty acids like stearic, oleic and palmitic acids (Andrews and Pearson, 1965). The predominant microorganisms responsible for the hydrolysis of lipids are the species belonging to the groups *Bacillus*, *Clostridium* and *Serratia*. There are two main groups of enzymes that are responsible for the hydrolysis of lipids - Lipases, which catalyze the reversible hydrolysis of fatty acid ester bonds into simpler lipids; and Phospholipases, which are involved in the hydrolysis of phospholipids (Elefsiniotis, 1993).

b. Fermentation of fatty acids:

Glycerol can be converted to pyruvic acid via glycolysis and then fermented to VFAs as described in section 2.5.2.1. (Andrews and Pearson, 1965) . The metabolism of long chain fatty acids takes place via a mechanism called β -oxidation, as the carbon at the beta position (second from the carboxyl atom) is oxidized. The stoichiometry of the β -oxidation reaction is as follows (Gujer and Zehnder, 1983).



2.5.3 FACTORS AFFECTING VFA PRODUCTION

Research towards the better understanding of VFA production during anaerobic digestion has been carried on for quite a few years (Andrews and Pearson, 1965, Ghosh et al., 1975). There have been studies on the feasibility of phase separation techniques,

identification of the limitations of the process, and investigation of the effect of parameters like HRT, temperature, pH, and agitation speed on the acid phase fermentation of raw wastewater and primary sludge in various reactor configurations.

Eastman and Ferguson (1981) identified the hydrolysis of particulate organic matter to soluble substrates as the rate-limiting step during the acid generation phase, while Elefsiniotis (1993) concluded that the conversion of soluble metabolic intermediates to VFAs and other end-products was the most critical parameter in determining the rate-limiting step. Pitman et al. (1992) investigated the fermentation for VFA production using recirculation of primary sludge between primary sedimentation tanks and primary sludge thickeners. The main disadvantage of this process was the increase in the nutrient and solids loading to the biological processes.

Perot et al. (1988) studied the influence of pH, temperature and agitation speed on the VFA production in fermenters, where pH was controlled between 5 and 7, temperature between 39°C and 54°C and agitation speed between 378 and 622 rpm. The optimum conditions achieved in the above study were a pH of 6.8 at 50°C and 545 rpm. They also suggested that a pH of 5.0 seemed to be the lowest possible for the survival of hydrolytic bacteria.

According to Gupta et al. (1985), there is a consistent improvement in the VFA production from primary sludge in batch systems, from 10°C to 30°C. However, pH control at 7.0 did not affect the production. A retention time of 9 days was required at 10°C and 20°C but at 30°C, 6 days was reported to be optimum. Skalsky and Daigger

(1995) also reported that VFA production increased with increase in temperature from 14°C to 23°C.

Gon Calves et al. (1994) studied the influence of retention time on the fermentation of raw wastewater in the range of 1.1 to 4.3 hours at a constant temperature of 20°C, and results indicated an optimum retention time of 4.3 hours in a upflow sludge blanket reactor, while Andrews and Pearson (1965) reported a optimum retention time of 2.4 days. Elefsiniotis and Oldham (1994a) reported a continuous increase in VFA production when HRT was increased from 6 to 12 hours and there was a drop at 15 hours due to onset of methanogenesis. In addition, Elefsiniotis and Oldham (1994b) have showed that a decrease in pH from 5.1 to 4.5 did not affect the specific VFA production rates, but an increase to 6.1 reduced the production rates.

2.6 APPLICATIONS OF ACID-PHASE DIGESTION

An improved knowledge of acid phase fermentation is important in a variety of situations. Digester stability may improve from physical separation of the acid and methane phases. The concentration of soluble organics is increased in the primary clarifiers and sludge thickeners which affects the subsequent treatment processes. Optimum design and improved performance of fermenters can be also achieved. Furthermore, the soluble organic products of the acid phase digestion can be used to enhance Biological Nutrient Removal (BNR) processes (Eastman and Ferguson, 1981; Elefsiniotis, 1993).

Until recently, the traditional standards for the discharge of effluent from wastewater treatment facilities have focused on removal of contaminants such as BOD₅,

COD and TSS. Now that these parameters are dealt with effectively by conventional primary and secondary treatment, other concerns are gaining more prominence. Among these issues is eutrophication, which is defined as the enrichment of surface water bodies by nutrients (nitrogen and phosphorus) and the consequent deterioration of water quality due to luxuriant growth of the plants (Danesh, 1997). In the following sections biological nitrogen removal and biological phosphorus removal are discussed.

2.6.1. BIOLOGICAL NITROGEN REMOVAL

Nitrogen can occur in many forms in wastewater and undergo numerous transformations in the treatment process. These transformations allow for the conversion of ammonia nitrogen to products, like nitrogen gas, that can be easily removed from the wastewater.

Most of the nitrogen removal is accomplished through nitrification and denitrification. Nitrification is carried out by autotrophic microorganisms, which use inorganic carbon as carbon source. The nitrification process consists of two steps as follows (Oleszkiewicz, 1995).

1. Ammonia is oxidized to nitrite by *Nitrosomonas* and *Nitrosococcus*.

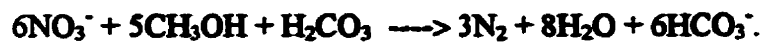


2. Oxidation of nitrite to nitrate by *Nitrobacter* and *Nitrosocystis*.



The main factors affecting nitrification are SRT, growth rate, dissolved oxygen, temperature and pH.

Denitrification is the removal of nitrogen in the form of nitrate by conversion to nitrogen gas under anoxic conditions. Facultative heterotrophs use organic carbon as a source of energy and carbon, and NO_3^- as the final electron acceptor. The typical stoichiometric equation for denitrification is as follows (Oleszkiewicz, 1995).



The major factors affecting denitrification are carbon source, dissolved oxygen, pH and temperature. The example in the above reaction uses methanol as an external carbon source. Due to cost considerations, a substitute for methanol is being sought (Oleszkiewicz, 1995). Recent studies have indicated that the use of acetic acid has resulted in successful removal of nitrogen in denitrification experiments (Danesh, 1997). Therefore, the VFAs produced during the acid-phase anaerobic digestion can be used as a substitute organic carbon source for denitrification.

2.6.2. BIOLOGICAL PHOSPHORUS REMOVAL

Phosphorus is removed from wastewater when the microorganisms are subjected to alternating anaerobic/aerobic environment. Bio-P bacteria like *Acenitobacter* are able to store considerable amounts of phosphorus as poly-phosphates in their cells. They use this source of energy to transport the volatile fatty acids (VFAs) across their cell walls under either anaerobic or aerobic conditions. Under anaerobic conditions, they do not have to compete with other aerobic or denitrifying organisms. When an anaerobic contact zone,

free of nitrates and dissolved oxygen but with a supply of VFAs, is provided, the bio-P bacteria will use the energy to transfer VFAs into their cells and store them as polyhydroxyalkonates (PHA), mainly poly- β -hydroxybutyrate (PHB). When passing into the aerobic zone, the Bio-P bacteria metabolize the PHB and use this energy to store internally all available phosphorus in solution. When these phosphorus-rich cells are wasted from the system with the sludge, phosphorus removal occurs (Comeau et al, 1986; Barnard, 1995).

It has been noticed that there is a relationship between the amount of VFAs added and the amount of phosphorus eventually removed from the solution. Pitman et. al (1992) reported that the addition of VFAs could enhance the excess biological phosphorus removal. VFAs are essential for the microorganisms involved in the biochemical pathways responsible for biological removal of phosphorus. It has been found that 7 - 9 mg of VFA are required per mg phosphorus to be removed (Barnard, 1993). Sufficient concentrations of these readily biodegradable components in the wastewater allow low phosphorus residuals (< 1.0 mg P/l) in the effluent (Gon Calves et al., 1994). Abu-ghararah and Randall (1991) and Randall et al. (1994) reported that C₁ - C₅ carboxylic acids except propionic improved phosphorus removal, and also that branched molecules of butyric and valeric acids were superior to their linear isomers. Manoharan (1988) reported that the effectiveness of the VFAs in biological phosphorus removal had the descending order of acetic > propionic > butyric acid. Carlsson et. al. (1996) showed that the effect of VFA on phosphorus uptake depends on pH in the range 6-8.

2.7 REACTOR CONFIGURATIONS

One of the main objectives during the process of anaerobic digestion is to maintain a sufficient amount of active biomass in the reactors. Over the years, many suspended and attached growth reactor configurations have come into operation like batch reactors, completely mixed reactors, anaerobic contact process with recycle, column reactors like the packed bed, fluidized bed and expanded bed reactors, sludge blanket reactors and baffled reactors (McCarty and Smith, 1986; Metcalf and Eddy, 1991). The different reactor configurations are shown in Figure 2.4. The type of reactor to be considered for a particular process depends on operational parameters like the nature of wastewater, reaction kinetics governing the process, process requirements and local environmental conditions along with construction, operational and maintenance costs (Metcalf and Eddy, 1991). Reactors are also characterized by their ability to control the process variables, specially the microbial solids (Jewell, 1987). Though a number of reactor types is possible, the type of digester to be selected depends upon the feedstock and economic considerations, rather than the bacterial reactions (Hobson, 1980).

The reactor configuration selected for this study on the acidogenesis of primary sludge along with starch-rich industrial wastewater is the completely mixed reactor with a clarifier and a recycle system. This kind of reactor has been in operation for a number of years and is considered as a dispersed or a suspended growth system (McCarty and Smith, 1986). Completely mixed reactors are easy to operate and produce statistically reliable results, which are necessary for research. In these reactors, the particles upon entering the

tanks are dispersed immediately throughout the tank. These particles leave the tank in proportion to their statistical population (Metcalf and Eddy, 1991). Completely mixed reactors also allow for independent HRT and SRT control, when recycle is provided.

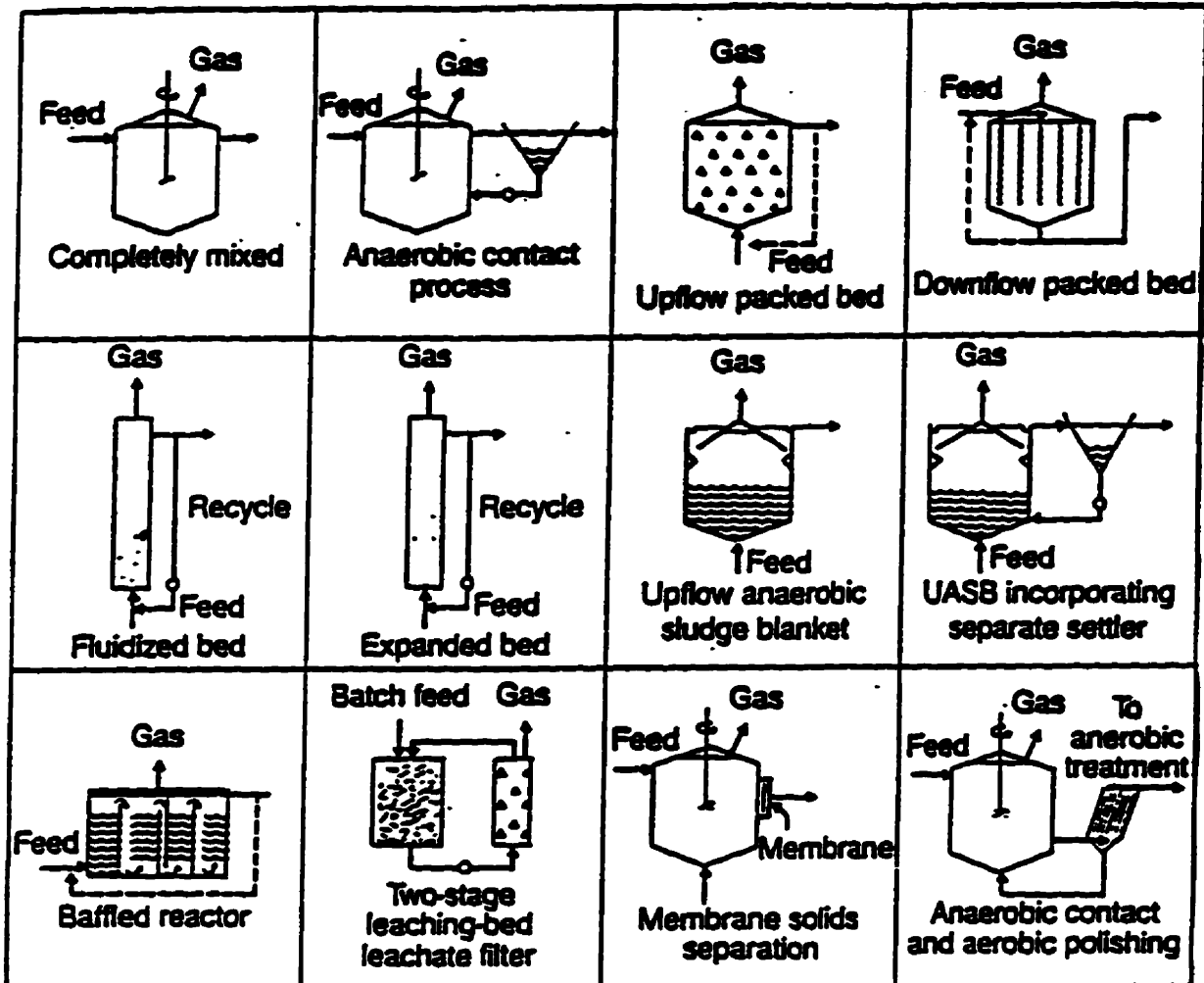


Figure 2.4: Reactor configurations

(from McCarty and Smith, 1986)

CHAPTER 3

RESEARCH OBJECTIVES

As discussed previously, most of the research on anaerobic digestion has been focused on the optimization of the methane-producing phase. A detailed knowledge on the acid-phase of anaerobic digestion is necessary as described in Section 2.6. There have been several studies on the acid phase digestion in the recent past. Research has been carried out to determine the feasibility of phase separation and to explore the effect of temperature, HRT, and agitation speed on the production of VFAs from raw wastewater and from municipal primary sludge, in batch reactors, and continuous flow reactors having various configurations. The kinetics of the process and the effect of wastewater characteristics have also been investigated.

Most of the research on potato processing plant wastewater has been on the combined wastewater, which comprises of the washing water and the starch wastewater. The starch wastewater is by itself easily biodegradable and may enhance the VFA production if combined with municipal primary sludge. It should be noted that in agricultural areas, the wastewater treatment plants of small towns usually receive a significant amount of food processing wastewaters. A representative example is the town of Portage la Prairie, Manitoba, Canada, where 40 to 50 % of the wastewater coming into the treatment plant of this town is from a potato processing industry (Takach, 1996).

The most important present day application of acidogenesis is in biological nutrient removal, viz. nitrogen and phosphorus. It has been discussed that there is a direct relationship between the amount of VFA present to the amount of phosphorus removed. In this case, it is necessary to try to optimize the conditions in which the VFA production is maximized. There is a lack of information regarding the performance of continuous flow reactors in the temperature range of 22°C to 35°C, as far as acidogenesis is concerned. Optimizing the different environmental and operational parameters of the acid-phase anaerobic digestion of municipal primary sludge and combined wastewater would result in improved design of the nutrient removal process.

Keeping the above considerations in mind, the following objectives were formulated in the design of this study:

1. Explore the effect of addition of an industrial waste to municipal primary sludge on the acidogenesis.
2. Investigate the effect of an operational parameter (HRT) on the acid-phase digestion.
3. Investigate the effect of an environmental parameter (Temperature) on the acid-phase digestion.

To meet the above objectives, two bench scale continuous flow reactors, with clarifiers, were set up. Provisions were made to control the HRT and temperature, and different analyses were performed regularly to examine the behavior of the two systems. The net VFA production and the production rate along with the substrate solubilization gave a good conception about the extent of acidogenesis.

CHAPTER 4

MATERIAL AND METHODS

4.1 SOURCE OF WASTEWATER

The primary sludge used in this research was obtained from The South End Water Pollution Control Center in Winnipeg, Manitoba. The sludge was generally received once every ten days, and stored in a cold chamber at 6°C in closed containers. The TS of the sludge was determined and it generally varied between 35000 mg/l and 40000 mg/l. The sludge was diluted with tap water to a concentration of 5000mg/l. This diluted sludge was fed to two continuously stirred feed buckets, which were also kept in the cold chamber.

The industrial wastewater was obtained from The Old Dutch Food Company in Winnipeg, Manitoba. This industry generates two sources of wastewater. One is the washing wastewater and the other is the starch wastewater. A lot of starch is produced when the potatoes are sliced. In this plant, the starch-rich wastewater is passed through a series of settling tanks and the effluent is discharged into the sewers. The settled starch is taken away by farmers and used as feedstock. The wastewater for this study was collected just before it entered the first settling tank. In this case also, the TS was first determined and then the waste was diluted to 5000 mg/l with tap water.

4.2 SYSTEM CONFIGURATION

Two identical treatment trains were established. The reactors were continuously mixed by steel mechanical stirrers. The feed into the reactors was pumped continuously from the feed buckets. In the clarifiers, after settling, the effluent was disposed and the settled biomass was recycled back into the reactor. There was a sampling / wasting port on the reactor. Figure 4.1 shows the schematic diagram of the system configuration.

The details of the pieces of equipment used are as follows:

1. Reactors: Made of Plexiglas, with internal diameter of 10.7 cms. The total volume was 2.25 liters, with a liquid volume of 2 liters. The reactors were attached with mechanical stirrers.
2. Clarifiers: Modified Imhoff cone, active volume 2 liters.
3. Peristaltic pumps: Cole Parmer
4. Masterflex pump heads.
5. Masterflex speed controllers.

4.3 STARTUP PROCEDURE

Digested sludge from The North End Water Pollution Control Center in Winnipeg, Manitoba, acting as seed was fed into the reactors. The initial TS of the seed was 25970 mg/l. The reactors were seeded with 500 ml of diluted seed containing 10,000 mg/l TS. The reactors were fed with the influent from the respective feed buckets. Initially it was decided to feed the reactors with TS of 10000 mg/l. It was observed that there was a

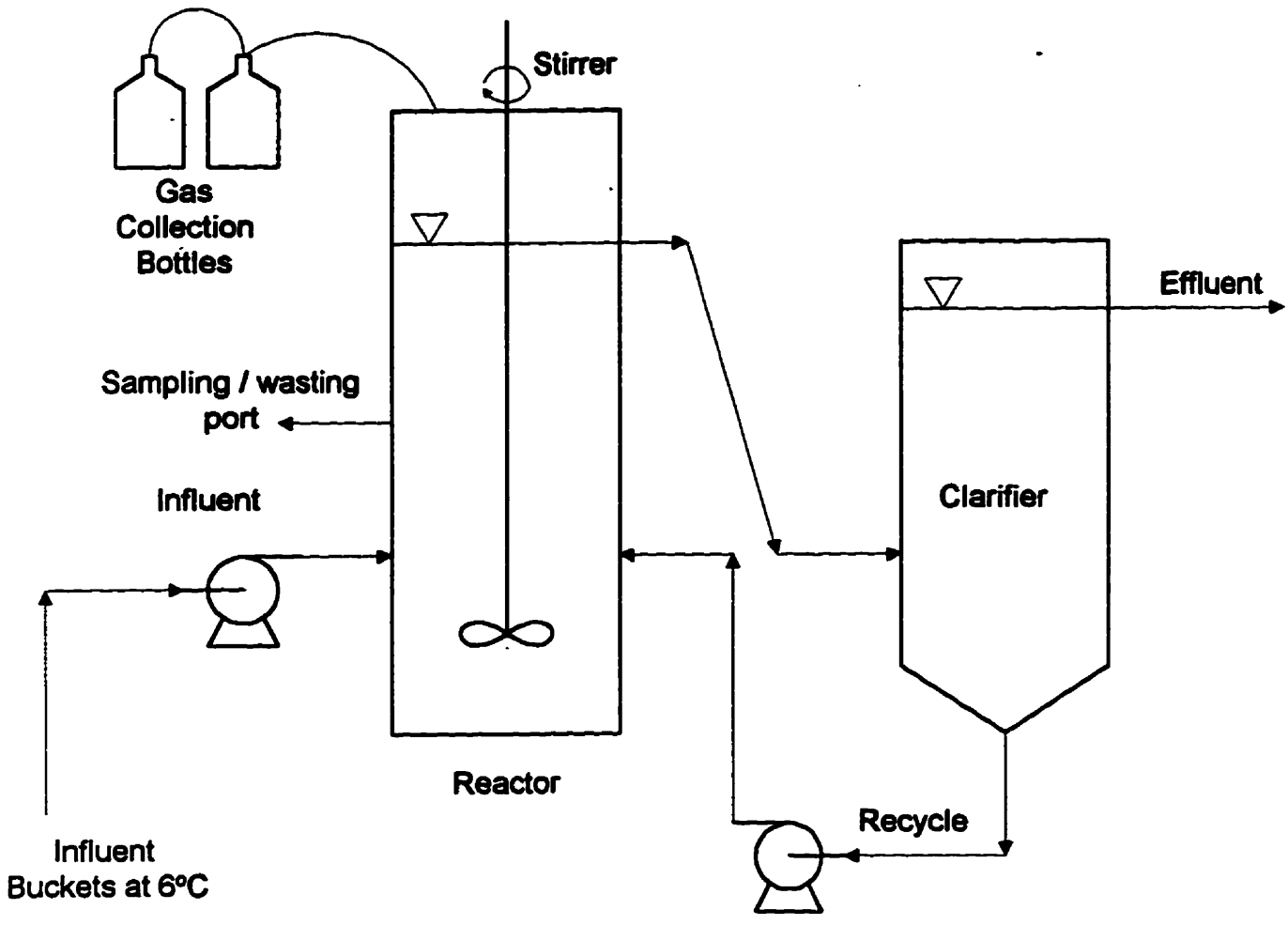


Figure 4.1 : Experimental Set Up

tendency for the influent hoses to clog up. Hence, it was decided to reduce the feed concentration to 5000 mg/l, in order to minimize operational problems.

4.4 MONITORING AND SAMPLE COLLECTION

The system was monitored everyday throughout the duration of the experiment. The HRT was checked daily from the volume of the effluent and considering the amount wasted. A calculated amount of the biomass was wasted everyday, to maintain an approximate constant SRT. Samples were collected from three different sources:

1. **Influent:** Samples were taken directly from the continuously mixed feed buckets.
2. **Reactors:** Samples were taken from the reactors through the sampling port.
3. **Effluent:** Samples were taken from the effluent container after the contents were well mixed. Samples for effluent VFA and COD determination were taken from the clarifier.

The samples were analyzed for pH, solids (TS, TSS, VS & VSS), soluble COD and VFA. Once a week total COD was determined, along with total nitrogen and total Kjeldahl nitrogen (TKN). All the parameters were analyzed in duplicates. Sampling scheduling and parameters of importance are summarized in Table 4.1. Storage time before analysis was kept to a minimum. In most cases (>90%), the analyses were conducted on the same day. If not, they were completed the following day.

The systems were run at different conditions. Initially, in Run 1, both reactors were fed with municipal wastewater. The temperature was ambient (22°C) and HRT was 18 hours. In Run 2, industrial wastewater was introduced in System 1 at an 1:1 ratio by

volume. In the following phase (Run 3), the HRT was increased to 30 hours, at ambient temperature. In the subsequent phases of the study (Runs 4 and 5), the temperature was increased to 30°C and 35°C respectively at an HRT of 30 hours. Table 4.2 gives the details of the operational parameters of the study.

Table 4.1: Sampling schedule

Parameters	Sampling times
HRT	Daily
pH	Thrice per week
Solids	Thrice per week
VFAs	Thrice per week
Soluble CODs	Thrice per week
Total COD	Once a week
TKN and Ammonia Nitrogen	3 - 4 times per run
Head-space gas	Occasional sampling

Table 4.2: Operational Parameters

Runs	System 1					System 2				
	1	2	3	4	5	1	2	3	4	5
Waste	M	M,I	M,I	M,I	M,I	M	M	M	M	M
Temp. (°C)	22	22	22	30	35	22	22	22	30	35
HRT (hours)	18	18	30	30	30	18	18	30	30	30

M : Municipal Wastewater

I : Industrial Wastewater

4.5 ANALYTICAL PROCEDURES

The majority of the tests were conducted in accordance to the Standard Methods (1992). The details are discussed in the following section.

4.5.1 DETERMINATION OF pH

The pH was determined using a Fisher Scientific Accumet (model 230) pH meter. The pH meter was calibrated every time using standard buffer solutions of pH 4.0, 7.0 and 10.0. The probe of the pH meter was inserted into the sample and gently stirred, until a steady reading was registered.

4.5.2 DETERMINATION OF VARIOUS FORMS OF SOLIDS

A known amount of sample was placed in a pre-weighed crucible and kept at 103°C for about an hour. Afterwards it was cooled in a desiccater and weighed again, to determine the TS. This crucible was ashed in a muffle furnace at 550°C for an hour to get the VS. A known amount of sample was filtered through a Whatman (943-AH) glass microbe filter in a pre-washed, oven dried, weighed crucible, using a vacuum pump, and then dried at 103°C to get the TSS. This crucible was then ashed in a muffle furnace at 550°C, cooled and weighed to get the VSS.

4.5.3 DETERMINATION OF CHEMICAL OXYGEN DEMAND (COD)

COD was determined by the closed reflux colorimetric method. Part of the sample was centrifuged in micro centrifuge tubes for 10 minutes. Then the clear part of the biomass was filtered through nylon filter papers (0.45 microns), diluted, and put in COD vials. The COD digestion acid and the catalyst were added and kept for digestion. After digestion for a minimum of three hours, the transmittance was read in a Spectrophotometer (Baush and Lomb, Spectronic 21) at 600 nm and the concentration read from a standard curve. The standard curve was plotted based on the transmittance values of known concentrations prepared in the laboratory. In the case of total COD, the same procedure was followed, except that the sample was neither centrifuged nor filtered.

4.5.4 DETERMINATION OF VOLATILE FATTY ACIDS (VFAs)

VFAs were analyzed using an Antek 3000 Gas Chromatograph, which was equipped with a flame ionization detector (FID). The injection, oven and detector temperatures were set at 150°C, 85°C and 170°C respectively. Hydrogen was used as the carrier gas. The samples were centrifuged in micro centrifuge tubes for 10 minutes. The supernatant was filtered and diluted. One microliter of the sample was injected into the GC. The VFA distribution was obtained in a graphical form from the integrator.

4.5.5 DETERMINATION OF TOTAL AMMONIA NITROGEN AND TKN

The total ammonia nitrogen and total Kjeldahl nitrogen (TKN) were analyzed using the Kjeldahl titrimetric method. For total ammonia nitrogen, the samples were diluted in the tubes and borate buffer and 6N NaOH (to adjust the pH to 10.5 -11.0) were added. The mixture was distilled in the Kjeltic Auto 1030 Analyzer. For TKN analysis, the samples were diluted and 2 Kjeltabs were added along with 10 mls of concentrated H₂SO₄. The mixture was then digested in the Tecator DS 20-1015 Digester, using the Exhaust System 1013 Scrubber. After cooling, it was distilled in the Kjeltic Auto 1030 Analyzer with the dispensation of a preset amount of alkali.

4.5.6 DETERMINATION OF HEAD-SPACE GAS

The Thermal Conductivity Gas Chromatograph GOW-MAC Series 550 was used for analyzing the gas produced. The GC was equipped with a Porapak Q column (80/100) and Helium was used as the carrier gas. Gas was collected from the collection ports in a 10 ml syringe and injected into the port. The composition of the gas was printed out in a graphical form, and the results compared to a standard curve obtained earlier.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 GENERAL CHARACTERISTICS

5.1.1 NATURE OF WASTEWATER

The efficiency of any treatment process depends largely on the characteristics of the raw wastewater. Thus regular analysis of the influent wastewater is essential for the proper design and performance of a treatment plant.

The South End Water Pollution Control Center in Winnipeg, Manitoba gets the wastewater mainly from residential areas and also from a few industries. Important physical and chemical analyses were performed on the primary sludge and the data are included in Appendix A (Tables A 2 and A 3).

The influent to the reactors was based on TS content. The TS of the primary sludge was generally about 30,000 to 40,000 mg/l. The TS concentration was adjusted to 5000 mg/l, as mentioned earlier, to maintain a uniform feed throughout the duration of the study. A summary of the feed characteristics to Reactor 2 is shown in Table 5.1.

The range of variation of most parameters was quite high, the variations in some being more than in others. Statistical analysis shows that the coefficient of variation (CoV) depends upon the parameters measured. Most of the parameters show a reasonably small variation (<15%), except for VFAs, COD and nitrogen values. The variation in the solids

concentrations was lower as it was the control parameter of the influent. The day to day variations may be due to reasons like rainfall and infiltration, clean up of different units and failure of equipment in the plant, which indirectly effect other parameters like VFAs, COD etc.

Table 5.1: Influent characteristics in Reactor 2.

Parameters	Mean	Standard Deviation	CoV
pH	7.02	0.21	3.1
TS	4930	455	9.2
TVS	3845	427	11.1
TSS	4265	427	10.0
VSS	3305	405	12.2
VFA	224	106	47.5
Soluble COD	457	194	42.5
Total COD	5339	981	18.4
NH ₃ -N	65.6	13.4	50.8
TKN	227	56	24.9

* All values except pH are in mg/l.

The industrial wastewater from The Old Dutch Food Company was received generally at a TS concentration of around 75,000 to 85,000 mg/l. In this case also the wastewater was diluted to 5000 mg/l, mixed with the diluted primary sludge (1:1 ratio by

volume) and then introduced into the feed bucket of Reactor 1. A summary of the feed characteristics to the to Reactor 1 is shown in Table 5.2. In this case, the CoV values are in general a bit more higher, where most of the parameters show 20 to 30% variation.

Table 5.2: Influent characteristics in Reactor 1.

Parameters	Mean	Standard Deviation	CoV
pH	6.13	0.65	10.6
TS	5780	1220	21.1
TVS	4995	1205	24.2
TSS	5110	1410	27.6
VSS	4550	1290	28.3
VFA	290	95.7	33.1
Soluble COD	545	175	32.1
Total COD	7722	1510	19.5
NH ₃ -N	26.3	13.4	50.8
TKN	157	65	41.5

* All values except pH are in mg/l.

5.1.2 COLD STORAGE STUDY

A study was performed on the stored raw sludge for 18 days. There was no significant variation in the VFA content. The variations observed were comparable to those expected during the chemical analysis through experimental errors. Since the sludge

was generally obtained once in 10 days, this study was not extended beyond 18 days. Table 5.3 shows the VFA content of the primary sludge during the study. The coefficient of variation is 7.5%, indicating that there was not much change in the VFA content of the primary sludge during the study period.

Table 5.3: VFA content in Influent during cold storage study

Date	Day	VFA content (mg/l as Acetic Acid)
Dec 22	1	2214
Dec 24	3	2271
Dec 26	5	2265
Dec 28	7	2538
Dec 30	9	2466
Jan 1	11	2553
Jan 4	14	2704
Jan 8	18	2622
Mean:		2454
Standard Deviation:		183
CoV:		7.5

5.1.3 BIOLOGICAL ACCLIMATION AND STABILITY OF THE REACTORS

The biological population in a reactor has to undergo a period of acclimation for ensuring successful and sustainable operation of the system. With changes in the environmental/operational parameters, reactor configuration, type/characteristics of wastewater, the acclimation period might change. After the acclimation period, the microbial population is at a steady state (equilibrium), where the biomass has adjusted itself to changing conditions and have started functioning in equilibrium with the prevailing environment.

The performance of a biological system at steady state conditions depends, among others, upon the fluctuations in the influent. As mentioned earlier (section 5.1.1), there was quite a large variation observed in certain influent parameters. Despite the variation, the system could maintain a steady state, which indicates the stability of the process.

In this study, Run 1 was the preliminary run, where both the reactors were operated at an HRT of 18 hours and at ambient temperature ($22 \pm 1^\circ\text{C}$), with municipal primary sludge. The acclimation was achieved within a short period of time (8 to 10 days) in both the reactors. The biomass was considered to be acclimated when there was less than 20% variation in the net VFA production (mean 284 mg/l and 272 mg/l; std. dev. 53 mg/l and 61 mg/l in Reactor 1 and Reactor 2 respectively) and the reactor pH (mean 5.59 and 5.63; std. dev. 0.17 and 0.16 in Reactor 1 and Reactor 2 respectively). Under these conditions, the system was assumed to be at a steady state. When the reactor VSS were taken into consideration, the acclimation period was longer, around 15 days. It should be

noted that the steady-state VSS concentration in each reactor changed with change in conditions of the study at different runs.

pH is an important parameter indicating the feasibility of acidogenesis. The influent pH was in the range of 6.7 to 7.3 and the reactor pH was in the range of 5.2 to 5.7 in Reactor 1 and 5.4 to 6.3 in Reactor 2. The onset of methanogenesis is indicated by a higher pH of around 7.0 (Bailey and Ollis, 1977; Perot et al, 1988). Hence a low pH suggests that the biomass was in the acid phase of anaerobic digestion. The fact that the influent pH was always around neutral and there was always a drop of more than one pH unit in the reactors suggests that acidogenesis was feasible.

Short chain volatile fatty acids (C_2 to C_6) are the major products of acidogenesis; minor products include formic and lactic acids and C_2 to C_4 alcohols (Andrews and Pearson, 1965). The net VFA production (expressed as acetic acid for comparison purposes) was very similar in the two reactors with a value of around 295 mg/l. The higher VFA concentration in the reactors clearly indicated the feasibility of acidogenesis under these conditions. A favorable environment for the growth and maintenance of a healthy population of acid producing microorganisms was established during this run.

5.2 EFFECT OF INDUSTRIAL WASTEWATER

In wastewater treatment, the biological processes are carried out by a number of species which are different from each other in many aspects. The functioning of these microorganisms is usually dominated by particular types of species, depending upon the environmental and operational conditions of the system like pH, temperature, retention

time and source of wastewater. Some species are present in large numbers and the overall process is a reflection of the activities of all the microorganisms in the system.

One of the sources of wastewater from The Old Dutch Food Company is rich in starch. This kind of wastewater has a high concentration of carbohydrates and is low in proteins and lipids. This industrial wastewater was mixed with primary sludge in a 1:1 ratio and fed to Reactor 1 in Run 2. The other conditions were not changed, i.e. HRT was 18 hours and temperature was 22°C. This was a change in the feed characteristic and hence there were several observable changes in the behavior of Reactor 1. It should be noted that there was no change in the operating conditions of Reactor 2 during this run.

5.2.1 pH

The pH of both reactors dropped to around 5.6 to 5.7 in Run 1 during the preliminary stage of the study. This indicated that acidogenesis was occurring, which was also supported by the net VFA production. In Run 2, when the starch-rich industrial wastewater was introduced into the Reactor 1, there was a further drop in pH to around 5.1, suggesting that acidogenesis was occurring to a larger extent. Figure 5.1 shows the variation of pH in both reactors during the first two runs of the study. It should be noted that towards the later part of Run 2, there was a drop in the pH of Influent 1.

5.2.2 VFA PRODUCTION

There was a production of VFAs in both reactors from nearly the beginning of this study, suggesting the feasibility of acidogenesis. The net production of VFAs in both

reactors was around 280 mg/l (expressed as acetic acid). This is an indication of the similarity of operation of the two reactors under the same conditions. Figure 5.2 shows the net VFA production in the two reactors during the first two runs of this study. With the introduction of the industrial wastewater, there was a noticeable change in the net VFA production in Reactor 1. The net VFA production went up by 110 mg/l (from 284 ± 53 mg/l to 394 ± 93 mg/l). This suggests that the starch-rich wastewater mixed in a 1:1 ratio with municipal primary sludge is more suitable for acidogenesis under these conditions.

Table 5.4 shows the specific production rates of the two reactors in the first two runs of this study. The net specific production rates (expressed as mg VFA produced/mg VSS*day) in Run 1 are similar in both reactors in the first run of the study (0.033 mg VFA/mg VSS*day and 0.027 mg VFA/mg VSS*day for Reactor 1 and Reactor 2 respectively). As the VSS concentration of the two reactors was very similar to each other, the similarity in the rates is expected. With the introduction of the starch-rich industrial wastewater, the specific production rate went up to 0.057 mg VFA/mg VSS*day, as compared to 0.029 mg VFA/mg VSS*day in Reactor 2. This is due to both the increased amount of VFA produced and a drop by 24% in the VSS of Reactor 1.

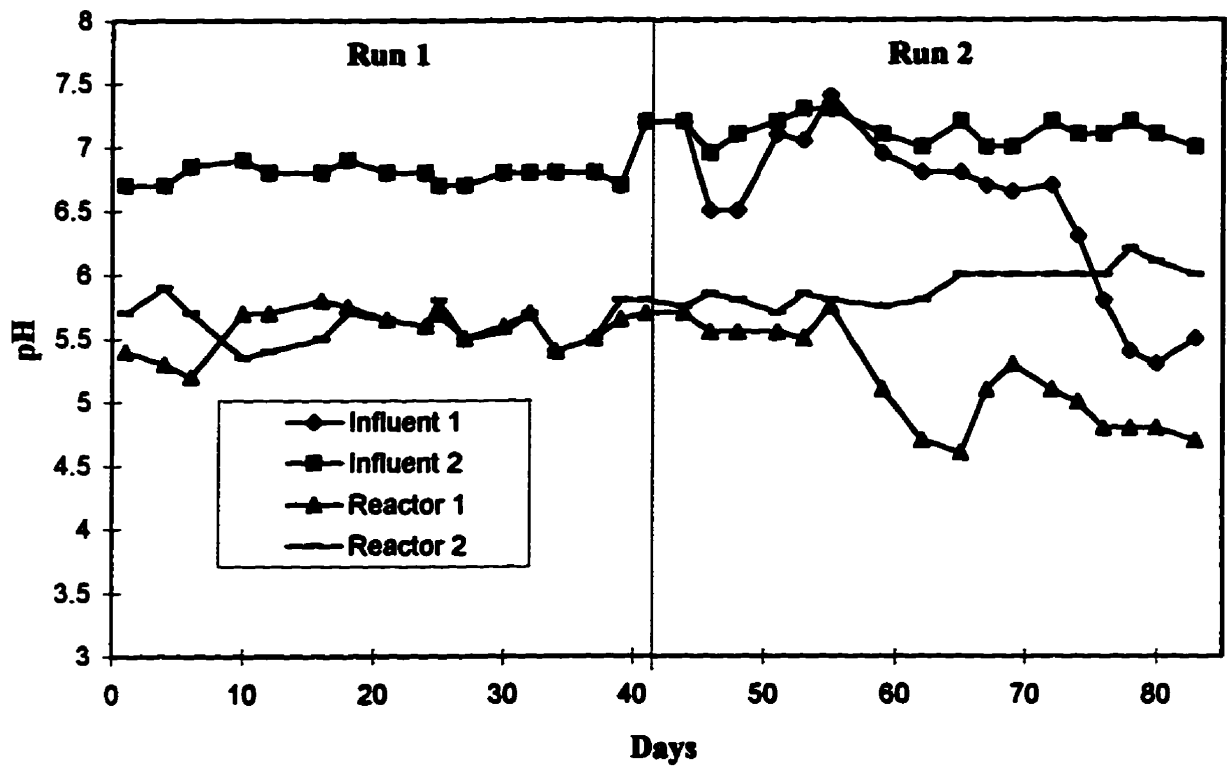


Figure 5.1 : Influent and Reactor pH in the two reactors

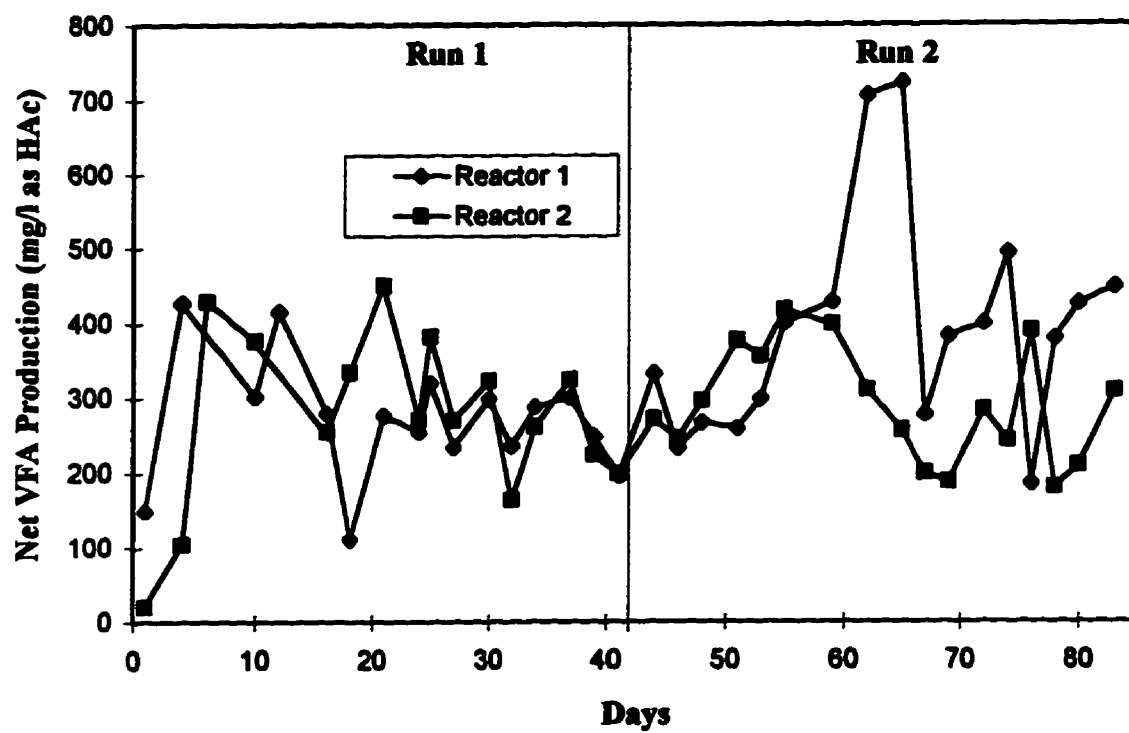


Figure 5.2: Net VFA production in the two reactors in Runs 1 & 2

Table 5.4 : Specific VFA production rates in Runs 1 & 2

Parameters	Reactor 1		Reactor 2	
	Run 1	Run 2	Run 1	Run 2
VSS (mg/l)	12303	9312	13634	12984
Specific production rate (mg VFA/mg VSS*day)	0.033	0.057	0.027	0.029

5.2.3 VFA SPECIATION

The VFAs identified during the course of this run were acetic, propionic, iso butyric, n-butyric, iso valeric and n-valeric acids. The identification of the individual VFAs in the acid phase digestion is important as it provides valuable information about the metabolic pathways of the process. VFAs are generally generated not only during acidogenesis of municipal wastewater, but also during the digestion of other industrial and agricultural wastes.

Figures 5.3 and 5.4 show the distribution of the individual VFAs during Runs 1 and 2. Acetic acid was the main VFA produced averaging between 61% and 66 % in Run 1 in both reactors. Propionic acid was the next most predominant acid in the range of 19 to 24 %. In Run 2 in Reactor 1 acetic acid was still the most predominant one with around 56% of the total VFAs, while there was a significant increase in the n-butyric acid from 2 to 16%.

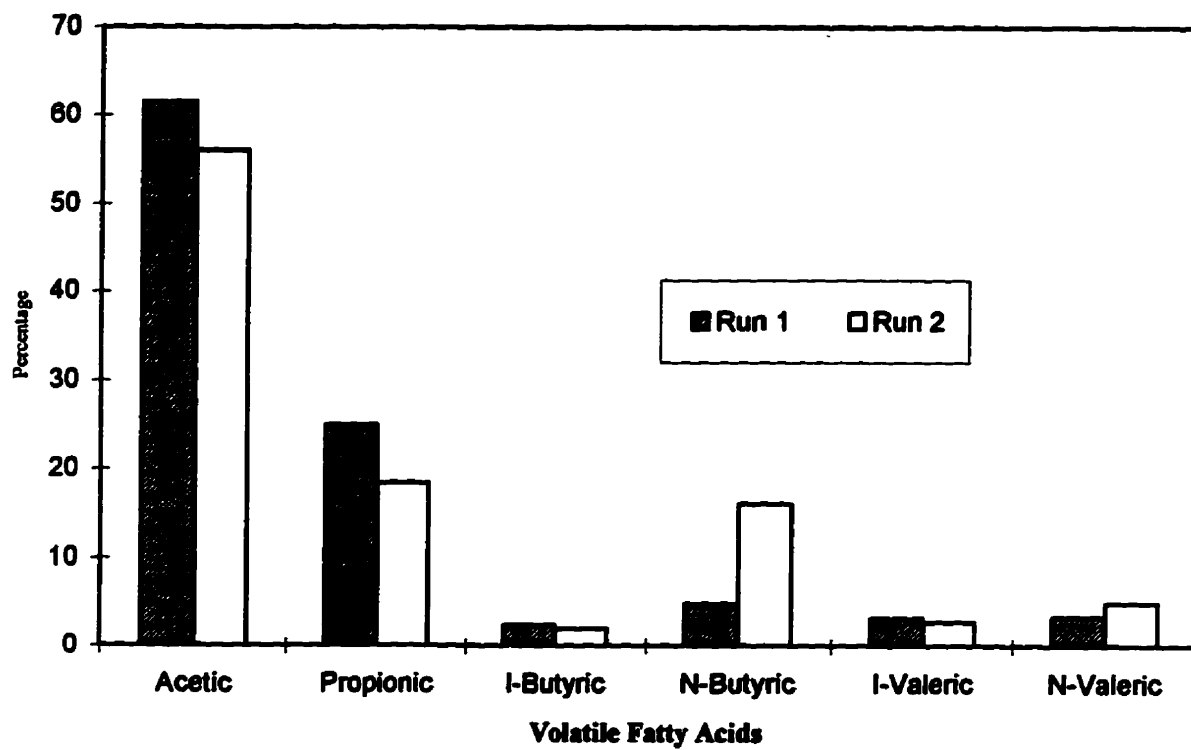


Figure 5.3 : VFA speciation for Reactor 1 in Runs 1 & 2

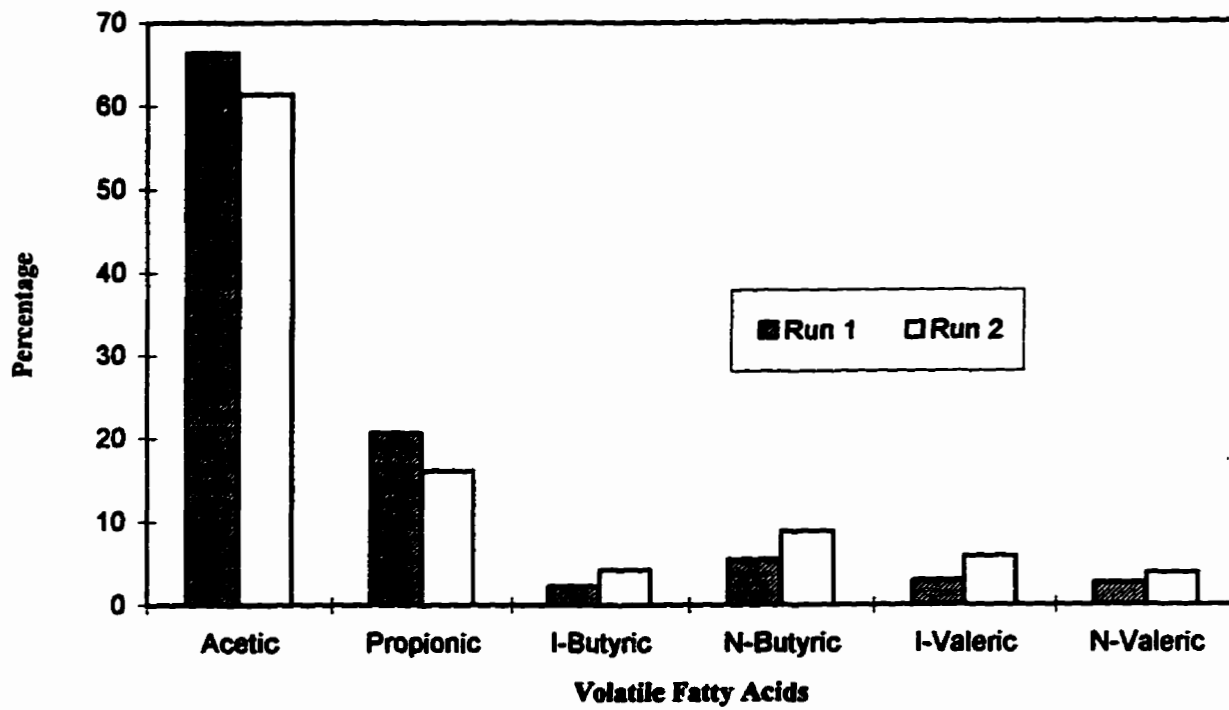


Figure 5.4 : VFA speciation for Reactor 2 in Runs 1 & 2

5.2.4 SUBSTRATE SOLUBILIZATION

Particulate organic matter first undergoes liquefaction by extracellular enzymes before taken up by the microorganisms. Since most of the organic matter in the feed is in the particulate form (> 95% as indicated by the VSS/VS ratio), solubilization is a crucial step in the digestion process. Hydrolysis depends on many factors like pH, temperature, substrate type, size and nature of biomass (Eastman and Ferguson, 1981).

The substrate solubilization can be estimated from a variety of parameters like soluble COD, TSS, VSS, SOC and TOC. All these parameters except for SOC and TOC were measured regularly throughout the study and the results are summarized in Appendix A (Tables A2 to A5).

The addition of the industrial wastewater to Reactor 1 not only had a significant effect on the net COD solubilization but also on the specific COD production rates. Figure 5.5 shows the net soluble COD profile of the two reactors, while Table 5.5 shows the COD production rates. The net soluble COD production increased significantly from 319 ± 81 mg/l to 514 ± 175 mg /l in Reactor 1 with the introduction of the industrial waste while that of Reactor 2 was 419 ± 186 mg/l in Run 2. The solubilization rates in Reactor 1 went up from 0.034 to 0.073 mg COD/mgVSS*day. In Reactor 2, the average solubilization rate was 0.041 mg COD/mgVSS*day in Runs 1 and 2 combined. This value is comparable to the rate in Run 1 in Reactor 1. It should be noted that individual COD values in Runs 1 and 2 in Reactor 2 showed a great deal of variation (Figure 5.5), mainly due to a potential analytical problem in using the spectrophotometer for COD at the beginning of the study in Run 1.

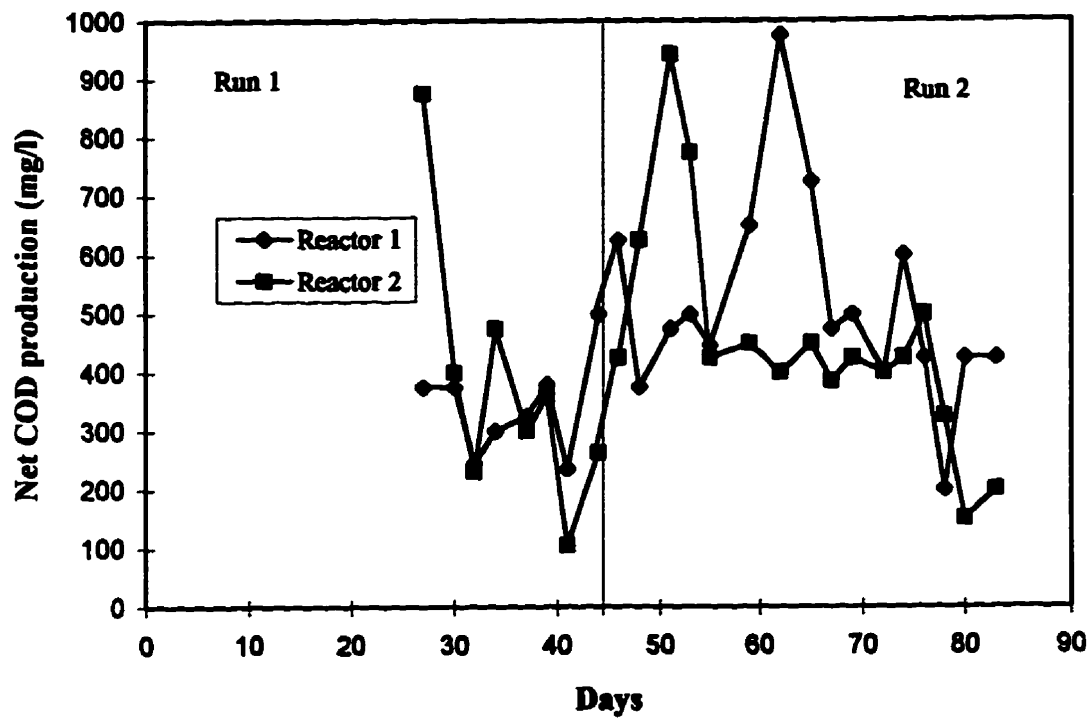


Figure 5.5: Production of net soluble COD in Runs 1 & 2

Table 5.5: Specific production rates of COD in Runs 1 & 2

Parameters	Reactor 1		Reactor 2	
	Run 1	Run 2	Run 1	Run 2
VSS (mg/l)	12303	9312	13634	12984
Specific production rate (mg COD/mg VSS*day)	0.034	0.073	---	0.041

The extent of organic substrate solubilization can be viewed from a different perspective i.e. the destruction of suspended solids. The percentage VSS and TSS reduction based on a mass balance of the two systems at steady state conditions is shown in Table 5.6. While the solids destruction in Reactor 1 increased, that in Reactor 2 decreased, which corresponds to the specific COD production rates. This parameter (solids destruction) depends upon the total amount of solids in the system and more importantly on the performance of the clarifiers. The increase in solids destruction in Reactor 1 can be attributed to the improved settling characteristics in Clarifier 1 with the introduction of the industrial wastewater. The decrease in Reactor 2 is basically due to deterioration of the settling characteristics in Clarifier 2.

Table 5.6: Solid destruction in Runs 1 & 2

Run	VSS (%)		TSS (%)	
	Reactor 1	Reactor 2	Reactor 1	Reactor 2
1	61	45	59	43
2	76	24	73	25

5.3 EFFECT OF HRT

HRT is an important parameter in the process as it indicates the contact time between the bacteria and the food sources. It is the average length of time that a molecule spends in the reactor and can be defined as the volume of the reactor divided by the average flow rate (Metcalf and Eddy, 1991). It provides an indication of the amount of substrate used by the microorganisms.

One of the objectives of this study was to investigate the effect of HRT on the acidogenesis of municipal primary sludge and the mixture of primary sludge and industrial wastewater. In Run 2 of this study, there was some leakage in the clarifier of system 1 and hence the feeding was stopped for a period of 24 hours. When the samples from that reactor were analyzed two days later, there was a drop in pH and a rise in the net VFA production by 65%, suggesting that acidogenesis might be favoured with an increase in HRT. Hence, it was decided to change the HRT from 18 to 30 hours in the 3rd run of this study, keeping all other parameters the same as in the previous run.

5.3.1 pH

Change in HRT from 18 to 30 hours led to a further drop in pH of Reactor 1. The average pH in Reactor 1 during Run 3 was 4.4 as compared to 5.1 in Run 2. This indicated that the conditions were favourable to further promote acidogenesis, which is evident by the additional increase in VFA production. The variation in HRT did not change the average pH of Reactor 2, which was 5.8 compared to 5.6 in the previous run.

5.3.2 VFA PRODUCTION

The profiles of the influent and reactor VFA contents of both systems are shown in Figures 5.6 and 5.7. Higher concentration of VFAs in both the reactors compared to that of the feed indicates that the conditions of growth and proliferation of the acid producing bacteria have been favourable.

Figure 5.8 compares the net VFA production of the two reactors as a function of HRT. An increase in HRT from 18 to 30 hours resulted in an increase in the net VFA production in both reactors. In Reactor 1, the net production went up by 37.6% (from 394 ± 93 mg/l to 542 ± 93 mg/l) and in Reactor 2 the production went up by 13.4% (from 290 ± 79 mg/l to 329 ± 52 mg/l). These results were in accordance to Andrews and Pearson (1965) who showed that net VFA production increased as HRT was increased to a value of 2.4 days. Elefsiniotis and Oldham (1994a) have also shown an increase in the net production when HRT was increased from 6 to 12 hours. A further increase in HRT in both cases above, resulted in decrease in the net VFA production, mainly due to the onset

of methanogenesis. The optimum HRT value was dependent on the characteristics of that particular type of wastewater.

A comparison of the specific rates (expressed as mg VFA produced/mg VSS*day) shows a totally different trend (Table 5.7). There was a reduction in the specific rates in both reactors with an increase in HRT. In Reactor 1, the specific rates decreased from 0.057 mg VFA/mg VSS*day to 0.041 mg VFA/mg VSS*day while in Reactor 2, the reduction was from 0.029 mg VFA/mg VSS*day to 0.013 mg VFA/mg VSS*day. Decrease in the specific rates in both reactors can be attributed to the increase in the reaction time due to increase in HRT. Moreover, the decrease in Reactor 2 was also due to increase in the reactor solids (VSS). At a higher HRT, the settling in the clarifier improved, resulting in more biomass being recycled back into the reactor, thus increasing the reactor VSS.

Table 5.7 : VFA specific rates as a function of HRT.

Parameters	Reactor 1		Reactor 2	
	Run 2	Run 3	Run 2	Run 3
HRT (hours)	18	30	18	30
VSS (mg/l)	9312	10552	12984	20062
Specific production rate (mg VFA/mg VSS*day)	0.057	0.041	0.029	0.013

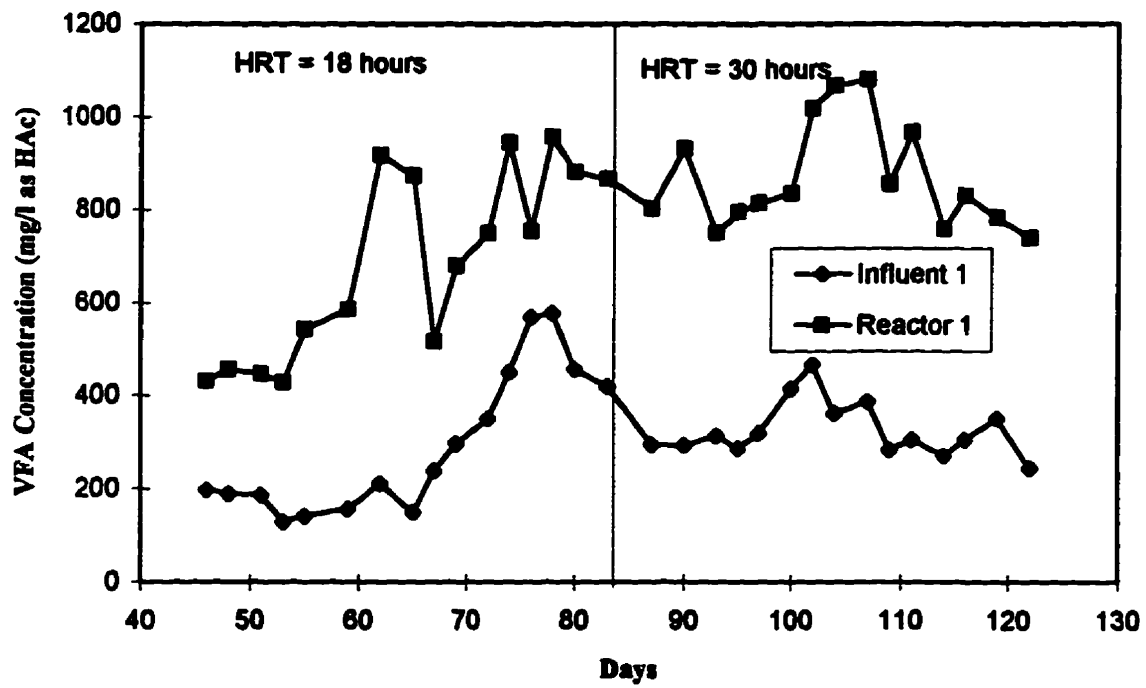


Figure 5.6: Influent and Reactor VFA profiles in Reactor 1 as a function of HRT

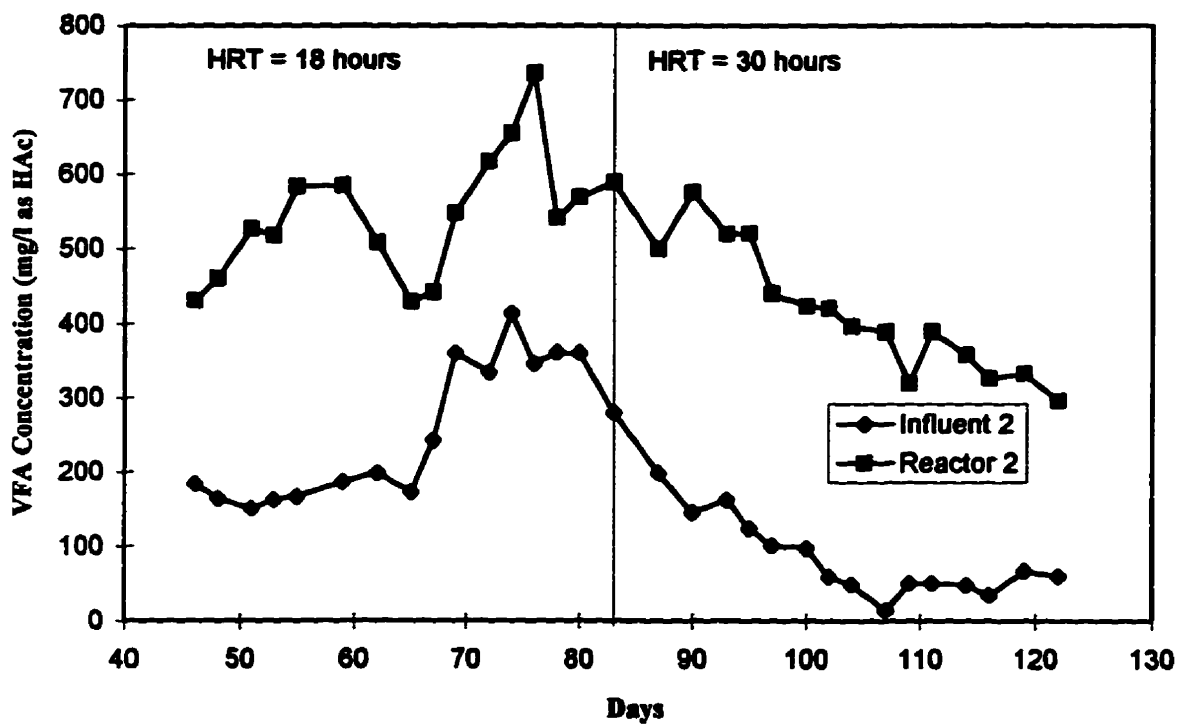


Figure 5.7: Influent and reactor VFA profiles in Reactor 2 as a function of HRT

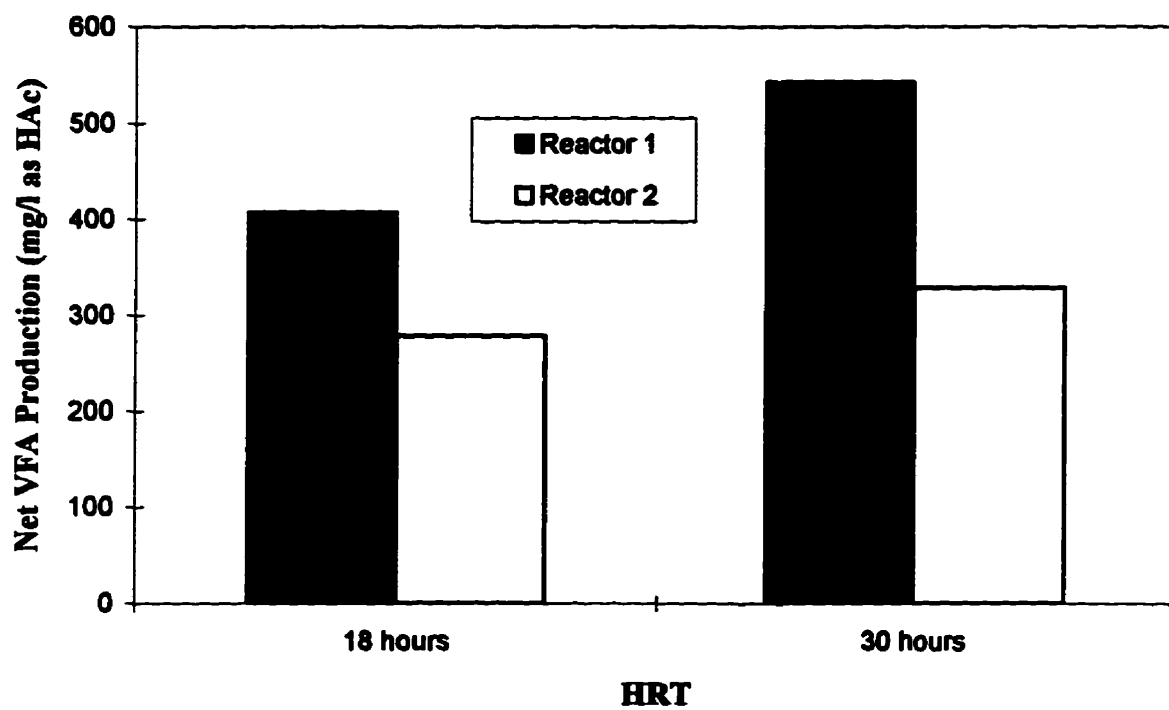


Figure 5.8: Net VFA Production in the two reactors as a function of HRT

5.3.3 VFA SPECIATION

The VFA speciation as a result of increase in HRT is similar to that observed in the previous run for both reactors. Acetic acid was the predominant VFA present. In Reactor 1 there was a significant percentage of n-butyric acid, in approximately equal amounts as propionic acid. The percentage of n-butyric acid in the feed to Reactor 1 is also comparatively higher. In Reactor 2, there was no remarkable change in the speciation of the VFAs, with acetic acid constituting the major fraction of the VFAs followed by propionic acid. The individual VFA concentrations are tabulated in Appendix A (Tables A4 and A5).

5.3.4 SUBSTRATE SOLUBILIZATION

Variation of HRT had a significant effect not only on the concentration of net soluble COD, but also on the specific rates expressed as mg COD produced/mgVSS*day. As was the case of the VFAs, here also there was an increase in the net soluble COD produced with increase in HRT (Figure 5.9), but there was a reduction in the specific rates, as shown in Table 5.8. The net soluble COD production increased from 514 ± 175 mg/l to 627 ± 176 mg/l in Reactor 1, but remained around the same in Reactor 2 (around 419 ± 186 to 440 ± 131 mg/l). Decrease in the specific rates in both reactors can be attributed to the increase in the reaction time. Moreover the decrease in Reactor 2 can be also due to increase in VSS in the reactor.

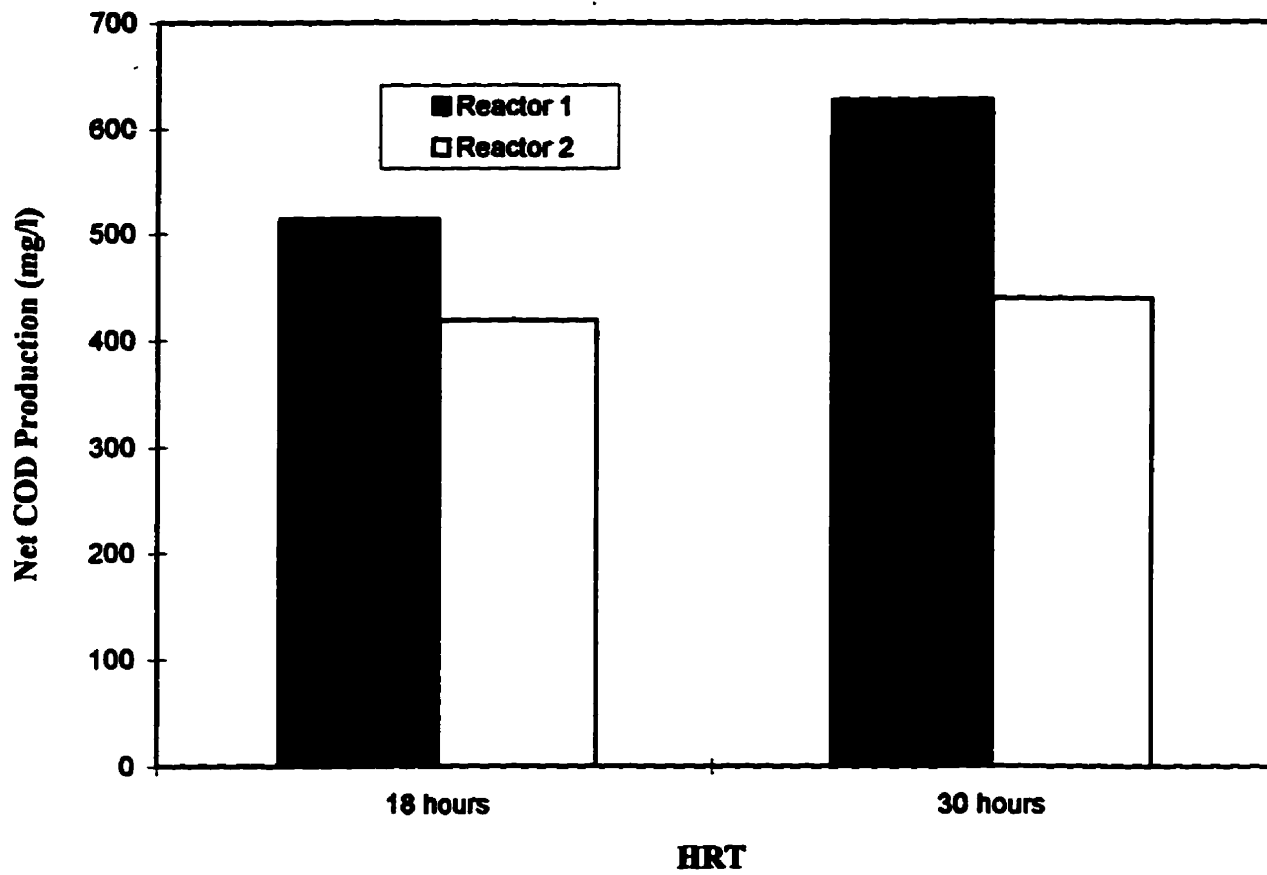


Figure 5.9 : Net Soluble COD production as a function of HRT

Table 5.8 : Soluble COD specific rates as a function of HRT.

Parameters	Reactor 1		Reactor 2	
	Run 2	Run 3	Run 3	Run 3
HRT (hours)	18	30	18	30
VSS (mg/l)	9312	10552	12984	20062
Specific production rate (mg COD/mg VSS*day)	0.073	0.047	0.041	0.018

The extent of organic substrate solubilization can be viewed from a different perspective i.e. the destruction of suspended solids. The percentage VSS and TSS reduction in the two systems, based on a mass balance at steady state conditions, is shown in Table 5.9. In Reactor 1, change in HRT did not have any significant effect on the percent VSS destruction. It might be due to the fact that a maximum value had been reached, hereafter increase in HRT does not effect the solids destruction. In case of Reactor 2, the picture was different. There was a significant increase in the solids destruction with the increase in HRT from 18 to 30 hours, mainly due to the improved performance of the clarifier. As a result, the concentration of the solids in the effluent was reduced significantly, resulting in higher solids destruction percentages. The trend in percent TSS reduction is very similar to that obtained from the percent VSS destruction. Since the VSS accounted for 75 - 85 % of the TSS in the influent in both reactors, a large

fraction, approximately equal to the VSS undergoes solubilization during digestion. This can be attributed to the metabolic requirements and the low pH in the reactors.

Table 5.9: Solid destruction as a function of HRT

Runs	HRT (hours)	% VSS		% TSS	
		Reactor 1	Reactor 2	Reactor 1	Reactor 2
2	18	76	24	73	25
3	30	77	66	75	64

5.4 EFFECT OF TEMPERATURE

Biological reactions are extensively dependent on temperature as temperature influences the overall efficiency of the biological treatment processes. Temperature not only influences the metabolic activities of the microbial population, but also has a profound effect on factors like gas transfer rates and settling characteristics of the biological solids (Metcalf and Eddy, 1991).

One of the objectives of this research was to study the effect of increase in temperature on the acidogenesis of municipal primary sludge and of a mixture of primary sludge and industrial wastewater. The previous stage (Run 3) of this study was at ambient temperature. In the following stage the temperature was increased to 30°C (Run 4) and then to 35°C in the final stage (Run 5), as mentioned in Section 4.4. HRT was maintained at 30 hours and all other parameters were unchanged.

5.4.1 pH

Change in temperature did not have a significant effect on pH, though there was observed an increasing trend in both systems. In Reactor 1, the pH increased from 4.44 to 4.56 to 4.76 when temperature was increased from 22°C to 30°C to 35°C accordingly. In Reactor 2, when the temperature was increased from 22°C to 30°C, there was a greater rise in pH from 5.81 to 6.21, but at 35°C the pH was 6.37 (Appendix A, Tables A4 and A5). The two reactors showed similar trends in pH variation with temperature.

5.4.2 VFA PRODUCTION

Increase in temperature had certain effects on the VFA production and the specific production rates in both reactors. Figure 5.10 shows a comparison of the profiles of the net VFA production (as HAc), while Figure 5.11 shows the summary of the net VFA production (as HAc) as a function of temperature.

In Reactor 1, with an increase in temperature from 22°C to 30°C, there was an increase in the net VFA production, but when the temperature was increased to 35°C, the VFA production went down. The same trend was followed by the VFA specific production rates as shown in Table 5.10. As the VSS values of the reactor were fairly constant throughout the final three runs, it can be said that perhaps, there is an optimum temperature of around 30°C for acidogenesis of this particular kind of wastewater. As seen in Figure 5.10, in Run 4, there was a disturbance in Reactor 1 (explained later in Section 5.5.3) and hence the large variation in the net production.

For Reactor 2, the situation was different. With increase in temperature, the VFA production went down, as shown in Figure 5.11. It should be noted that there was a significant reduction in the VSS in the reactor. With increase in temperature, the settling of the biomass in the clarifier became poorer and as a result there was a loss of biomass through the effluent. Hence the reduction in the reactor VSS. That meant that the amount of the biomass available to generate VFAs was reduced resulting in lower production. Increase in temperature makes the settling characteristics in the clarifier poorer (Johnson, 1995). A different trend is followed by the specific production rates. When temperature was increased from 22°C to 30°C, the production rates were the same. This indicated that a smaller amount of biomass (in Run 4) was able to produce VFAs at the same rate as in the previous run. At 35°C the specific rates decreased. In this case also, there might be a optimum temperature for the VFA production for this wastewater.

Table 5.10 : Specific VFA production rates as a function of temperature

Parameter	Reactor 1 (Runs)			Reactor 2 (Runs)		
	3	4	5	3	4	5
Temperature (°C)	22	30	35	22	30	35
VSS (mg/l)	10552	10866	11453	20062	12065	6920
VFA Specific rate (mgVFA/mgVSS.day)	0.041	0.048	0.033	0.013	0.014	0.008

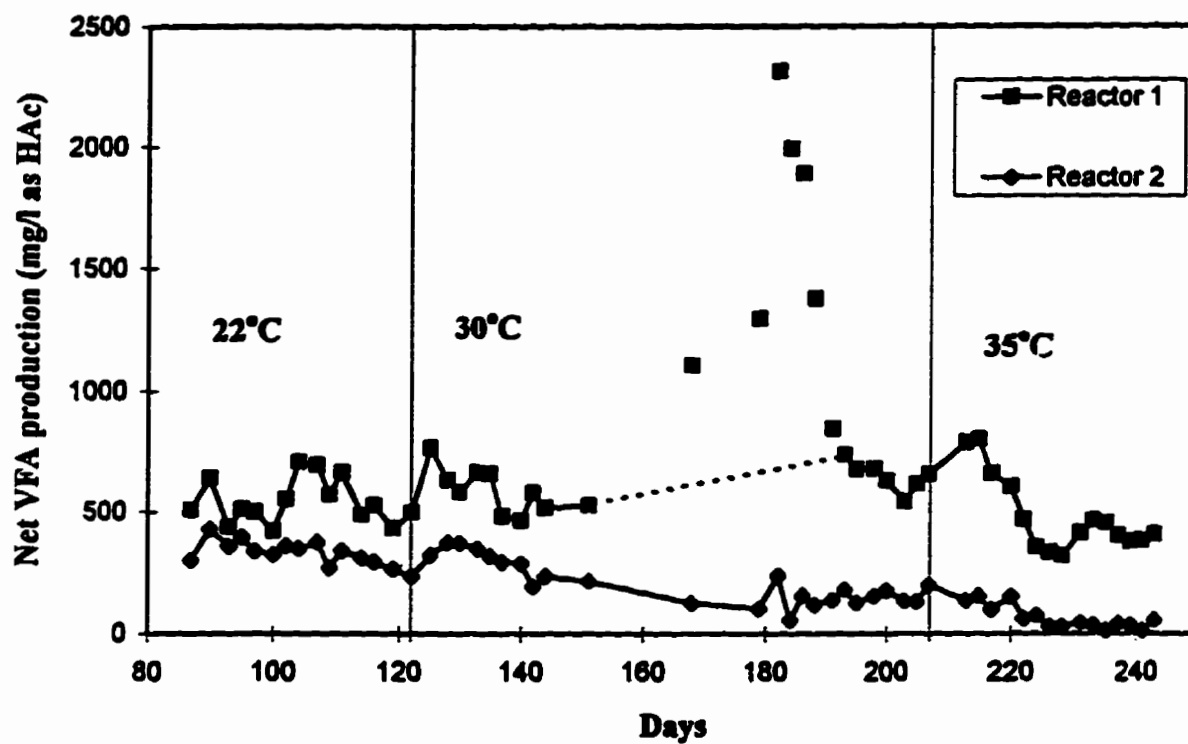


Figure 5.10: Net VFA production profile as a function of temperature

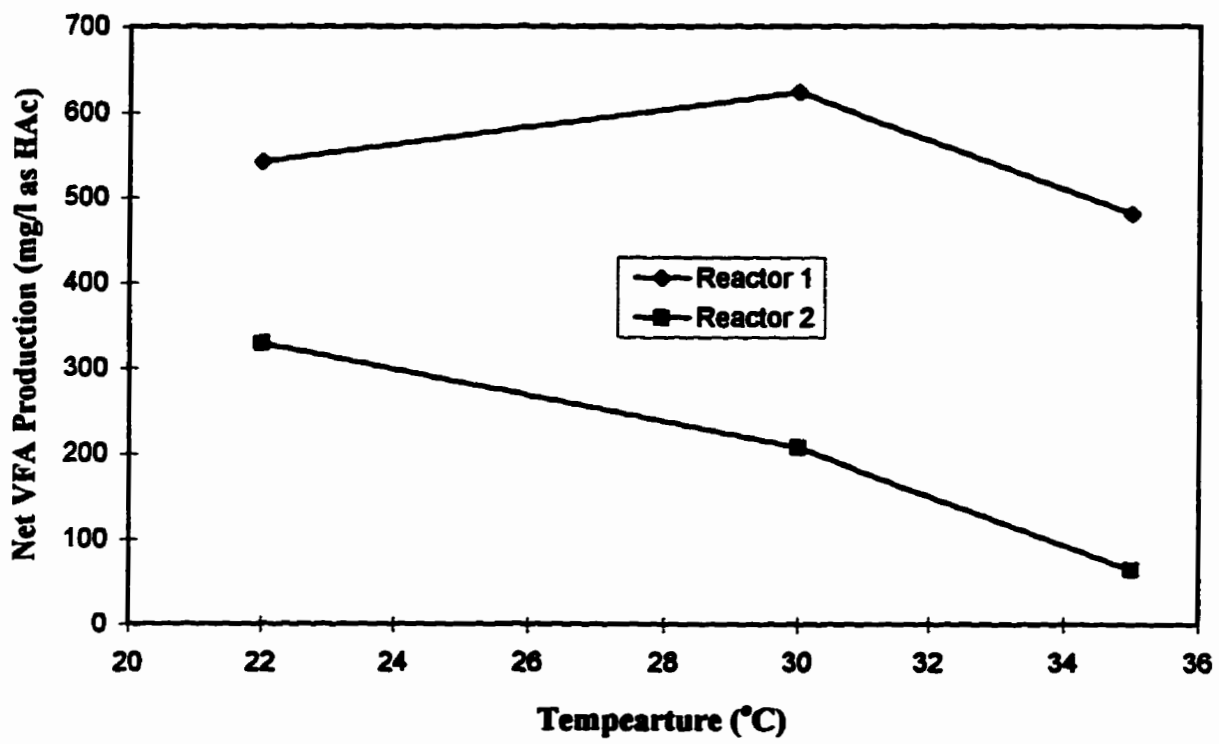


Figure 5.11: Variation of average VFA production with Temperature

5.4.3 VFA SPECIATION

Increase in temperature led to some changes in the VFA distribution in Reactor 1, as shown in Figure 5.12. The percentage of acetic acid was continuously increased from 57% to 76% as temperature was increased from 22°C to 35°C. There was also a continuous decrease in the n-butyric acid concentration from 22% to 5%, while the other VFAs did not show any appreciable variation.

In Reactor 2, there was not a major change in the VFA speciation, as shown in Figure 5.13. Acetic acid was the primary constituent with about 60 to 65% of the total VFAs, with propionic acid being the second most abundant, with 20 to 25%. All the other VFAs were between 1 and 5%.

5.4.4 SUBSTRATE SOLUBILIZATION

The increase in temperature had similar effects on substrate solubilization as did on the VFAs. Figure 5.14 shows the COD profiles of the two reactors. In Reactor 1, with an increase in temperature from 22°C to 30°C, there was an increase in the COD production, but when the temperature was increased to 35°C, the COD production went down. The same trend was followed by the COD specific production rates as shown in Table 5.11.

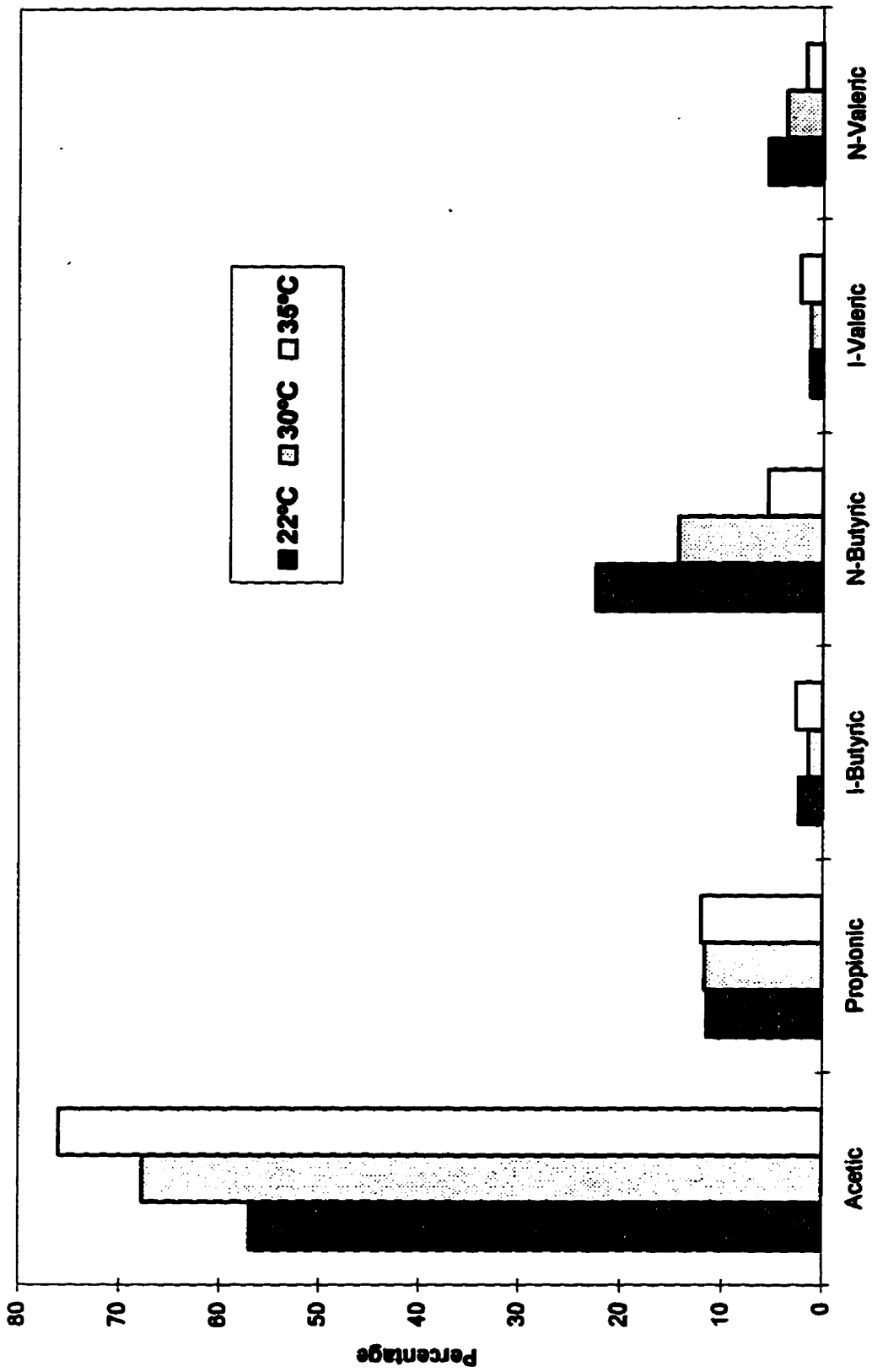


Figure 5.12: VFA speciation as a function of temperature in Reactor 1

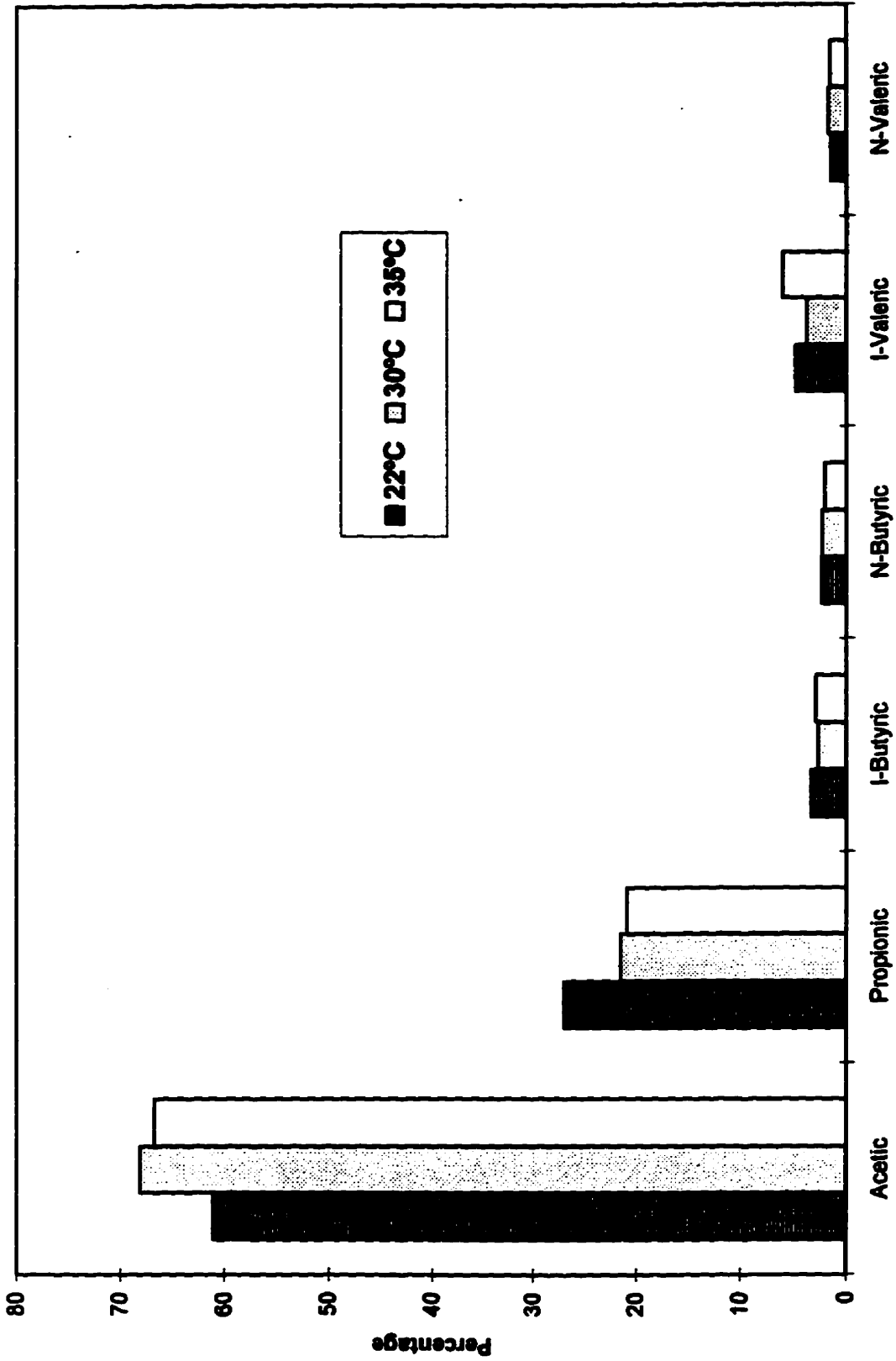


Figure 5.13: VFA speciation as a function of temperature in Reactor 2

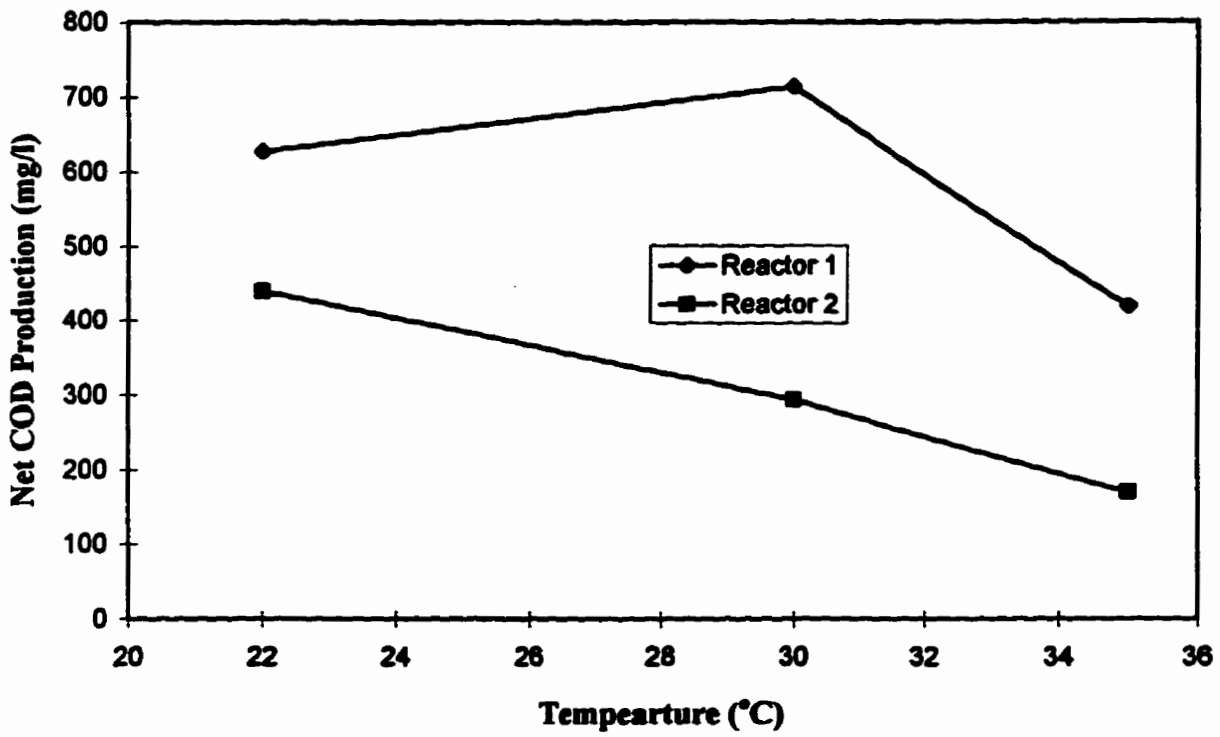


Figure 5.14: Variation of soluble COD produced with temperature

For Reactor 2, the situation was different. With an increase in temperature, the COD production went down. It should be noted that there was a significant reduction in the VSS as well. With an increase in temperature, the settling of the biomass in the clarifier became poorer and as a result there was a loss of biomass through the effluent. Hence the reduction in the reactor VSS. That meant that the amount of the biomass available to generate soluble COD was reduced, resulting in the low production. Increase in temperature makes the settling characteristics of the biomass poorer (Johnson, 1995). A different trend was observed for the specific production rates. There was a slight variation with the change in temperature, which was not significant. The specific rates in Runs 3,4 & 5 varied between 0.018 and 0.020 mg COD/mg VSS*day. The loss in the biomass of Reactor 2 did not seem to alter its ability to solubilize the organic matter.

Table 5.11: Specific COD production rates as a function of temperature

Parameter	Reactor 1 (Runs)			Reactor 2 (Runs)		
	3	4	5	3	4	5
Temperature (°C)	22	30	35	22	30	35
VSS (mg/l)	10552	10866	11453	20062	12065	6920
COD Specific rate (mg COD/mgVSS.day)	0.047	0.067	0.029	0.018	0.020	0.019

The percent solids (VSS and TSS) destruction based on a mass balance at steady state operation are tabulated in Table 5.12. For Reactor 1 the variation was not significant.

There was a slight drop when the temperature was increased from 22°C to 30°C. For Reactor 2 the percent reduction dropped significantly when the temperature was increased from 22°C to 30°C. It increased slightly when the temperature was increased to 35°C. This again was due to the poor settling in Clarifier 2, which resulted in the loss of solids through the effluent.

Table 5.12: Percent VSS and TSS reduction as a function of temperature.

Run	Temperature (°C)	VSS (%)		TSS (%)	
		Reactor 1	Reactor 2	Reactor 1	Reactor 2
3	22	77	66	75	64
4	30	67	43	64	38
5	35	69	50	68	47

5.5 GENERAL OBSERVATIONS

5.5.1 HRT

The HRT of a biological system determines the amount of time that a molecule spends in the reactor. In this study, both reactors were started at an HRT of 18 hours. In Run 1 there was a leakage in the clarifier of System 1 and hence the feeding was stopped for a period of 24 hours. When the samples from that reactor were analyzed two days later, there was a drop in pH and a rise in the net VFA production, suggesting that acidogenesis might be favoured with an increase in HRT. Hence, it was decided to change

the HRT from 18 to 30 hours in the 3rd run of this study, keeping all other parameters same.

Later in Run 4, when the system was disturbed considerably (as will be explained in Section 5.5.3) the HRT in Reactor 1 reached values of around 55 to 60 hours (as compared to the intended HRT of 30 hours). Analysis of samples from that period showed a much higher production in net VFA and a considerable drop in pH. This was another indication that increase in HRT would increase VFA production. Both incidents occurred accidentally. Hence it is suggested to perform a similar study at a higher HRT and come up with a optimum value.

5.5.2 SRT

Solids Retention Time (SRT) is an important operational parameter that can be used to control the activity of the microorganisms . It is defined as the average amount of time that microorganisms spend in the reactor and is controlled by the amount of sludge wasted from the system per day. SRT affects the type of species which can be present in the system. It also determines the extent of their activities due to the association with growth phases. Therefore in the process of acidogenesis, it is desirable to achieve an SRT that is favourable for the growth of acidogenic bacteria and suppresses the growth of methanogenic bacteria. It is also important that the SRT provide the system with maximum stability and least sludge.

In this study, SRT was not a control parameter. It was decided to maintain a average SRT of 10 days. However, in certain cases, due to high solids concentration in the

effluent, specially in Reactor 2, it was difficult to maintain that value. Hence it was decided to maintain a SRT value of 8 days, which was possible most of the time. It was expected that acidogenesis would be feasible at that SRT. Skalsky and Daigger (1995) reported that fermentation proceeds rapidly even at a SRT of as low as 2 days. The average reactor SRT for each run is shown in Table 5.13.

Table 5.13 : Reactor SRT (mean values)

Run	SRT of Reactor 1 (days)	SRT of Reactor 2 (days)
1	8.2	8.4
2	7.8	6.4
3	10.1	8.8
4	8.9	7.2
5	10.9	5.7

5.5.3 REPRODUCIBILITY

Reproducibility is defined as reproduction of a certain set of data under the same conditions if the experiment is repeated. Since biological systems are dependent on the activities of microorganisms, for a system to be reproducible, the microbial activity would have to be similar to that before the change. Eastman and Ferguson (1981) concluded that the steady state operations of acid phase digesters can be replicated and that the solubilization of the sludge solids is controlled by the operating conditions and not the

type of biomass initially present. Elefsiniotis and Oldham (1993) also reported the replication of the acid phase fermentation with less than 4% variation in the VFA production.

In this study, there was an opportunity to check the reproducibility of a biological system in Reactor 1. The behavior of the system before, during and after the disturbance is shown in Figure 5.15. In Run 4, after 32 days of stable operation, the system was disturbed unintentionally. Due to my absence, the feed concentration and HRT got disturbed to a large extent. HRT in Reactor 1 went up to as high as 55 hours and influent TS concentration was up to about 12000 mg/l for around 30 days. After detecting and solving the problem, the system was allowed to stabilize for 7 days, under identical conditions as before. Subsequent results show a very similar pattern to that obtained prior to the disturbance.

5.5.4 GAS PRODUCTION

Gas production is one of the main aims of the anaerobic digestion process. The acid phase is characterized by very low gas production mostly in the form of CO_2 , N_2 and H_2 , which are by-products of many metabolic pathways. Methane production should be very low or negligible in an ideal case, though Eastman and Ferguson (1981) and Ghosh (1987) reported some methane production in the acid phase, mainly due to improper separation of the two phases. There was an insignificant amount of gas production from the reactors throughout the entire duration of the study. Most of the gas produced during anaerobic digestion is during the methanogenesis of the biomass. Gas composition analysis

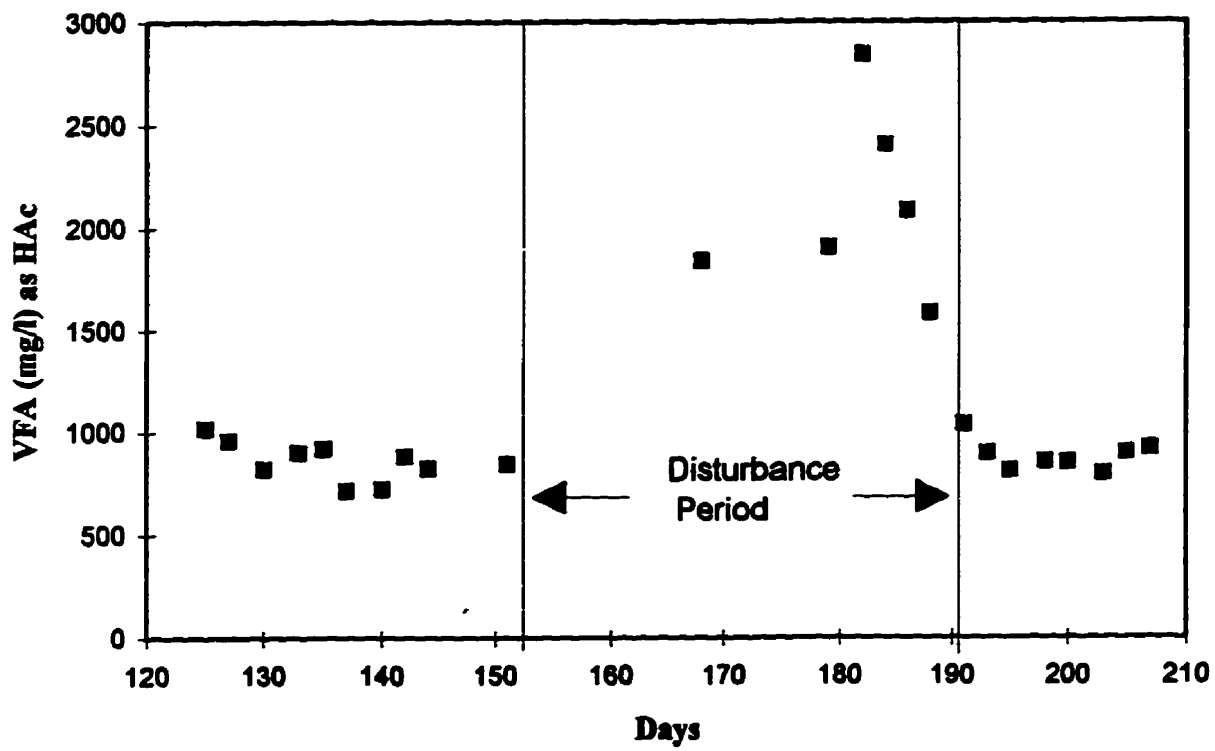


Figure 5.15: Reproducibility during Run 4 in Reactor 1

from time to time indicated that CO₂ was the predominant gas in the reactors, with negligible amounts of methane. As indicated by the low pH in the reactors throughout the period of study, the biomass was in the acid phase and hence the low gas production. It is also a proof that methanogenesis was suppressed successfully. Ghosh (1987) reported that gas yield decreases as HRT and temperature are increased.

However, in the clarifier of the second reactor, gas production was observed visually, specially at Runs 4 and 5 at higher temperatures. Gas bubbles were seen floating up towards the top of the clarifier. As the clarifiers were open to the atmosphere, it was impossible to measure the amount of gas produced in the clarifier. Gas production eventually led to scum formation on the top of the clarifier and eventually to the poor settling and loss of solids through the effluent.

5.5.5 CLARIFIER PERFORMANCE

The clarifiers were used for settling of the biomass coming out of the reactor. The settled biomass was recycled back into the reactor and the effluent was discharged.

Visual observation showed that the settling characteristics in the clarifiers changed with the change in operating conditions during the period of the study. In Run 1, the initial phase, settling was mediocre as the biomass was adjusting itself to the new environment. The comparatively shorter HRT meant a higher flow rate and less time for settling. As the industrial wastewater was introduced into Reactor 1 in Run 2, settling improved considerably. Starch has a specific gravity of 1.53 (Perry and Green, 1984), which is nearly 50% higher than water (specific gravity \approx 1.0) and municipal primary sludge

(specific gravity \approx 1.01 to 1.04) (Metcalf and Eddy, 1991; Qasim, 1994). As a result of the higher specific gravity, settling in Clarifier 1 improved remarkably compared to that of Clarifier 2. With the increase in HRT from 18 to 30 hours, settling in Clarifier 2 improved as more time was available for the biosolids to settle. With the increase in temperature from 22°C to 30°C and finally to 35°C, settling characteristics in Clarifier 2 deteriorated. The solids started floating up and were being lost through the effluent. Wang (1994) reported that the processes of settling and sludge digestion are not exactly compatible, as there is a tendency for the solids to float up and form a scum. In Clarifier 1, settling was good even when the temperature was increased.

The pH and the VFA concentrations of the reactor and the effluent were nearly the same in both systems throughout the study, though the pH in Clarifier 2 was considerably higher in the last run. At a pH of more than 7.0, there is a possibility that some methanogenesis was taking place (Perot et al., 1988). This is supported by the gas production in the clarifier, which could not be measured. The average VFA content of the reactors and the clarifier per run is shown in Table 5.14. There was no significant additional fermentation in the clarifier, mainly due to the short retention time of the biosolids in the clarifier. There is a possibility of the existence of a dynamic equilibrium between the rate of acid formation and the rate of volatilization.

Table 5.14: Average pH and VFA concentrations in Reactor and Effluent

Runs	System 1				System 2			
	Reactor 1		Clarifier 1		Reactor 2		Clarifier 2	
	pH	VFA	pH	VFA	pH	VFA	pH	VFA
1	5.59	520	5.46	577	5.63	544	5.59	508
2	5.12	688	5.17	671	5.77	546	6.14	660
3	4.44	868	4.45	831	5.81	413	6.18	405
4	4.56	1181	4.98	1166	6.21	508	6.99	436
5	4.76	789	5.92	832	6.37	276	7.47	241

* Values of VFAs are in mg/l

5.5.6 VFA/COD RATIOS

The individual VFAs were converted to COD using appropriate conversion factors as given in Appendix B. From these values, the percent COD in the form of VFAs is obtained. From the literature it has been seen that this ratio can vary remarkably. Gupta (1985) reported the ratio as 41% while Perot et al (1988) reported it as 46%. Both these studies were in batch reactors. The average values obtained for continuous reactors are 77% (Ghosh et al, 1975), 90% (Eastman and Ferguson, 1981) and 66% (Elefsiniotis, 1993).

Table 5.15 shows the mean and standard deviation of the percent COD in the form of VFA in all the runs of the study. In Reactor 1, after the addition of the industrial wastewater, the values were around 100% for the entire period of the study. It appears

that all the COD are present in the form of VFAs, which may lead to the conclusion that this particular mixture of wastewater is very effective in acidogenic fermentation of the soluble organic compounds present in the wastewater. In Reactor 2, the percent COD in the form of VFAs does not show any change with HRT. This observation is supported by the results obtained by Elefsiniotis (1993). When the temperature was increased to 35°C, the percentage dropped drastically in Reactor 2, which indicates that VFA production was more drastically affected than solubilization at the highest temperature tested. Overall, it is obvious that the conversion of soluble intermediates to end products is favoured by the addition of the starch-rich industrial wastewater.

Table 5.15: VFA/COD Ratios

Runs	Reactor 1		Reactor 2	
	Mean (%)	Std. Dev. (%)	Mean (%)	Std. Dev. (%)
Run 1	65.8	19.5	74.2	26.4
Run 2	103.1	29.5	86.3	33.1
Run 3	107.7	19.3	85.8	13.5
Run 4	106.4	11.3	90.8	17.7
Run 5	107.2	15.1	69.0	17.5

5.5.7 TRANSFORMATION OF NITROGEN COMPOUNDS

Nitrogen is present in wastewater mainly in the form of protein. The protein is hydrolyzed to amino acids, which in turn are used as fermentation substrates or building blocks of cell materials. The two forms of nitrogen, measured as total ammonia nitrogen and total Kjeldahl nitrogen in this study, for the influent, reactor and effluent of both systems are shown in Table A 11 and A 12 in Appendix A.

The influent concentration and the net production of ammonia nitrogen in System 1 are much lower than those in System 2. For System 1, the influent averaged around 26 mg/l and the net production was 8 mg/l, while the values for System 2 were 76 mg/l and 38 mg/l, respectively. This was expected because the influent to Reactor 1 was mainly comprised of carbohydrate from the starch-rich industrial wastewater. Ammonia is released during the deamination of amino acids, i.e. removal of the amino group (-NH₂) from the amino acid.

The extent of protein fermentation can be viewed from another perspective. An increase in the higher molecular weight VFAs, viz. iso butyric, iso valeric and n-valeric acids, can be attributed to protein fermentation (Elefsiniotis, 1993). Table 5.16 shows the percentage of iso butyric, iso valeric and n-valeric acids as a part of the total VFA in the reactors. In Run 1, due to the similar nature of the influent, the percentage is similar. But with the introduction of the industrial wastewater in Reactor 1, the percentage in Reactor 1 is significantly lower than that in Reactor 2, except for Run 3. This indicates that the degradation of proteinaceous material is more pronounced in Reactor 2, which is mainly due to the higher concentration of protein in the influent of this system.

Table 5.16: Percentage of VFAs related to protein degradation.

	Reactor 1 (% of related VFAs)	Reactor 2 (% of related VFAs)
Run 1	5.92	5.19
Run 2	6.59	9.60
Run 3	6.25	6.14
Run 4	4.33	5.36
Run 5	4.54	7.07

A mass balance of the system under steady state conditions shows a very good recovery of TKN, as shown in Table A13 in Appendix A. For System 1, the total recovery is 88%, while for System 2, it is 104%. Assuming that all the nitrogen is due to protein and that protein contains on an average 16% nitrogen (Gaudy and Gaudy, 1980), then the protein content can be calculated from the corresponding TKN value by subtracting the inorganic nitrogen concentration (NH₃-N only, in this case) and multiplying the difference by 6.25 (100 divided by 16). Influent protein concentration values are summarized in Table 5.17. The net ammonia production per unit protein in the influent is also shown in Table 5.17. It can be seen that an increase in temperature, from 22°C to 35°C (Runs 3 to 5), results in an increase in the net ammonia production per unit protein in the influent in both systems. When the two reactors are compared, it is evident that the net ammonia production in Reactor 2 is much greater than in Reactor 1, as indicated by the respective ratio. One reason might be the presence of starch in influent 1, which is easily

biodegradable. It has been found that in pure cultures, the presence of easily biodegradable carbohydrates can suppress protein hydrolysis (Elefsiniotis, 1993).

Table 5.17: Net Ammonia production per unit protein in the influent.

	Protein (mg/l)		Net NH ₃ production / protein in influent		Production
	Influent 1	Influent 2	(mg/l)	(mg/l)	Ratio
			Reactor 1 (R1)	Reactor 2 (R2)	R2/R1
Run 2	1163	1213	0.0163	0.0330	2.02
Run 3	705	698	0.0044	0.0344	7.82
Run 4	1019	1130	0.0047	0.0412	8.77
Run 5	453	950	0.0110	0.0442	4.02

5.5.8 TOTAL COD CONSIDERATIONS

Table 5.18 shows the ratio of the net soluble COD produced to the total influent COD. This ratio is expressed as the amount of soluble COD produced per amount of influent total COD. The influent total COD is an indication of the amount of food that is entering the system. Comparing the two systems, it is seen that the ratio is higher for Reactor 1 than for Reactor 2, except in Run 3. This might be due to the fact that the VSS concentration of Reactor 2 in that particular run was considerably higher (20062 mg/l).

In Reactor 1, the ratio increases with the introduction of the industrial wastewater. HRT does not have any significant effect on this ratio, while with increase in temperature

from 22°C to 30°C, the ratio increases and a further increase to 35°C causes the ratio to decrease. These results are in accordance to those discussed in substrate solubilization under the effect of temperature (section 5.4.4). It can be concluded that 30°C might be an optimum temperature for this particular type of wastewater. For Reactor 2, there is a variation in Runs 1 and 2 though the conditions are identical, as explained in section 5.2.4, due to a potential analytical problem. However, if the average of the two runs is taken into account, a ratio of 0.053 mg soluble COD/mg total influent COD is obtained, which is comparable to that in Run 1 of Reactor 1. HRT does not effect the ratio, while increase in temperature decreases the ratio. This can be correlated to the behaviour observed for substrate solubilization in Reactor 2 as a function of temperature (section 5.4.4).

Table 5.18: Net soluble COD produced / Total influent COD

Runs	Reactor 1			Reactor 2		
	Influent Total COD (mg/l) c1	Net COD produced (mg/l) c2	Ratio c1/c2	Influent Total COD (mg/l) c3	Net COD produced (mg/l) c4	Ratio c3/c4
1	6416	319	0.049	6416	---	---
2	7990	513	0.064	6322	456	0.053
3	9594	627	0.065	6043	440	0.073
4	8625	713	0.083	4449	239	0.066
5	5983	419	0.070	4542	169	0.037

5.5.9 DEGRADATION PATHWAYS

A summary of the VFAs generated in the acid phase anaerobic digestion of municipal primary sludge and the starch-rich industrial wastewater is presented in Table 5.19. Acetic acid is the most prevalent VFA, as it is formed directly from the fermentation of carbohydrates and proteins, as well as anaerobic oxidation of lipids via a number of metabolic pathways (Section 2.5.2). Propionic acid is primarily formed from carbohydrates, but can also be produced from proteins and lipids. Butyric acid is mainly generated from proteins and lipids, though it can be also formed from carbohydrates through pyruvate via an alternate pathway through acetyl CoA, acetoacetyl CoA, β -hydroxybutyryl CoA and crotonyl CoA (Gottschalk, 1986). Since the percent of n-butyric acid increased in Reactor 1 after the addition of the starch-rich industrial wastewater, it can be said that the pathway followed for butyric acid formation is through pyruvate, even though Gottschalk (1986) suggests that in a mixed culture, this pathway is considered to be a minor one. Iso butyric and the two isomers of valeric acid are largely associated with the fermentation of proteins as described in section 5.5.7.

5.5.10 POTENTIAL APPLICATION OF FINDINGS

The results obtained in this research have contributed towards a better understanding of the acid phase anaerobic digestion of primary sludge and mixture of primary sludge and industrial wastewater. It was observed that under all conditions, the 1:1 mixture of municipal primary sludge and starch-rich industrial wastewater had a higher

Table 5.19: Summary of range of percent VFA distribution

VFAs	Reactor 1	Reactor 2
Acetic	56.0- 75.8	61.0-68.1
Propionic	11.6-18.4	16.1-27.0
Iso Butyric	1.9-5.4	2.2-4.2
N-Butyric	5.4-22.3	2.0-8.7
Iso Valeric	1.2-2.7	2.9-6.0
N-Valeric	1.7-5.4	1.5-3.8

production of VFAs than the municipal primary sludge alone. As mentioned earlier (section 2.6.2), there is a direct relationship between the amount of VFAs present and the amount of phosphorus released under anaerobic conditions. For example, in Run 3 (HRT of 30 hours and temperature of 22°C), the difference in the net VFA production between the two reactors was 213 mg/l, i.e. there was an additional 213 mg/l VFAs production in the mixed wastewater compared to the primary sludge alone. Considering that 7 to 9 mg VFAs are required per mg of phosphorus removed (Barnard, 1993), it would be possible to remove additional phosphorus from wastewater effectively. It should be noted that the removal of phosphorus also depends on other operational conditions like solids content, flow distribution etc. Hence, it can be suggested that the 1:1 mixture be used for production of VFAs to get an overall better phosphorus removal from the wastewater.

CHAPTER 6

CONCLUSIONS

The effect of the industrial wastewater addition and the operational and environmental parameters investigated had profound consequences on the acid-phase digestion. Based on the results of this work, the following conclusions can be drawn:

1. A favorable environment for the activities of the acidogenic bacteria was established. Acidogenesis was feasible under all conditions, as indicated by low pH, high VFA production and very low gas production. Methanogenesis was successfully suppressed.
2. Net VFA and COD production as well as the specific production rates (expressed as mgVFA(or COD)/mgVSS*day) increased with the introduction of the starch-rich wastewater into one of the reactors.
3. HRT also had a profound effect on the net VFA production. Increase in HRT from 18 hours to 30 hours increased the VFA production by 37% in the mixture in Reactor 1 and 14 % in Reactor 2.
4. Variation in temperature had mixed effects on acidogenesis. For the mixture in Reactor 1, the net VFA production went up by 15% when temperature was increased from 22°C to 30°C, but decreased by 23% at 35°C, indicating that 30°C might be the optimum for the biomass present in this particular kind of wastewater. For the primary sludge in Reactor 2, increase in temperature decreased the production due to poor clarifier performance at high temperatures.

5. In Reactor 1 acetic acid was the most prevalent VFA averaging about 57 to 75% , followed by propionic and n-butyric which were nearly the same of around 15 to 17%. In Reactor 2 acetic acid was the predominant VFA with around 65% while propionic acid followed with 20% of the total VFAs. The addition of industrial wastewater had a remarkable impact on the VFA speciation where the percentage of n-butyric acid was increased, while HRT did not have much of an impact. Increase in temperature led to the reduction in the percentage of the n-butyric acid present.
6. The percent solubilization of organic matter (measured as VSS or TSS destruction) increased with the introduction with the industrial wastewater. HRT did not have a considerable effect on this parameter, but increase in temperature had an adverse effect on it, due to poor settling of the biomass in the clarifier at an elevated temperature.
7. The steady-state operation of an acid phase digester can be replicated and the performance of the system is controlled by the operating conditions and not the type of biomass initially present.
8. The extent of protein degradation was more pronounced in the municipal primary sludge than in the mixture. A mass balance of the two systems showed a very good recovery of TKN in both systems. The amount of net ammonia production per unit protein in the influent is higher in the municipal primary sludge than the mixture, while this parameter showed an increase with increase in temperature in both reactors.

CHAPTER 7

FUTURE RECOMMENDATIONS

Considerations for further research should be focussed on the following areas:

- During this study there was ample proof that increase in HRT increases the VFA production. In this study, HRT was increased upto 30 hours. Effect of further increase in HRT should be evaluated to obtain a optimum value for acidogenesis.
- The performance of the systems should be evaluated at lower temperatures, i.e. lower than room temperatures. This study proved that the system was failing at 35°C. The feasibility of acidogenesis at lower temperatures has not been investigated adequately. Therefore, more information is needed in this area.
- The mixture of municipal primary sludge and industrial wastewater in this study was in the ratio of 1:1. Different ratios of mixtures might give a totally different outlook to the performance of the system and potentially lead to an optimum ratio.
- Throughout this study, the feedstock was diluted to a TS content of 5000 mg/l . In most treatment plants, primary sludge will have a higher concentration. Hence it would be useful to investigate the performance of the process using a more concentrated feed.

- As explained in Chapter 2, (section 2.6), the main application of this study has been recently associated with the removal of phosphorus from wastewater. However VFAs might be used as a organic carbon source in denitrification. Since there is a limited amount of research in this area, further studies on denitrification using VFAs is necessary to evaluate the performance of the process.

- This was a laboratory scale experiment. This study can be extended to a pilot scale operation to evaluate the real life performance of the process.

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APPENDIX A

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*** All values in Tables A2 through A7 are in mg/l (except pH).**

Table A1: HRT values of the two systems (hours).

Date	Reactor 1	Reactor 2	Date	Reactor 1	Reactor 2	Date	Reactor 1	Reactor 2	Date	Reactor 1	Reactor 2
1-Sep			1-Oct	19.49	18.91	1-Nov	18.11	18.11	1-Dec	30.15	28.27
2-Sep			2-Oct	17.9	17.25	2-Nov	18.46	18.46	2-Dec	30.66	28.75
3-Sep	22	18.36	3-Oct	16.57	16.11	3-Nov			3-Dec		
4-Sep			4-Oct	21.66	19.5	4-Nov	17.82	18.31	4-Dec	28.34	28.05
5-Sep	20	17.7	5-Oct			5-Nov	17.2	17.55	5-Dec	28.66	28.66
6-Sep			6-Oct	17.14	18	6-Nov	17.5	17.95	6-Dec	33.7	33.7
7-Sep	22.77	18.35	7-Oct	17.77	16.8	7-Nov			7-Dec		
8-Sep			8-Oct			8-Nov	16.92	16.92	8-Dec	33.5	32.35
9-Sep	26.6	16	9-Oct	19.26	16.9	9-Nov			9-Dec	31.48	27.56
10-Sep			10-Oct			10-Nov	18.18	19.05	10-Dec		
11-Sep	18.48	17.7	11-Oct			11-Nov			11-Dec	31.75	30.76
12-Sep	17.14	16	12-Oct	19.35	16	12-Nov	17.09	17.73	12-Dec	31.48	29.08
13-Sep	19.2	16	13-Oct	19.46	17.14	13-Nov	18.04	19.16	13-Dec	33.03	30.79
14-Sep	20	19.5	14-Oct	20.45	20	14-Nov			14-Dec	32.6	31.24
15-Sep	18.18	17.87	15-Oct			15-Nov	17.54	18.22	15-Dec		
16-Sep			16-Oct	18.88	17.89	16-Nov			16-Dec	29.25	28.7
17-Sep	17.65	17.85	17-Oct	25	17.6	17-Nov	23.58	21.9	17-Dec		
18-Sep	17.7	17.45	18-Oct	18.42	17.5	18-Nov	38.28	40.05	18-Dec	28.7	31.2
19-Sep	17.23	17.23	19-Oct			19-Nov	29.63	25.81	19-Dec	29.53	28.05
20-Sep	17.77	17.77	20-Oct			20-Nov	36.4	27.42	20-Dec		
21-Sep			21-Oct	21.36	20.14	21-Nov	35	28.4	21-Dec	30.49	28.33
22-Sep	17.77	17.6	22-Oct	20.47	20.67	22-Nov	30.6	26.7	22-Dec	30.4	27.6
23-Sep	18	17.56	23-Oct			23-Nov			23-Dec		
24-Sep	16.75	17.6	24-Oct		19.46	24-Nov	32.15	29.76	24-Dec	31.3	28.62
25-Sep	16.91	17.95	25-Oct		18.65	25-Nov	32.26	31.16	25-Dec	30.6	26.7
26-Sep	16.2	17.66	26-Oct		17.58	26-Nov	33.58	29.44	26-Dec		
27-Sep	16	16.3	27-Oct			27-Nov	29.23	28.15	27-Dec	33.2	27
28-Sep	17.14	16.71	28-Oct			28-Nov	31.5	31.5	28-Dec	32.2	28.4
29-Sep	17.55	17.2	29-Oct	20.42	16.48	29-Nov	32.38	32.38	29-Dec	28.7	30.09
30-Sep	19.49	18.91	30-Oct	19.59	17.45	30-Nov	29.77	28.73	30-Dec	32	31.17
			31-Oct	18.46	16.55				31-Dec		

Table A2: Influent characteristics for Reactor 1

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
25-Aug	6.7				4570	154.94	75.63	8.23	46.44	19.31	17.13	380.07	
28-Aug	6.7				4910	228.85	65.10	10.67	43.55	21.33	20.03	275.60	
30-Aug	6.65				5000	162.01	39.44	27.93	40.56	31.50	21.13	341.33	
3-Sep	6.9				4820	139.05	22.54	13.90	20.85	20.26	6.73	271.68	375
5-Sep	6.8				4900	124.36	4.12	6.44	2.45	8.45	2.36	140.15	1125
9-Sep	6.8	4500		3630	5740	238.27	10.20	14.60	6.87	21.06	3.37	275.61	1800
11-Sep	6.8				5300	132.74	6.39	6.96	3.34	8.20	1.95	152.99	1850
14-Sep	6.8	4710		3500	4260								
16-Sep	6.8				5460								
17-Sep						171.16	5.00	6.33	2.96	12.58	5.07	183.33	440
18-Sep	6.7	4680		3640	5680	133.68	13.90	6.53	5.48	6.06	2.44	159.42	715
20-Sep	6.7	5190		4170	6920	183.82	33.10	9.37	16.42	12.06	9.42	241.07	425
23-Sep	6.8	4640		4010	4900	168.95	11.00	13.29	9.43	17.09	12.28	211.86	375
25-Sep	6.8	4910		3980	5660	186.26	23.48	7.29	13.71	11.44	9.03	211.79	470
27-Sep	6.8	4000		3400	4650	178.94	20.35	12.22	13.42	15.64	8.74	227.39	1025
30-Sep	6.8	4670		3730	5450	138.53	6.86	11.25	4.70	13.43	6.93	186.99	650
2-Oct	6.7	3990		3040	4640	158.81	39.90	12.63	23.57	16.67	16.57	232.97	620
4-Oct	7.2	4640		3630	4960	144.59	30.36	22.37	26.82	31.14	31.89	239.86	740
7-Oct	7.2	4500		3480	4900	73.13	4.05	4.01	1.80	7.09	1.37	85.24	613
Average	6.83	4575		3646	5216								
Std. Dev.	0.15			308	575								

Run 2

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
9-Oct	6.5	3260		2140	4080	94.65	59.40	13.73	26.69	16.90	23.21	197.24	525
11-Oct	6.5	2720		2330	3680	97.49	42.95	16.13	26.38	19.70	24.87	187.79	500
14-Oct	7.1	4920		4180	5980	111.47	22.83	21.81	22.86	21.34	22.23	186.09	500
16-Oct	7.05	6200		6420	6360	85.43	20.89	9.33	14.89	10.25	6.19	128.52	450
18-Oct	7.4	6980		5240	7140	88.67	12.25	17.21	14.60	16.34	16.73	140.99	400
22-Oct	6.95	5940		4200	7160	110.14	14.88	12.21	15.92	13.86	10.67	155.90	450
25-Oct	6.8	2880		2400	4300	124.07	60.51	7.16	28.12	10.79	9.61	209.57	225
28-Oct	6.8	2890		2420	3980	110.58	19.42	6.86	14.29	6.56	5.68	149.25	250
30-Oct	6.7	3440		2980	3980	155.18	35.62	12.45	37.03	16.77	15.76	237.15	475
1-Nov	6.65	4320		3940	4740	212.62	30.59	14.25	43.52	17.31	15.51	296.32	550
4-Nov	6.7	6380		6120	7800	249.43	30.89	15.48	65.36	17.36	17.42	350.16	450
6-Nov	6.3	7660		7140	7960	300.37	57.99	17.89	93.69	20.25	23.70	449.69	600
8-Nov	5.8	7740		7520	8640	341.22	93.88	15.80	189.52	18.35	22.99	588.45	700
10-Nov	5.4	6500		7280	8680	390.46	64.54	9.16	133.08	13.50	19.60	576.00	900
12-Nov	5.3	7940		7400	8680	300.79	71.43	10.27	98.63	15.16	22.45	455.53	900
15-Nov	5.5	8410		8020	8650	280.36	73.58	8.43	81.37	12.33	16.09	418.42	500
Average	6.47	5629		5062	6318								
Std. Dev.	0.64	2147		2179	1977								

Table A2 cont'd

Run 3

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
19-Nov	6.6	6160	5560	7080	6300	203.16	50.80	6.02	47.90	7.69	12.50	283.31	600
22-Nov	6.1	7720	6600	8260	7000	204.36	29.05	11.66	54.81	12.49	18.52	291.66	500
25-Nov	6.05	6120	6120	7240	6440	183.34	43.39	13.74	104.12	13.12	6.79	312.05	600
27-Nov	5.8	6720	6320	7440	6760	169.16	42.39	8.61	100.06	7.33	5.29	285.33	1000
29-Nov	5.2	6200	5680	6960	5960	186.22	36.59	9.31	129.03	7.93	5.07	318.11	800
2-Dec	5.1	6480	6080	7200	6440	249.94	52.66	9.84	150.54	10.26	9.56	414.02	600
4-Dec	5.15	5260	4960	6260	5500	264.51	51.09	9.53	177.27	10.26	9.51	465.27	800
6-Dec	5.3	4700	4020	5560	5140	202.15	52.61	5.19	129.59	18.43	21.80	360.67	700
9-Dec	5.15	5400	4860	6120	5240	240.65	52.02	5.78	135.56	5.31	6.17	366.29	975
11-Dec	5.65	4400	4000	5120	4480	171.61	40.25	6.19	96.44	7.14	7.13	282.68	650
13-Dec	5.9	5320	5140	5760	5180	176.81	44.27	11.00	98.95	12.97	14.77	304.26	460
16-Dec	5.7	5760	5100	6060	5320	164.97	30.81	6.54	96.07	7.93	7.46	270.53	650
18-Dec	5.35	4660	4020	5300	4480	196.43	18.52	5.36	116.93	5.85	6.17	304.03	650
21-Dec	5.45	4440	3660	5260	4360	216.72	24.73	9.68	134.86	10.73	10.55	360.03	525
24-Dec	6.45	4720	4120	5960	5100	149.42	11.59	6.34	99.30	10.02	8.63	243.27	350
Average	5.66	5640	5115	6376	5583								
Std. Dev.	0.48	1005	978	936	853								

Run 4

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
27-Dec	6.15	4680	3660	5480	4580	160.88	20.20	12.80	80.14	15.74	10.89	266.32	380
30-Dec	6.55	4640	4200	5120	4200	201.58	36.73	24.58	76.26	25.31	21.59	330.93	430
1-Jan	6.4	5560	4660	5960	5050	156.50	18.66	18.41	59.32	19.66	7.71	240.67	400
4-Jan	6.4	4660	4320	5420	4400	163.70	6.63	16.54	66.66	18.37	2.59	239.65	460
6-Jan	6	5060	4520	6140	5250	170.25	16.26	13.61	66.19	14.09	3.25	264.79	500
8-Jan	5.3	4620	4260	5100	4180	153.49	5.82	15.43	62.31	15.92	2.55	235.76	500
11-Jan	5.3	4480	5780	5200	4320	171.57	9.03	15.31	61.74	19.24	6.33	260.17	460
13-Jan	4.9	4640	3900	5480	4420	204.92	23.46	9.48	91.03	10.66	10.44	305.05	430
15-Jan	6.3	5050	4400	5760	4660	194.40	22.26	13.92	67.25	18.45	26.92	309.44	400
22-Jan	6.2	4320	3950	4640	4520	192.65	33.06	11.97	103.33	16.91	18.56	319.16	400
6-Feb	4.9	6260	6650	11520	10250	545.02	104.41	26.49	52.79	38.26	45.42	733.60	1450
19-Feb	5.2	10400	9600	11950	10100	467.97	84.64	13.92	49.05	22.15	27.54	609.26	1350
22-Feb	5.5	9600	9000	11050	10150	367.44	93.52	21.18	52.72	23.55	34.31	526.27	1025
24-Feb	6.1	12350	11560	12800	11900	280.62	76.28	14.09	42.57	16.21	27.31	406.61	650
26-Feb	6.5	3650	3300	4350	3750	110.41	53.99	9.06	24.15	6.65	17.15	192.46	900
28-Feb	6.8	4150	3700	4800	4150	136.03	36.28	14.17	22.78	11.01	12.35	206.24	780
3-Mar	7	4650	3600	5150	4300	138.93	24.88	14.21	18.52	9.49	13.77	195.28	430
5-Mar	7.1	4650	4200	5350	4650	113.76	16.73	13.84	14.54	9.55	15.99	161.82	280
7-Mar	7.2	4650	4200	5400	4600	105.25	11.78	10.66	10.85	6.65	6.34	136.61	350
10-Mar	7	5550	4900	5850	5150	135.56	14.62	12.65	16.24	8.65	10.58	176.63	350

Table A2 contid

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
12-Mar	7.1	4700	4350	4850	4400	157.75	18.21	20.27	27.15	17.45	16.76	225.90	580
15-Mar	6.9	5250	4750	5050	5320	182.12	19.76	24.64	10.88	28.14	8.55	254.65	420
17-Mar	7	4600	4000	5280	4770	189.76	24.93	32.61	41.41	23.28	17.66	284.68	540
19-Mar	6.3	4500	3950	5150	4850	182.34	21.15	31.56	18.23	22.11	15.47	265.67	650
Average	6.25	4765	4276	5342	4592								
Std. Dev.	0.73	447	534	413	412								

Run 5

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
25-Mar	5.3	4250	3700	4650	4400	281.52	81.88	28.34	148.39	23.73	7.95	488.03	760
27-Mar	5.95	4400	3950	4700	4250	212.64	57.71	13.65	76.60	9.07	5.62	330.09	600
28-Mar	5.5	4150	3550	4000	3900	217.38	52.64	16.25	71.73	13.86	11.62	335.37	500
1-Apr	6	4150	3700	4750	4000	187.25	39.45	14.42	66.77	11.14	8.66	286.51	420
3-Apr	6.45	4200	3300	4650	4100	242.57	50.34	12.58	66.09	11.29	17.02	354.00	680
5-Apr	6.5	4500	3900	5150	4550	245.27	35.82	15.61	70.53	10.88	11.00	346.15	540
7-Apr	6.5	4500	3300	5050	3800	239.25	44.32	16.13	65.90	12.24	15.08	347.46	680
9-Apr	6.5	4550	3950	5500	4450	150.38	36.32	34.79	63.54	42.66	55.65	318.55	440
12-Apr	6.2	4150	3550	5000	4250	148.44	9.86	19.82	41.24	12.55	11.88	212.50	440
14-Apr	6.1	4350	3650	4750	3900	155.61	21.15	21.59	38.21	14.95	13.37	230.33	520
16-Apr	5.9	4650	3850	5400	4550	173.21	15.39	22.08	28.99	14.55	13.98	237.38	650
18-Apr	6.15	4700	4250	5250	4800	195.89	17.48	16.99	31.99	10.52	9.86	265.35	420
20-Apr	6	4500	3850	5250	4350	200.90	30.07	22.07	35.93	11.63	12.50	279.21	420
22-Apr	5.9	4350	3600	5400	4350	196.72	35.86	14.35	30.41	10.52	11.92	277.19	540
24-Apr	6	4800	4100	5750	4550	236.17	34.44	17.04	35.52	14.44	13.53	318.60	580
Average	6.04	4413	3747	5090	4280								
Std. Dev.	0.37	210	270	334	290								

Table A3: Influent characteristics to Reactor 2

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
25-Aug	6.7				4570	154.94	75.83	8.23	46.44	19.31	17.13	360.07	
28-Aug	6.7				4910	226.85	65.10	10.67	43.55	21.33	20.03	275.60	
30-Aug	6.65				5000	162.01	39.44	27.93	40.56	31.50	21.13	341.33	
3-Sep	6.9				4820	139.05	22.54	13.90	20.95	20.26	6.73	271.66	375
5-Sep	6.8	4500	3630		4900	124.36	4.12	6.44	2.45	8.45	2.36	140.15	1125
9-Sep	6.8				4450	238.27	10.20	14.60	6.97	21.06	3.97	275.61	1800
11-Sep	6.9				5740	132.74	8.39	6.96	3.34	8.20	1.95	152.59	1850
14-Sep	6.8	4710	3500		5360								
16-Sep	6.8				5400								
17-Sep						171.16	5.00	8.33	2.96	12.56	5.07	193.33	440
18-Sep	6.7	4680	3640		5660	133.69	13.90	6.53	5.46	6.06	2.44	159.42	715
20-Sep	6.7	5190	4170		6820	183.82	33.10	9.37	16.42	12.06	9.42	241.07	425
23-Sep	6.8	4640	4010		4680	168.95	11.80	13.29	9.43	17.99	12.28	211.86	375
25-Sep	6.8	4910	3880		5660	166.26	23.46	7.29	13.71	11.44	9.03	211.78	470
27-Sep	6.8	4000	3400		4650	178.94	20.35	12.22	13.42	15.64	6.74	227.39	1025
30-Sep	6.8	4670	3730		5450	136.53	6.86	11.25	4.70	13.43	6.93	166.99	650
2-Oct	6.7	3660	3040		4640	156.81	36.90	12.63	23.57	16.67	16.97	232.97	620
4-Oct	7.2	4640	3630		4860	144.59	30.36	22.37	26.82	31.14	31.69	239.88	740
7-Oct	7.2	4500	3480		4600	73.13	4.05	4.01	1.60	7.09	1.37	85.24	613
Average	6.83	4675	3646		5216	115.71	51.81	5.87	17.42	9.70	7.44	183.83	700
Std. Dev.	0.15	367	308		575	104.00	35.74	10.13	16.07	12.46	9.68	164.22	575

Run 2

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
9-Oct	6.95	4540	3580		4850	115.71	51.81	5.87	17.42	9.70	7.44	183.83	700
11-Oct	7.1	5100	3910		5760	104.00	35.74	10.13	16.07	12.46	9.68	164.22	575
14-Oct	7.2	4680	3500		5280	115.65	8.94	11.61	11.85	13.80	5.11	150.09	525
16-Oct	7.3	4620	4410		5160	96.05	36.13	10.47	23.27	12.61	4.07	162.14	900
18-Oct	7.3	4410	3560		4880	119.11	18.01	12.84	18.19	15.37	4.77	166.82	675
22-Oct	7.1	4520	3520		5180	124.75	11.10	22.15	27.46	23.19	8.97	186.56	750
25-Oct	7	2930	3440		5340	134.97	20.22	14.74	28.58	19.20	9.86	196.12	300
28-Oct	7.2	4610	2980		4650	136.57	5.30	16.16	19.24	1.45	9.10	172.63	250
30-Oct	7	4780	3680		5440	159.00	23.78	19.64	41.70	25.45	11.63	242.19	875
1-Nov	7	4480	3500		5280	254.16	31.67	22.29	52.81	30.44	19.42	360.59	725
4-Nov	7.2	4460	3740		5160	225.16	22.03	26.76	60.98	33.93	16.66	333.62	450
6-Nov	7.1	4370	3700		5070	267.10	39.53	29.22	80.87	39.93	25.28	412.81	600
8-Nov	7.1	4310	3630		4750	227.64	26.23	25.63	68.53	33.96	21.54	345.94	700
10-Nov	7.2	4760	3640		5240	246.54	22.55	25.63	65.27	33.79	21.62	361.65	500
12-Nov	7.1	4420	3460		5720	227.01	34.81	24.87	77.88	32.39	26.34	360.05	600
15-Nov	7	4480	3680		5340	195.08	13.60	22.88	46.96	25.95	16.41	279.92	300
Average	7.12	4491	3569		5219	115.71	51.81	5.87	17.42	9.70	7.44	183.83	700
Std. Dev.	0.11	467	204		278	104.00	35.74	10.13	16.07	12.46	9.68	164.22	256

Table A3 cont'd.

Run 3

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
19-Nov	7.1	5000	4180	4180	5540	144.77	14.17	14.68	22.73	18.29	11.71	188.31	300
22-Nov	7.2	5380	4200	4200	5640	105.71	2.44	18.68	12.55	20.13	8.37	145.78	400
25-Nov	7.2	4720	3980	3980	5400	105.37	13.56	22.98	18.7	23.04	8.37	162.17	600
27-Nov	7.2	4330	3760	3760	5160	83.96	9.14	17.15	12.95	17.79	3.39	124.41	500
29-Nov	7	4860	3980	3980	5140	71.39	2.56	16.73	8.39	15.73	1.89	100.97	400
2-Dec	7.3	4080	3400	3400	4440	68.84	5.97	12.57	7.84	14.77	2.22	97.63	250
4-Dec	7.2	4020	3320	3320	5180	34.91	3.8	9.87	6.53	15.8	2.53	59.84	200
6-Dec	7.3	3520	2980	2980	4420	28.23	5.81	5.28	5.4	13.25	1.72	48.90	200
9-Dec	7.3	4190	3200	3200	4720	8.21	1.81	4.63	1.87	4.66	0.72	14.13	100
11-Dec	7.25	3880	2980	2980	3900	37.95	3.16	4.63	2.81	7.56	1.89	51.14	100
13-Dec	7.2	3880	3180	3180	4540	40.01	2.86	3.58	1.55	7.39	0.76	50.71	125
16-Dec	7.15	3800	3140	3140	4800	33.95	5.84	3.58	3.89	6.68	1.02	48.18	200
16-Dec	7.35	3620	3080	3080	4300	20.28	4.48	3.8	4.88	6.94	1.89	34.83	200
21-Dec	6.95	3420	2800	2800	4780	53.95	3.76	5.36	2.31	6.96	1.28	67.08	220
24-Dec	7.2	3600	3080	3080	4080	48.88	4.04	2.51	3.23	6.99	1.54	60.28	220
Average	7.19	4182	3416	3416	4801	37.67							
Std. Dev.	0.11	582	484	484	559	502							

Run 4

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
27-Dec	7.2	4080	3220	3220	4760	98.23	21.28	13.68	15.35	17.23	3.5	146.59	380
30-Dec	7.2	3820	2840	2840	4300	123.09	17.18	18.17	12.58	18.81	3.88	171.32	375
1-Jan	7.2	4140	3300	3300	4920	111.78	15.82	18.73	12.13	20.97	3.59	180.19	360
4-Jan	7.2	3940	3020	3020	5200	102.25	15.86	17.23	12.77	22	3.65	150.75	400
6-Jan	7.1	3680	2920	2920	4340	147.41	29.35	19.15	17.04	21.98	5.48	212.21	350
8-Jan	6.4	4480	3440	3440	4840	156.69	21.29	23.29	11.61	27.72	4.13	216.51	350
11-Jan	6.35	3600	2560	2560	4000	152.06	23.63	19.24	12.19	24.52	4.95	210.13	650
13-Jan	6.3	4100	2920	2920	4880	177.25	36.85	14.32	20.12	17.27	9.84	248.79	400
15-Jan	7.25	3980	3100	3100	4260	183	32	13.82	14.34	16	8.31	252.84	430
22-Jan	7	4080	3460	3460	5140	165.35	48.84	14.84	43.04	23.65	19.44	299.93	400
8-Feb	7.2	4940	4120	4120	5700	375.22	93.54	39.58	61.22	57.95	18.92	595.59	480
19-Feb	7.2	4550	3700	3700	5450	331.45	71.75	27.08	14.59	32.89	6.54	441.67	480
22-Feb	6.95	4350	3350	3350	4950	239.88	67.57	24.42	23.15	22.59	12.55	347.97	975
24-Feb	7.1	4300	3400	3400	5200	312.48	55.25	19.42	4.29	15.77	3.21	384.95	900
28-Feb	6.8	4150	3300	3300	4900	264.35	65.77	18.51	11.19	13.91	4.5	348.18	580
28-Feb	7	4450	3450	3450	5100	268.84	72.99	19.92	11.89	20.32	4.7	382.88	500
3-Mar	6.85	4350	3100	3100	5100	228.65	57.28	15.77	13.51	13.43	5.39	304.49	720
5-Mar	7.1	4250	3500	3500	4650	197.55	43.18	15.45	7.24	12.89	5.36	259.03	480
7-Mar	7.1	4200	3200	3200	4900	214.11	50.58	17.86	7.99	14.44	3.85	283.58	350
10-Mar	7	4300	3350	3350	5000	272.88	67.45	14.95	16.86	13.16	5.44	360.62	610
12-Mar	7	3950	3150	3150	4520	245.06	73.87	24.39	19.01	26.23	9.84	358.22	350

Table A3 contd.

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
15-Mar	7	3850	3200	4500	3450	307.03	77.41	22.92	3.77	24.08	11.52	409.41	310
17-Mar	7.25	4000	3100	5000	3900	301.25	84.59	24.84	5.11	14.43	7.59	403.73	350
19-Mar	7	4200	3300	5000	3950	214.04	86.68	25.25	6.31	19.62	8.56	322.95	440
Average	6.99	4154	3250	4858	3781								
Std. Dev.	0.26	294	309	392	409								

Run 5

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
25-Mar	7	3900	2850	4300	2800	112.2	6.46	8.22	5.91	8.16	3.01	153.66	240
27-Mar	6.9	4150	3550	4700	3950	128.48	15.4	8.88	9.98	9.27	2.68	180.95	240
29-Mar	7.1	4400	3150	4850	3900	126.43	7.72	7.19	4.37	9.79	1.92	147.51	240
1-Apr	7.1	3950	3100	4700	4050	147.37	14.64	12.4	6.36	13.86	3.15	182.14	320
3-Apr	7	3950	3250	4650	4200	244.89	39.83	11.16	19.3	13.69	4.25	308.75	540
5-Apr	7.1	4250	3200	4800	3900	254.96	27.67	11.62	9.84	13	1.2	300.56	350
7-Apr	7.0	4650	3450	4650	3950	247.33	33.72	11.92	18.15	13.33	5.89	308.69	520
9-Apr	7.35	3950	2850	4650	3800	185.72	19.09	13.13	4.79	16.41	4.07	225.58	460
12-Apr	7	4100	2850	4650	3550	198.34	13.19	8.99	2.29	13.57	2.16	228.07	460
14-Apr	6.75	4650	3250	5200	4150	182.71	18.32	8.05	7.59	14.53	8.59	201.93	400
16-Apr	6.95	4300	2500	5000	3450	161.03	6.24	5.83	2.47	4.13	3.07	176.02	650
18-Apr	7	4050	2700	4650	3900	205.36	9.63	5.05	2.65	15.46	3.39	229.56	350
20-Apr	7	4150	2650	4650	3950	178.44	8.76	4.96	1.47	13.82	2.05	199.31	350
22-Apr	7	4250	2550	4900	3450	175.81	11.33	4.91	3.04	14.76	3.41	201.17	460
24-Apr	7.1	4650	2800	5000	3250	154.03	3.09	2.89	3.86	13.99	2.54	170.88	420
Average	7.03	4223	2953	4850	3750								
Std. Dev.	0.13	263	345	196	379								

Table A4: Reactor 1 characteristics

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
25-Aug	5.4	25380	18800	26080	19150	365.02	305.90	14.98	63.72	21.74	35.83	528.48	
28-Aug	5.3	21780	16120	21950	16170	565.55	462.29	17.14	72.37	16.81	50.20	702.45	
30-Aug	5.2	16780	12380	17350	12710	352.51	177.50	21.84	34.77	31.17	32.43	1043.88	
3-Sep	5.7	15530	11640	16750	12600	412.14	143.02	21.04	43.52	32.05	35.49	573.53	1925
5-Sep	5.7	14150	10550	14820	11000	322.58	90.96	12.34	6.54	17.60	9.68	612.73	965
9-Sep	5.8	10980	8270	11020	8510	292.09	98.73	9.45	8.78	10.61	6.11	416.99	1650
11-Sep	5.75	11010	8320	11300	8500	311.55	103.73	10.86	16.39	14.33	9.99	386.84	1400
14-Sep	5.65	14650	11120	15030	11440	340.33	94.90	10.04	15.46	13.12	6.51	429.18	
16-Sep	5.6	15080	12000	15210	11550	354.45	113.42	9.68	16.90	12.17	11.45	447.97	750
17-Sep	5.7	15980	11910	16940	12400	346.79	117.69	8.37	17.77	10.27	13.77	479.11	675
18-Sep	5.5	17680	13450	16970	12970	372.02	119.19	12.51	20.29	15.35	15.48	474.90	800
20-Sep	5.6	16080	13770	18720	14020	330.50	96.77	12.68	18.28	15.87	12.58	509.89	750
23-Sep	5.7	16250	12310	16810	12740	363.41	126.60	13.90	25.45	16.18	17.38	447.41	715
25-Sep	5.4	17070	13070	17170	13090	337.65	104.58	12.73	21.33	16.32	18.38	514.99	1325
27-Sep	5.5	15980	12280	16300	12500	333.17	107.64	16.81	33.72	22.50	20.83	466.72	975
30-Sep	5.65	15240	11610	16670	12680	308.29	96.91	15.16	27.34	20.83	15.17	481.05	1000
2-Oct	5.7	15440	12480	16650	12940	296.13	96.12	11.50	23.92	18.49	10.17	435.61	975
4-Oct	5.7	15040	11420	15430	11740							417.30	975
7-Oct	5.7	15040	11420	15430	11740							417.30	975
Average	5.59	16223	12303	16725	12598								1113
Std. Dev.	0.17	3324	2416	3356	2395								

Run 2

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
9-Oct	5.35	14140	10650	14830	11400	307.17	104.73	7.44	28.84	11.48	10.51	430.42	1150
11-Oct	5.55	11690	8920	12280	9010	303.65	106.66	12.01	47.76	16.53	22.23	454.51	975
14-Oct	5.55	12750	9480	13790	10670	301.71	92.08	13.59	51.27	19.52	20.18	444.51	975
16-Oct	5.5	12820	13180	13180	10670	290.31	83.40	13.87	53.26	21.37	17.65	427.18	950
18-Oct	5.75	13050	10130	13750	11420	375.15	109.79	18.64	57.75	23.31	17.99	541.23	847
22-Oct	5.1	14880	11780	15180	11560	381.78	132.71	15.95	104.57	23.25	30.66	594.08	1100
25-Oct	4.7	14120	11520	14400	11610	529.12	256.44	14.07	180.15	22.27	53.78	915.80	1200
28-Oct	4.8	9240	7640	9360	7080	485.62	259.27	12.32	189.13	16.73	46.29	871.88	975
30-Oct	5.1	9880	8000	10420	8400	312.39	124.39	11.93	98.91	17.20	25.44	514.68	950
1-Nov	5.3	11040	9140	11280	9360	448.22	120.49	17.90	122.92	25.91	35.07	678.58	1050
4-Nov	5.1	12160	9880	12540	10240	476.18	136.98	19.80	158.57	27.80	42.32	749.58	650
6-Nov	5	10250	8920	10720	9060	629.04	180.64	21.44	173.82	30.06	54.01	942.88	1200
8-Nov	4.8	6050	7100	9040	7520	429.99	180.17	17.02	169.92	24.80	56.12	753.43	1125
10-Nov	4.8	7160	6060	8360	6840	598.53	175.32	20.56	228.77	25.52	50.50	955.15	1100
12-Nov	4.8	10100	8580	10840	8680	582.80	132.81	12.77	182.15	20.89	57.87	880.54	1225
15-Nov	4.7	13180	11500	13220	11400	594.53	137.33	9.91	167.43	15.91	65.98	895.81	925
Average	5.12	11518	9312	12062	9603								
Std. Dev.	0.37	2269	1697	2142	1725								

Table A4 cont'd.

Run 3

Date	pH	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
19-Nov	4.55	13120	13780	11720	609.85	98.06	8.21	88.39	11.9	52.19	800.84	1150
22-Nov	4.5	13390	14020	11460	631.192	99.57	151.52	108.92	18.41	50.72	930.91	1000
25-Nov	4.45	11480	14760	12560	521.17	119.45	15.82	126.49	18.64	39.45	749.97	1400
27-Nov	4.5	13660	14440	12620	545.34	126.71	15.36	147.43	14.45	45.37	795.06	1400
29-Nov	4.4	13020	11950	12000	478.97	126.99	15.68	258.56	15.06	60.58	814.12	1450
2-Dec	4.3	11460	10180	10240	421.31	124.42	18.15	361.08	15.17	73.02	633.86	1550
4-Dec	4.3	11920	10420	10620	549.98	144.03	19.06	404.29	15.26	86.39	1017.32	1700
6-Dec	4.1	14060	12380	14780	623.95	154.53	18.4	340.45	14.17	106.36	1065.81	1700
9-Dec	4.3	11160	9820	13640	689.09	148.05	16.11	302.03	11.03	78.84	1079.86	1500
11-Dec	4.3	11640	10340	12200	568.75	115.75	11.87	219.17	7.86	49.08	854.25	1200
13-Dec	4.3	10040	8940	10600	655.95	135.25	16.02	225.1	10.07	47.39	964.68	1000
16-Dec	4.4	10400	9200	11420	561.78	99.71	10.68	137.16	9.24	27.66	757.73	1025
18-Dec	4.5	11680	10360	12760	572.68	93.35	13.68	212.72	12.13	33.24	830.03	1100
21-Dec	4.45	12260	10580	12800	540.09	79.65	11.93	214.73	10.14	28.12	782.24	1100
24-Dec	5.3	10360	9340	9720	532.89	67.48	11.51	177.21	11.69	28.57	739.21	1100
Average	4.44	11960	10553	12558	611.81							
Std. Dev.	0.26	1247	1075	1350	1135							

Run 4

Date	pH	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
27-Dec	5.15	11460	10040	12460	669.84	127.88	17.01	246.46	15.19	45.77	1019.17	1375
30-Dec	5.1	10400	9200	10700	649.55	145.5	19.06	207.43	16.28	49.04	981.31	1300
1-Jan	5.15	10350	9240	10660	560.25	133.08	20.72	157.71	16.4	37.8	822.54	1075
4-Jan	5.1	12000	10080	12730	627.06	135.42	23.43	160.42	19.26	46.32	901.06	1250
6-Jan	5.1	12140	10580	13040	658.26	135.1	25.15	141.15	23.52	42.86	920.97	1250
8-Jan	4.2	11620	10230	10640	514.22	97.37	19.93	116.75	22.85	29.47	717.75	1100
11-Jan	4.3	10680	9580	10960	522.46	93.65	19.77	120.76	22.13	27.58	724.04	1050
13-Jan	3.6	11400	10500	13140	612.83	141.72	12.18	159.59	15.45	49.7	884.07	1100
15-Jan	4.65	11680	10440	12640	564.32	135.5	12.75	154.07	15.59	45.6	824.69	1300
22-Jan	4.2	11520	10610	12650	560.29	126.77	15.45	187.52	22.93	50.22	845.30	1300
6-Feb	4.3	10440	8940	11260	1371.72	217.98	28.44	300.51	33.87	72.81	1636.88	2400
19-Feb	4.15	13520	11250	14970	1296.68	307.31	12.44	403.33	12.54	113.17	1904.22	2900
22-Feb	4.1	17650	15800	18750	1945.26	346.92	16.06	737.77	9.91	158.09	2841.59	4000
24-Feb	4	16600	14700	17350	1702.55	270.19	13.21	582.31	9.08	115.41	2402.63	4000
26-Feb	3.9	13750	13150	15650	1485	257.81	12.55	452.33	6	114.11	2083.30	2900
28-Feb	4	13150	11450	13970	1280.62	138.93	13.98	208.84	5.63	56.09	1582.37	1900
3-Mar	4.5	12650	10800	13400	874.3	137.44	11	43.84	4.71	18.29	1037.51	1350
5-Mar	4.65	13500	11550	13950	773.53	122	14.31	9.82	7.05	6.14	897.42	900
7-Mar	4.7	12350	10700	13050	705.83	109.17	11.44	5.52	6.32	3.84	812.56	1100
10-Mar	5	12150	10550	14400	761.77	96.07	11.9	2.09	6.39	1.91	854.68	850

Table A 4 contd.

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
12-Mar	5	11850	10150	11850	10050	758.29	84.29	17.72	2.97	15.84	3.09	852.28	1150
15-Mar	4.9	12000	10550	12950	11250	632.15	100.38	39.31	40.58	37.03	11.53	797.20	800
17-Mar	4.8	11950	10550	12000	11550	757.49	109.71	24.4	25.09	20.04	9.8	896.42	1000
19-Mar	4.8	11850	10150	12850	11150	787.43	102.11	22.32	21.04	22.38	10.85	919.95	1000
Average	4.58	12382	10688	13280	11350								
Std. Dev.	0.47	1799	1809	1914	1635								

Run 5

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
25-Mar	4.3	14700	13500	15450	13650	1008	143.33	31.18	158.28	22.88	27.52	1282.57	1800
27-Mar	4.3	13400	12400	13750	12700	882.61	128.11	24.92	145.64	19.05	25.87	1130.01	1300
29-Mar	4.5	13550	11750	15050	12900	787.79	132.35	23.08	87.24	10.39	22.58	980.53	1200
1-Apr	4.65	13250	11800	15150	12950	732.67	128.42	19.8	31.24	15.28	13.36	889.24	880
3-Apr	4.7	13200	11750	14050	12350	695.29	108.93	18.21	8.52	15.77	12.71	819.28	1050
5-Apr	5	11850	10650	12750	11100	584.98	87.35	18.75	15.67	16.61	15.57	688.74	800
7-Apr	5	12750	10800	13650	11150	579	82.93	18.21	11.84	16.45	4.43	679.53	950
9-Apr	4.9	14900	13450	15100	13000	514.17	89.8	20.63	46.49	22.75	10.49	636.35	950
12-Apr	5	14250	12900	15550	13150	515.62	72.08	24.64	23.08	23.16	8.02	625.39	800
14-Apr	4.65	13900	12050	14550	12400	554.71	75.98	24.51	58.3	20.02	15.4	694.07	950
16-Apr	4.45	14500	12800	15850	13800	584.37	83.78	25.27	32.33	21.18	10.69	680.84	1050
18-Apr	4.8	10400	9050	10850	10050	522.73	91.38	22.06	30.75	19.79	15.85	654.36	700
20-Apr	5.2	11150	9700	12300	10750	563.32	76.81	20.74	3.35	18.95	3.39	655.64	620
22-Apr	5.1	11800	10300	12750	11850	531.83	111.05	21.08	9.15	18.78	8.48	659.19	680
24-Apr	4.8	11800	9800	12350	10150	553.9	134.17	25.7	25.29	22.85	19.25	722.93	840
Average	4.76	13027	11453	13943	12117								
Std. Dev.	0.28	1366	1377	1480	1202								

Table A5: Reactor 2 characteristics

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
25-Aug	5.7	9880	8620	10650	9380	245.76	66.09	10.45	49.36	18.00	20.49	400.28	
28-Aug	5.9	5750	4760	6020	4850	507.58	179.73	19.66	65.54	28.86	34.12	379.51	
30-Aug	5.7	14630	11600	14800	11940	367.30	261.46	14.76	48.47	14.61	25.73	770.02	
3-Sep	5.35	14810	11940	15410	12290	765.30	520.25	33.31	72.01	33.68	49.05	647.75	1350
5-Sep	5.4	13610	10070	13710	11010	263.83	97.71	6.28	19.41	10.37	10.11	394.57	1160
9-Sep	5.5	12920	10150	13180	10400	424.66	157.70	12.48	39.01	18.53	18.68	609.33	980
11-Sep	5.7	15030	12630	16460	13020	428.82	150.83	16.28	27.02	23.39	15.38	602.36	1325
14-Sep	5.65	17980	13780	18390	14270								
16-Sep	5.6	19820	15340	20000	15320								
17-Sep						361.67	91.36	9.27	14.91	9.76	6.40	463.71	650
18-Sep	5.8	20900	15820	21410	16310	418.39	107.89	7.88	18.45	18.02	9.94	540.93	850
20-Sep	5.5	22010	16720	22960	17200	391.82	101.32	10.16	23.01	10.26	12.39	510.54	1300
23-Sep	5.55	19210	14710	19480	14930	429.22	82.16	12.03	22.07	12.57	11.35	533.68	775
25-Sep	5.7	18560	13960	18740	14150	311.20	46.57	6.12	14.99	9.36	6.20	375.33	700
27-Sep	5.4	17370	13310	18420	14410	398.66	70.16	9.73	19.08	10.61	9.17	488.47	1500
30-Sep	5.5	17720	13740	19090	14690	344.38	137.10	11.76	17.12	14.07	10.36	460.44	950
2-Oct	5.8	16000	13560	16340	13900	325.46	87.42	17.50	37.04	21.29	16.83	458.49	980
4-Oct	5.8	17810	13540	18640	14420	317.29	81.44	16.43	32.25	22.44	13.36	438.08	646
7-Oct	5.75	20620	16190	21270	16440	280.48	57.43	10.20	15.45	13.33	6.00	356.26	975
Average	5.83	16474	12862	17072	13266								
Std. Dev.	0.16	4106	2916	4163	2973								

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
9-Oct	5.65	17620	13110	18330	14320	317.81	93.80	6.00	25.77	11.50	9.83	430.01	1125
11-Oct	5.8	17750	13490	17640	13620	315.52	99.46	18.24	37.45	24.27	17.92	459.59	1200
14-Oct	5.7	16600	14010	18640	14110	374.23	95.11	20.71	40.46	31.10	24.66	528.43	1487
16-Oct	5.65	20560	21180	21180	16180	367.87	98.55	21.16	38.58	30.34	17.31	517.15	1575
18-Oct	5.8	20240	15400	20300	15820	417.98	118.42	21.46	40.70	25.24	18.74	563.59	1100
22-Oct	5.75	21520	16180	21750	16180	417.72	100.37	26.50	49.75	35.76	20.58	594.86	1200
25-Oct	5.8	19880	14630	21680	15820	352.02	92.84	25.35	45.91	35.00	16.57	507.97	700
28-Oct	6	16250	13620	18400	13950	299.84	69.05	30.46	30.69	39.19	12.72	428.61	700
30-Oct	6	15390	11860	15680	12210	286.24	91.03	27.78	43.37	38.36	16.50	441.41	1260
1-Nov	6	15280	11860	15680	12120	379.52	88.78	28.93	51.20	42.91	28.57	547.54	1150
4-Nov	6	14340	11240	14900	11320	423.81	104.45	33.92	59.72	47.32	28.16	617.38	650
6-Nov	6	15220	12060	15420	12220	441.10	115.64	33.62	68.67	49.33	34.58	654.61	1025
8-Nov	6	14840	11460	15620	12020	436.17	150.17	17.02	169.92	24.80	58.12	735.11	1200
10-Nov	6.2	15450	11730	15980	12310	369.51	73.15	30.56	71.13	47.38	25.63	541.55	825
12-Nov	6.1	14560	11060	15600	12200	374.12	94.95	34.16	71.68	44.72	32.39	599.22	750
15-Nov	6	15960	12520	16020	12720	426.48	82.94	32.07	51.60	38.09	25.63	588.78	500
Average	5.93	17221	12984	17696	13386								
Std. Dev.	0.14	2391	1604	2427	1579								

Table A5 contd.

Run 3

Date	pH	TSS	TVSS	YS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
19-Nov	5.85	18540	14420	18980	14520	355.99	105.21	23.73	22.68	25.73	17.21	488.85	800
22-Nov	5.7	19740	14900	20980	15780	416.35	115.61	25.76	24.3	31.77	19.76	575.26	900
25-Nov	5.7	25960	20160	26560	20320	358.97	129.79	26.31	15.94	33.63	10.13	519.55	1100
27-Nov	5.9	20880	20780	27540	21160	345.15	143.05	31.02	14.07	39.02	6.25	520.57	850
29-Nov	5.9	27860	21920	28360	22080	293.33	120.19	24.01	12.69	31.89	6.72	439.25	950
2-Dec	5.65	22500	21700	27120	21440	267.09	133.61	22.14	13.43	30.79	6.52	422.45	800
4-Dec	5.9	25860	20420	28160	21100	265.48	144.22	14.8	10.8	26.46	5.69	419.67	800
6-Dec	5.6	28020	20740	29960	22800	255.77	140.39	11.72	5.34	20.64	3.12	396.19	750
9-Dec	5.7	27120	20760	28320	22280	248.72	140.4	8.57	7.73	19.28	4.82	398.71	700
11-Dec	5.7	27340	21700	28080	21900	203.65	116.52	7.09	6.24	12.16	3.94	319.24	500
13-Dec	5.7	27100	20320	27280	21180	254.09	135.69	8.34	11.57	13.48	5.68	398.79	600
16-Dec	5.6	24740	20620	26500	21600	243.66	119.25	6.74	4.52	12.52	2.63	357.67	
18-Dec	5.85	27280	22100	28880	22820	221.79	113.75	5.3	2.64	9.3	1.52	328.50	460
21-Dec	5.75	25360	20080	27920	21520	241.03	94.46	5.91	5.13	9.4	1.56	332.16	460
24-Dec	6.3	25700	20120	27940	21720	205.42	93.9	5.09	5.01	9.35	2.3	295.67	500
Average	5.81	25173	20063	26769	20823								
Std. Dev.	0.16	2777	2294	2679	2406								

Run 4

Date	pH	TSS	TVSS	YS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
27-Dec	6.15	25960	21100	28200	22360	306.35	154.61	15.8	11.66	20.2	7.71	488.10	780
30-Dec	6.05	25540	21100	27420	21480	385.9	150.25	18.66	6.57	23.93	6.41	545.20	630
1-Jan	6.2	25160	19480	27220	20560	385.72	137.24	17.44	7.56	22.55	5.72	531.52	780
4-Jan	6.2	23080	17640	26110	20310	352.48	135.96	17.23	6.48	23.35	6.01	498.36	700
6-Jan	6.25	20700	15440	21380	16020	395.62	119.34	16.96	7.97	24.52	5.59	527.84	750
8-Jan	5.45	22040	16220	23340	17440	379.09	121.56	16.26	5.926	22.92	5.04	510.01	600
11-Jan	5.5	22160	16700	23300	17660	338.7	129.86	23.77	17.21	37.03	6.46	498.43	650
13-Jan	5.6	20720	14400	21740	15800	312.15	116.06	15.65	10.18	16.03	6.49	440.20	600
15-Jan	6.5	20120	13840	21540	14580	338.95	126.32	13.87	16.66	23.82	13.62	488.00	900
22-Jan	6	18220	12320	20710	13560	378.44	124.4	11.29	14.46	22.56	11.07	515.41	
6-Feb	6.5	16950	11640	18320	12250	505.65	135.94	30	27.58	46.64	12.07	691.69	780
19-Feb	6.15	14800	10500	15230	11250	404.36	119.39	14.64	20.76	16.65	9.23	542.44	700
22-Feb	6.3	12500	8400	13350	9200	432.67	129.17	17.16	23.18	20.89	11.37	584.66	1100
24-Feb	6.25	11500	8200	12650	8950	315.69	64.79	13.27	6.46	14.44	53.69	439.96	1050
26-Feb	6.2	12650	9250	13650	9700	396.14	96.89	11.58	12.79	14.45	6.65	504.33	780
28-Feb	6.3	11900	8500	12300	8750	379.16	93.37	11.54	6.66	13.12	4.47	479.56	740
3-Mar	6.3	10900	7600	11200	8100	363.49	71.28	8.33	9.54	10.74	4.44	442.84	950
5-Mar	6.2	10350	7660	11720	8730	355.65	76.85	6.96	6.41	9.03	4.23	439.93	700
7-Mar	6.3	10450	7950	11320	8810	322.69	85.62	6.77	6.36	7.73	3.3	408.08	700
10-Mar	6.8	10450	7900	11100	8750	385.35	123.49	10.73	13.65	14.43	5.05	514.32	880

Table A5 contd.

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
12-Mar	6.4	11200	8450	11800	9020	398.03	128.82	10.18	16.6	15.28	5.46	533.72	680
15-Mar	6.5	11450	8390	11990	9210	396.41	125.95	15.71	17.32	22.68	12.05	542.38	620
17-Mar	6.5	11750	8200	12350	8600	394.56	128.91	13.85	15.2	18.46	5.37	533.70	620
19-Mar	6.5	10850	6300	11300	8720	385.68	125.46	13.07	6.62	24.72	5.46	520.92	600
Average	6.21	18308	12085	17480	12900								
Std. Dev.	0.32	5647	4604	6169	4842								

Run 5

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
25-Mar	6.45	10150	7500	10450	6900	189.57	69.7	9.55	7.12	18.11	3.85	270.68	420
27-Mar	6.5	8200	6500	9100	7150	220.9	81.6	10.85	9.72	20	3.07	315.16	500
29-Mar	5.5	8650	6250	8500	6850	176.62	53.55	10.22	9.63	20.91	2.77	247.97	500
1-Apr	6.45	8050	5950	8300	6150	243.22	75.33	10.15	9.5	19.13	6.63	333.31	500
3-Apr	6.4	8750	6150	9200	6550	282.72	68.89	9.96	6.48	20.78	6.17	368.60	720
5-Apr	6.45	8050	6150	8150	6300	272.82	95.04	9.36	8.16	17.78	3.29	374.61	540
7-Apr	6.45	9550	6500	10150	7450	251.97	76.73	6.06	5.9	13.675	3.27	334.26	680
9-Apr	6.65	10200	6450	10700	7500	181.91	61.63	6.36	5	16.32	3.97	253.30	580
12-Apr	6.45	9900	7050	10150	7850	200.12	56.38	12.94	4.36	16.55	4.92	270.61	620
14-Apr	6.3	9900	6550	10800	7000	171.35	55.03	7.68	6.25	13.62	4.91	236.71	590
16-Apr	6.4	10050	7350	11750	7900	142.11	39.1	5.92	3.77	10.93	2.95	188.62	720
18-Apr	6.45	11550	7700	12100	8200	182.84	63.78	7.21	3.43	45.24	5.18	271.85	500
20-Apr	6.45	9500	7850	10000	7950	173.17	52.85	7	3.31	12.45	3.49	232.75	580
22-Apr	6.4	11450	8400	12300	8950	163.8	42.3	6.45	4.06	11.73	5.04	215.38	580
24-Apr	6.3	10000	7850	11050	8250	163.84	51.1	6.49	3.49	14.36	6.56	224.70	500
Average	6.37	9597	6920	10167	7530								
Std. Dev.	0.25	1098	741	1324	868								

Table A6 contd.

Run 3

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
19-Nov	4.6	1340	1160	2120	2160	580.59	102.71	9.1	110.39	15.19	58.17	767.98	1300
22-Nov	4.45	1940	1560	3120	2160	557.28	101.39	12.59	99.51	16.28	49.94	755.47	1300
25-Nov	4.7	2420	2180	332	2660	449.46	102.71	12.64	90.45	14.82	31.97	631.02	1100
27-Nov	4.5	1490	1290	2220	1720	442.6	109.34	15.64	101.92	15.9	31.29	639.65	1200
29-Nov	4.5	1260	960	2200	1660	449.77	121.56	14.54	222.55	14.01	54.75	751.21	1500
2-Dec	4.3	700	600	1660	1300	488.23	124.7	14.78	314.81	13.36	66.46	861.82	1400
4-Dec	4.4	860	700	1880	1370	589.31	182.57	20.28	472.91	17.07	177.15	1182.67	1900
6-Dec	4.05	960	920	1970	1450	483.21	133.74	16.17	299.53	13.32	76.16	659.72	1400
9-Dec	4.2	1120	960	2050	1460	611.32	136.76	14.51	290.44	9.81	72.09	979.19	1500
11-Dec	4.2	620	460	1460	960	568.79	122.75	11.63	204.79	8.01	55.65	654.24	1050
13-Dec	4.3	730	660	1710	1200	748.63	160.32	17.08	269.56	11.63	68.1	1122.18	950
16-Dec	4.5	660	780	1870	1360	532.11	94.8	11.41	141.41	7.92	28.7	735.32	1200
18-Dec	4.65	740	580	1520	1100	529.93	86.25	13.33	180.45	9.74	27.35	754.36	1050
21-Dec	4.7	570	460	1520	1160	581.31	92.75	13.1	216.23	11.16	32.98	840.81	1050
24-Dec	4.65	570	400	1240	960	507.66	74.63	11.71	188.1	12.01	25.01	726.67	1025
Average	4.45	1065	809	1792	1515								
Std. Dev	0.20	534	476	601	486								

Run 4

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
27-Dec	5	1000	860	2260	1560	670.37	139.88	20.63	263.15	17.76	47.4	1030.16	1700
30-Dec	5.05	640	620	1640	1560	662.54	164.4	22.08	229.75	16.66	48.72	1007.05	1300
1-Jan	5.05	640	540	1740	1340	527.9	147.34	21.05	157.33	17.42	37.5	802.22	1150
4-Jan	5.1	670	500	1750	1260	575.44	144.39	23.09	177.92	19.43	43.1	867.26	1250
6-Jan	5.05	640	660	2000	1440	338.88	108.17	27.1	120.8	23.89	30.48	559.09	850
8-Jan	4.6	640	500	2000	1460	467.81	90.49	16.59	106.42	20.53	23.91	653.13	650
11-Jan	4.65	700	620	1740	1220	488.74	93.48	17.91	122.81	21.14	25.15	688.30	1100
13-Jan	4	630	590	1940	1520	510.77	131.3	13.32	152.94	15.18	37.93	762.66	1050
15-Jan	4.5	740	570	1800	1340	558.56	134.76	12.28	180.8	15.74	45.49	822.70	1250
22-Jan	5.1	1120	1020	2220	1740	487.52	125.64	16.04	194.63	25.66	56.72	782.26	1250
8-Feb	4.3	1100	860	1740	1240	1361.2	232.72	35.116	336.24	39.78	78.25	1872.81	2400
19-Feb	4.2	1200	1250	2250	1620	1517.48	377.15	15.91	482.65	17.52	155.57	2267.41	2900
22-Feb	4.1	1800	1350	3100	2450	1874.96	360.55	14.69	745.33	12.1	185.31	2792.18	4500
24-Feb	4	1550	1250	2750	2000	1521	271.45	16.16	710.44	10.7	154.67	2335.57	3700
26-Feb	3.9	2050	1850	3010	2550	1640.98	271.26	14.24	449.01	6.68	119.29	2252.99	3200
28-Feb	4	1800	1600	2650	2200	1184.27	20.45	14.33	240.84	6.54	78.19	1424.69	2050
3-Mar	4.7	1900	1400	2600	1900	971.2	154.33	12.07	54.51	5.2	20.33	1157.71	1600
5-Mar	5.5	1300	975	1850	1550	696.88	108.08	11.8	10.23	4.63	6.73	806.69	1050
7-Mar	4.7	1050	850	2300	1800	784.27	112.23	10.97	5.76	5.75	3.25	872.66	1050
10-Mar	5.6	1250	900	2200	1650	734.69	96.12	11.8	4.25	7.67	2.22	829.98	1050

Table A6 contd.

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
12-Mar	6.4	1150	900	1850	1450	730.27	80.21	18.38	4.17	15.07	3.72	820.87	1100
15-Mar	6.7	1050	850	1850	1200	637.55	87.99	23.13	27.31	19.46	9.65	700.95	950
17-Mar	6.55	1150	850	2050	1600	801.87	111.3	25.32	33.2	21.49	11.12	951.89	1150
19-Mar	6.7	1200	950	1800	1300	749.38	97.08	20.22	22.32	15.98	5.46	870.31	1150
Average	4.99	1157	935	2141	1633								
Std. Dev	0.87	402	359	408	371								

Run 5

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
25-Mar	5.8	1350	1200	1800	1350	2225.28	145.52	30.48	158.93	22	31.22	2504.84	1550
27-Mar	4.3	1200	900	1850	1450	848.27	81.6	10.85	9.72	20	3.08	942.53	1250
29-Mar	5.4	1000	850	2350	1850	755.53	132.46	25.19	102.48	18.09	31.64	980.08	1150
1-Apr	6.1	900	800	1500	1050	782.97	136	18.15	25.97	13.38	9.59	916.30	1050
3-Apr	5.8	1150	1000	1800	1250	662.71	68.89	9.98	8.47	20.78	8.17	748.58	1300
5-Apr	6.8	900	700	1650	1350	595.98	90.04	9.34	8.12	17.78	3.21	693.78	880
7-Apr	6.5	1400	900	2000	1300	607.95	79.72	18.59	16.27	15.1	5.43	707.56	950
9-Apr	6.6	1150	900	2300	1800	552.29	68.53	20.29	27.01	19.75	7.5	656.56	880
12-Apr	6.6	1150	900	1850	1250	423.65	53.61	20.42	22.63	16.93	6.92	511.03	880
14-Apr	4.7	750	500	2000	1500	558.38	80.1	22.36	68.68	21.17	14.63	708.96	950
16-Apr	6.4	1350	1050	1900	1850	453.82	72.25	22.74	29.93	20.88	10.45	588.99	880
18-Apr	5.4	900	850	1750	1550	493.83	89.33	22.81	34.36	20.5	15.7	627.09	670
20-Apr	6.45	1250	950	1950	1550	547.42	75.71	20.98	3.65	19.24	3.03	639.17	610
22-Apr	6.7	800	800	1250	900	471.09	87.12	21.19	9.71	22.37	8.56	581.53	620
24-Apr	5.7	700	500	1800	1350	531.81	133.51	20.85	23.74	22.72	11.23	691.36	880
Average	5.92	1063	827	1830	1410								
Std. Dev	0.76	229	205	286	256								

Table A7: Effluent characteristics for reactor 2

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
25-Aug	5.3												
26-Aug	5.3			1340	980								
30-Aug	5.3			1920	1320								
3-Sep	5.25												
5-Sep	5.4			4740	3700								925
9-Sep	5.4	620	580	2220	1540								1575
11-Sep	5.35			2200	1580								725
14-Sep	5.4	680	630	1530	1030								725
16-Sep	5.6												
17-Sep													375
18-Sep	5.6	1580	1120	2620	1830								525
20-Sep	5.5	1280	1000	2380	1700								750
23-Sep	5.7	2680	2000	3280	2740								750
25-Sep	5.9	4000	3530	6480	5520								770
27-Sep	5.9	5660	4500	7740	6200	398.04	72.37	9.52	18.59	9.60	9.65	484.73	900
30-Sep	6	1450	1150	1840	1450	492.52	92.48	14.31	28.61	17.14	18.44	614.46	1175
2-Oct	5.9	1320	1070	2140	1550	378.98	101.92	17.77	41.18	22.56	19.19	523.97	1100
4-Oct	5.85	920	740	2520	1720	338.00	86.44	13.70	33.88	20.15	12.52	459.08	1350
7-Oct	5.8	4040	3020	4800	3360	353.19	81.50	11.11	20.85	13.29	6.78	465.02	1550
Average	5.58	2295	1758	3187	2415								
Std. Dev	0.26	1706	1335	1887	1610								

Run 2

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
9-Oct	5.9	1670	1360	2480	1900	902.47	288.50	21.83	75.97	28.33	24.18	1210.97	1300
11-Oct	5.9	3070	2380	4100	3080	381.25	117.91	17.40	42.03	24.98	21.78	540.70	1300
14-Oct	6	1080	700	1640	1080	415.32	131.57	25.85	52.60	37.55	24.23	611.07	1200
16-Oct	5.9	580		1380		338.74	98.27	18.92	30.81	24.94	18.28	477.81	1700
18-Oct	6	5400	4030	6100	4680	443.52	130.45	20.96	46.19	25.84	18.03	621.04	1125
22-Oct	5.9	2080	1500	2810	1920	515.78	135.99	28.85	59.15	41.21	21.77	725.24	1300
25-Oct	6.1	3410	2620	3520	2560	362.87	102.88	27.04	42.21	40.53	17.80	532.27	850
28-Oct	6	3810	2820	4700	2760	325.34	84.99	24.58	37.04	34.84	13.63	470.57	700
30-Oct	6.25	3520	2780	4280	3240	377.28	136.21	32.16	55.84	47.43	20.44	593.15	1425
1-Nov	6.2	2360	1880	2880	1980	408.58	115.35	32.44	63.85	48.85	27.36	613.31	1100
4-Nov	6.3	3400	2880	4180	3280	427.65	133.25	18.51	171.59	26.98	40.81	678.53	850
6-Nov	6.3	3260	2650	3880	2980	507.55	149.88	36.29	79.81	53.78	35.74	758.03	1125
8-Nov	6.5	3300	2620	4020	3240	477.89	134.33	37.57	79.92	53.58	38.20	717.39	1175
10-Nov	6.4	3140	2340	3820	2760	470.59	116.79	38.79	74.29	50.58	36.74	692.34	1100
12-Nov	6.3	3120	2380	4220	2700	474.24	126.00	35.71	84.24	51.70	34.27	705.82	975
15-Nov	6.35	4280	3340	4880	3720	461.45	92.94	26.16	54.84	33.55	23.14	625.03	575
Average	6.14	2984	2408	3650	2789								
Std. Dev	0.20	1200	816	1221	863								

Table A7 contd.

Run 3

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
19-Nov	6.05	880	740	1920	1500	481.29	153.75	28.15	34.51	34.32	24.11	685.77	1000
22-Nov	6	1280	1000	2380	1480	354.59	151.19	27.13	25.94	28.55	23.35	545.98	600
25-Nov	6.05	620	640	1780	1220	366.14	138.44	27.31	23.93	35.09	12.67	551.20	1000
27-Nov	6.1	780	700	1720	1380	234.24	88.89	18.35	11.18	21.62	6.28	351.18	600
29-Nov	6.1	1100	840	2080	1580	321.4	137.23	22.43	18.89	29.67	7.93	491.37	950
2-Dec	6.3	780	680	1720	1320	288.31	14.44	18.24	14.89	16.89	6.72	343.44	600
4-Dec	6.25	640	480	1770	1280	234.21	122.56	15.02	12.18	23.22	5.38	375.63	700
6-Dec	6.3	1180	820	1980	1430	114.8	59.15	7.12	9.03	12.01	3.44	185.21	600
9-Dec	5.9	1310	900	2030	1350	227.11	133.74	9.21	7.94	18.23	4.82	384.33	700
11-Dec	6.3	680	440	1530	1040	258.87	172.89	11.54	9.19	19.99	5.32	432.82	900
13-Dec	6.25	630	630	1620	1050	277.48	165.19	10.59	10.73	17.82	5.16	443.87	500
16-Dec	6.35	750	580	1680	1140	238.48	131.87	7.44	6.28	12.68	3.35	367.50	
18-Dec	6.2	680	440	1500	1180	241	116.71	6.19	9.01	11.88	3.07	356.95	480
21-Dec	6.2	680	480	1620	1040	228.33	97.84	6.02	6.33	10.04	1.91	323.94	480
24-Dec	6.3	500	440	1100	680	174.311	79.05	5.63	6.05	9.52	2.02	255.73	500
Average	6.18	854	650	1759	1255								
Std. Dev	0.13	243	183	297	198								

Run 4

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
27-Dec	6.9	800	440	1500	1000	296.58	157.91	15.58	14.18	23.65	8.13	486.08	700
30-Dec	6.8	1020	780	1800	1150	331.83	180.9	21	15.17	27.86	7.5	517.21	780
1-Jan	6.8	880	680	1680	1180	307.85	135.73	20.14	16.41	25.92	7.1	470.90	600
4-Jan	7	900	670	1640	1080	307.38	141.33	17.68	13.18	28.63	6.33	470.37	180
6-Jan	6.9	1240	940	1980	1120	176.71	59.23	10.79	12.88	16.38	3.78	257.02	350
8-Jan	6.95	980	620	1780	1280	222.08	101.27	15.45	8.22	23.25	4.68	344.40	650
11-Jan	6.8	1400	980	2380	1340	228.63	113.55	18.77	11.85	28.71	5.28	388.58	850
13-Jan	6.85	1780	1180	2200	1540	295.48	145.55	14.79	20.1	27.21	12.08	482.37	800
15-Jan	7	1580	920	2330	1580	331.81	142.01	14.58	19.15	28.67	14.23	485.84	1000
22-Jan	6.9	1740	1050	2420	1650	372.09	137.82	12.49	22.75	24.91	13.01	529.75	
6-Feb	7.3	1940	1360	3250	2640	475.83	153.46	29.32	29.58	50.84	13.18	688.49	780
19-Feb	7.1	2800	2050	3400	2500	351.24	133.97	15.1	28.28	28.88	13.23	514.88	700
22-Feb	7.1	1450	1000	2200	1450	324.49	108.83	13.53	16.87	15	6.15	448.98	720
24-Feb	6.9	2250	1550	3300	2800	309.88	98.54	9.78	10.28	13.63	5.39	417.55	780
26-Feb	7.2	3500	2450	4000	2650	371.57	101.91	13.08	18.1	16.18	7.13	492.79	780
29-Feb	7	2800	2050	3250	2250	323.22	101.08	10.43	10.47	12.57	5.92	433.58	650
3-Mar	6.8	1700	1170	2450	1600	296.37	68.88	7.47	9.53	7.79	4.58	372.38	900
5-Mar	6.7	3950	2700	4200	3350	201.21	59.78	7.41	6.78	8.11	3.47	288.88	480
7-Mar	6.9	2350	1900	2900	2150	253.18	83.5	7.1	7.26	6.9	3.43	339.41	600
10-Mar	7.3	1850	1350	2500	1600	308.12	108.23	8.64	12.15	12.22	4.38	416.84	650

Table A7 contd.

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
12-Mar	7.1	2350	1650	2700	1950	254.38	110.72	8.05	7.85	13.97	4.8	388.58	680
15-Mar	7.1	2400	1750	2700	2050	310.41	110.14	11.69	14.48	17.75	6.45	432.48	620
17-Mar	7.15	2050	1650	2850	2050	302.28	114.61	11.55	13.72	17.75	5.93	427.05	640
19-Mar	7.2	2000	1450	2800	2050	335.34	107.07	10.21	13.15	17.63	6.28	452.80	720
Average	6.99	1888	1348	2583	1834								
Std. Dev	0.17	818	594	718	628								

Run 5

Date	pH	TSS	TVSS	TS	TVS	Acetic	Propionic	I-Butyric	N-Butyric	I-Valeric	N-Valeric	Total VFA	S-COD
25-Mar	7.5	1450	1100	2100	1800	181.21	71.82	8.9	8.7	7.2	4.41	238.72	420
27-Mar	7.7	1800	1550	3100	2300	167.75	71.85	8.88	10.52	19.51	5.04	254.12	480
29-Mar	7.5	2050	1250	2900	2000	160.42	65.15	9.67	7.97	20.88	4.33	240.50	480
1-Apr	6.5	2500	1800	3050	2000	238.05	82.99	9.39	10.39	20.21	5.12	332.24	500
3-Apr	7.4	1500	950	2050	1350	258.91	87.79	8.88	9.83	22.89	7.88	381.48	720
5-Apr	8	1400	900	1650	1050	239.51	96.45	8.59	8.29	19.31	3.12	343.01	580
7-Apr	7.6	2800	1400	3000	1750	234.11	75.49	8.43	8	14.25	3.45	317.40	500
9-Apr	7.9	1750	1050	3050	2200	265.16	104.52	14.16	7.87	29.57	5.8	388.28	620
12-Apr	7.8	1550	875	2100	1250	138.57	54.32	6.69	4.75	14.08	3.59	201.28	500
14-Apr	7.6	1950	1100	3050	1950	144.44	54.42	8.01	8.05	14.61	4.8	211.27	600
16-Apr	7.4	2350	1650	3250	2400	92.4	39.78	5.58	3.71	10.99	2.41	139.10	500
18-Apr	7.4	2100	1450	2900	1950	100.3	52.28	5.92	4.19	13.22	4.37	180.23	380
20-Apr	7.25	3350	2200	3650	2300	84.88	44.37	5.8	2.79	11.69	3.42	135.87	480
22-Apr	7.4	1400	900	1900	1050	100.42	41.19	5.54	3.51	11.57	4.69	149.81	350
24-Apr	7.1	2800	1850	3050	1900	95.71	41.91	5.52	3.33	12.19	5.31	146.28	480
Average	7.47	2043	1335	2720	1803								
Std. Dev	0.36	593	408	592	449								

Table A8: SRT values of the two systems (days)

Run 1		
Date	Reactor 1	Reactor 2
9-Sep	9.1	13.1
14-Sep	10.2	11.3
20-Sep	8.8	12.5
23-Sep	4.9	5.5
25-Sep	3.3	3.0
27-Sep	5.7	2.2
30-Sep	7.8	9.0
2-Oct	11.1	9.5
4-Oct	13.0	13.7
7-Oct	7.7	4.0
Average	8.2	8.4
Std. Dev.	2.95	4.38

Run 4		
Date	Reactor 1	Reactor 2
27-Dec	8.56	8.99
30-Dec	9.13	10.41
1-Jan	10.83	11.07
4-Jan	13.12	9.87
6-Jan	10.02	12.32
8-Jan	13.34	19.62
11-Jan	9.59	12.78
13-Jan	11.35	9.15
15-Jan	11.74	11.28
22-Jan	7.80	8.80
8-Feb	7.80	6.53
19-Feb	6.75	3.84
22-Feb	8.78	6.30
24-Feb	8.82	3.97
26-Feb	8.82	3.97
28-Feb	5.33	2.83
3-Mar	5.37	3.11
5-Mar	5.78	4.87
7-Mar	9.4	3.14
10-Mar	8.8	4.39
12-Mar	8.5	3.84
15-Mar	9.3	3.58
17-Mar	8.3	3.73
19-Mar	8.0	4.29
Average	8.97	7.19
Std. Dev.	2.09	4.24

Run 2		
Date	Reactor 1	Reactor 2
9-Oct	8.6	7.3
11-Oct	5.3	4.3
14-Oct	16.2	15.0
18-Oct	13.0	2.9
22-Oct	8.9	8.1
25-Oct	11.1	4.3
28-Oct	3.2	4.0
30-Oct	6.2	3.2
1-Nov	8.8	4.8
4-Nov	6.2	2.8
6-Nov	5.4	3.4
8-Nov	2.7	3.3
10-Nov	4.4	3.8
12-Nov	7.3	3.5
15-Nov	6.5	2.8
Average	7.8	6.3
Std. Dev.	3.66	3.20

Run 5		
Date	Reactor 1	Reactor 2
25-Mar	8.44	5.11
27-Mar	10.33	3.14
29-Mar	10.37	3.75
1-Apr	14.50	2.48
3-Apr	8.81	4.85
5-Apr	11.41	5.12
7-Apr	8.83	3.48
9-Apr	11.21	4.61
12-Apr	10.50	6.04
14-Apr	18.07	4.47
16-Apr	9.00	3.34
18-Apr	7.98	3.98
20-Apr	7.7	7.88
22-Apr	12.9	12.87
24-Apr	14.7	14.70
Average	10.98	5.71
Std. Dev.	2.94	3.53

Run 3		
Date	Reactor 1	Reactor 2
19-Nov	7.4	7.8
22-Nov	5.4	8.1
25-Nov	3.4	10.2
27-Nov	7.1	9.6
29-Nov	9.3	9.1
2-Dec	7.9	8.7
4-Dec	11.2	10.6
6-Dec	10.1	6.3
9-Dec	8.7	5.8
11-Dec	16.2	12.3
13-Dec	9.6	8.1
16-Dec	8.8	9.3
18-Dec	13.39	9.42
21-Dec	16.19	8.18
24-Dec	17.51	8.57
Average	10.1	8.81
Std. Dev.	4.08	1.62

Table A9: Net VFA production and production rates

Run 1

System 1						System 2				
Date	Influent VFAs	Reactor VFAs	Reactor VSS	Net production	Production rate	Influent VFAs	Reactor VFAs	Reactor VSS	Net production	Production rate
25-Aug	380.07	529.49	18800	149.422	0.011	380.07	400.28	8620	20.207	0.003
28-Aug	275.60	702.45	16120	426.851	0.035	275.60	379.51	4760	103.913	0.029
30-Aug	341.33	1043.68	12380	702.355	0.076	341.33	770.02	11800	428.696	0.048
3-Sep	271.88	573.53	11640	301.646	0.035	271.88	647.75	11940	375.869	0.042
5-Sep	197.11	612.73	10550	415.627	0.053	197.11	1330.82	10970	1133.713	0.138
9-Sep	140.15	418.99	8270	278.836	0.045	140.15	394.57	10150	254.419	0.033
11-Sep	275.61	386.84	8320	111.231	0.018	275.61	609.33	12630	333.722	0.035
14-Sep	152.59	429.18	11120	276.597	0.033	152.59	602.36	13760	449.778	0.044
17-Sep	193.33	447.97	12000	254.836	0.028	193.33	463.71	15340	270.372	0.024
18-Sep	159.42	479.11	11910	319.697	0.036	159.42	540.93	15820	381.514	0.032
20-Sep	241.07	474.90	13450	233.824	0.023	241.07	510.54	16720	269.464	0.021
23-Sep	211.88	509.89	13770	298.002	0.029	211.88	533.68	14710	321.799	0.029
25-Sep	211.79	447.41	12310	235.612	0.028	211.79	375.33	13960	163.539	0.016
27-Sep	227.39	514.99	13070	287.595	0.029	227.39	488.47	13310	261.073	0.026
30-Sep	166.98	466.72	12260	299.741	0.033	166.98	490.44	13740	323.460	0.031
2-Oct	232.97	481.05	11610	248.076	0.028	232.97	456.49	13560	223.525	0.022
4-Oct	239.88	435.61	12460	195.726	0.021	239.88	438.08	13540	198.193	0.020
7-Oct	85.24	417.30	11420	332.054	0.039	85.24	356.26	16190	271.022	0.022
Average				284.12	0.033				272.68	0.034
Std. Dev				53.03	0.014				61.00	0.027

Run 2

System 1						System 2				
Date	Influent VFAs	Reactor VFAs	Reactor VSS	Net production	Production rate	Influent VFAs	Reactor VFAs	Reactor VSS	Net production	Production rate
9-Oct	197.24	430.42	10950	233.178	0.028	183.83	430.01	13110	246.184	0.025
11-Oct	187.78	454.51	8920	266.733	0.040	164.22	459.56	13480	295.343	0.029
14-Oct	186.06	444.51	9480	258.446	0.036	150.08	526.43	14010	376.348	0.036
16-Oct	128.52	427.18	10130	298.659	0.039	162.14	517.15	15400	355.010	0.031
18-Oct	140.99	541.23	10130	400.246	0.053	166.82	583.56	15400	416.740	0.036
22-Oct	155.90	584.08	11760	428.176	0.049	186.56	584.86	16180	398.296	0.033
25-Oct	209.57	915.80	11520	706.232	0.082	198.12	507.97	14930	309.848	0.028
28-Oct	149.25	871.88	7640	722.635	0.126	172.63	428.61	13820	255.979	0.025
30-Oct	237.15	514.68	8000	277.524	0.046	242.19	441.41	11860	199.216	0.022
1-Nov	296.32	678.56	9140	382.248	0.056	360.59	547.54	11860	186.955	0.021
4-Nov	350.16	749.58	9980	399.427	0.053	333.92	617.38	11240	283.463	0.034
6-Nov	449.68	942.88	8920	493.196	0.074	412.81	654.81	12080	242.006	0.027
8-Nov	568.45	753.43	7100	184.962	0.035	345.94	735.11	11460	389.168	0.045
10-Nov	576.00	955.15	6060	379.144	0.063	361.65	541.55	11730	179.897	0.020
12-Nov	455.53	880.54	8580	425.006	0.066	360.05	569.22	11060	209.166	0.025
15-Nov	418.42	865.81	11500	447.387	0.052	279.92	588.78	12520	308.861	0.033
Average				393.95	0.057				290.78	0.029
Std. Dev				93.08	0.025				78.75	0.007

Table A9 contd.

Run 3

System 1						System 2				
Date	Influent VFAs	Reactor VFAs	Reactor VSS	Net production	Production rate	Influent VFAs	Reactor VFAs	Reactor VSS	Net production	Production rate
19-Nov	293.31	800.84	11520	507.533	0.035	198.31	498.85	14420	300.536	0.017
22-Nov	291.66	930.81	11180	639.149	0.046	145.76	575.28	14900	429.497	0.023
25-Nov	312.05	749.97	10000	437.920	0.035	162.17	519.55	20160	357.386	0.014
27-Nov	285.33	795.09	12100	509.733	0.034	124.41	520.57	20780	398.159	0.015
29-Nov	318.11	814.12	11950	496.014	0.033	100.97	439.25	21920	338.283	0.012
2-Dec	414.02	833.88	10180	419.840	0.033	97.63	422.45	21700	324.819	0.012
4-Dec	465.27	1017.32	10420	552.051	0.042	59.84	419.67	20420	359.830	0.014
6-Dec	360.87	1065.81	12380	704.937	0.046	48.90	398.19	20740	347.293	0.013
9-Dec	386.29	1079.86	9920	693.567	0.056	14.13	388.71	20760	374.587	0.014
11-Dec	282.88	854.25	10340	571.371	0.044	51.14	319.24	21700	268.094	0.010
13-Dec	304.28	964.68	8840	660.404	0.060	50.71	389.79	20320	339.088	0.013
16-Dec	270.53	757.73	9200	487.204	0.042	48.18	357.87	20820	309.695	0.012
18-Dec	304.03	830.03	10360	525.999	0.041	34.63	326.50	22100	291.869	0.011
21-Dec	350.03	782.24	10580	432.216	0.033	67.09	332.18	20080	265.091	0.011
24-Dec	243.27	739.21	9340	495.843	0.042	60.29	295.87	20120	235.588	0.009
Average				542.26	0.041				329.19	0.013
Std. Dev				93.15	0.008				52.14	0.003

Run 4

System 1						System 2				
Date	Influent VFAs	Reactor VFAs	Reactor VSS	Net production	Production rate	Influent VFAs	Reactor VFAs	Reactor VSS	Net production	Production rate
27-Dec	256.32	1019.17	10040	762.848	0.061	145.59	468.10	21100	322.518	0.012
30-Dec	330.93	961.31	9200	630.381	0.055	171.32	545.20	21100	373.880	0.014
1-Jan	240.87	822.54	9240	581.668	0.050	160.19	531.52	19480	371.325	0.015
4-Jan	239.85	901.05	10080	661.206	0.052	150.75	498.36	17640	347.607	0.016
6-Jan	264.79	920.97	10580	656.175	0.050	212.21	527.84	15440	315.636	0.016
8-Jan	235.76	717.75	10230	481.987	0.038	216.51	510.01	16220	293.492	0.014
11-Jan	260.17	724.04	9580	463.670	0.039	210.13	498.43	16700	288.297	0.014
13-Jan	305.05	884.07	10500	579.017	0.044	246.79	440.20	14400	193.412	0.011
15-Jan	309.44	824.89	10440	515.454	0.039	252.64	488.00	13840	235.358	0.014
22-Jan	319.16	845.30	10610	526.136	0.040	299.93	515.41	12320	215.484	0.014
8-Feb	733.60	1836.88	8940	1103.286	0.099	565.59	691.68	11840	126.093	0.009
19-Feb	609.28	1904.22	11250	1294.941	0.092	441.67	542.44	10500	100.764	0.008
22-Feb	528.27	2841.59	15800	2313.322	0.117	347.97	584.88	8400	236.913	0.023
24-Feb	408.81	2402.63	14700	1993.822	0.109	384.95	439.96	8200	55.012	0.005
26-Feb	192.46	2083.30	13150	1890.847	0.115	349.16	504.33	9250	155.162	0.013
28-Feb	206.24	1582.37	11450	1376.126	0.096	362.88	479.56	8500	116.684	0.011
3-Mar	195.26	1037.51	10800	842.258	0.062	304.48	442.84	7600	138.362	0.015
5-Mar	161.82	897.42	11550	735.595	0.051	259.03	439.93	7860	180.894	0.018
7-Mar	138.61	812.58	10700	673.950	0.050	283.58	408.08	7950	124.518	0.013
10-Mar	178.83	854.68	10550	676.048	0.051	360.62	514.32	7900	153.705	0.016
12-Mar	225.90	852.28	10150	626.378	0.049	356.22	533.72	8450	177.504	0.017
15-Mar	254.65	797.20	10550	542.548	0.041	409.41	542.38	8360	132.967	0.013
17-Mar	284.68	898.42	10550	613.739	0.047	403.73	533.70	8200	129.970	0.013
19-Mar	265.67	919.95	10150	654.280	0.052	322.95	520.92	8300	197.968	0.019
Average				623.53	0.048				207.65	0.014
Std. Dev				98.72	0.007				92.07	0.004

Table A9 contd.

Run 5

Date	System 1					System 2				
	Influent VFAs	Reactor VFAs	Reactor VSS	Net production	Production rate	Influent VFAs	Reactor VFAs	Reactor VSS	Net production	Production rate
25-Mar	496.03	1282.57	13500	766.54	0.047	133.68	270.68	7500	137.00	0.015
27-Mar	330.09	1130.01	12400	799.92	0.052	160.95	315.16	6500	154.21	0.019
29-Mar	335.37	990.53	11750	655.16	0.045	147.51	247.97	6250	100.46	0.013
1-Apr	286.51	889.24	11600	602.73	0.042	182.14	333.31	5950	151.17	0.020
3-Apr	354.00	819.26	11750	485.26	0.032	308.75	368.60	6150	59.85	0.008
5-Apr	346.15	698.74	10650	352.59	0.028	300.55	374.81	6150	74.25	0.010
7-Apr	347.48	679.53	10600	332.07	0.025	306.69	334.26	6500	27.57	0.003
9-Apr	318.55	636.35	13450	317.80	0.019	225.58	253.30	6450	27.72	0.003
12-Apr	212.50	625.39	12600	412.88	0.026	226.07	270.61	7050	44.54	0.005
14-Apr	230.33	694.07	12050	463.75	0.031	201.93	236.71	6550	34.77	0.004
16-Apr	237.38	690.84	12600	453.47	0.029	176.02	188.82	7350	12.80	0.001
18-Apr	255.35	654.36	9050	399.01	0.035	229.56	271.85	7700	42.29	0.004
20-Apr	279.21	655.64	9700	376.43	0.031	199.31	232.75	7650	33.44	0.003
22-Apr	277.19	659.19	10300	382.00	0.030	201.17	215.39	8400	14.22	0.001
24-Apr	318.6	722.93	9800	404.33	0.033	170.68	224.70	7650	53.82	0.006
Average				480.26	0.033				64.54	0.008
Std. Dev				156.93	0.009				48.55	0.006

* All values except production rate are expressed in mg/l
production rates are expressed in mg VFA produced/ mg VSS*day

Table A10: Total COD of the two systems

Date	System 1			System 2		
	Feed 1	Reactor1	Effluent 1	Feed 2	Reactor 2	Effluent 2
9-Sep	5750	11365	3550	5750	16375	3275
11-Sep	5675	13950	1530	5675	21000	3250
14-Sep	7750	16250	2350	7750	20500	1980
20-Sep	6100	19425	1750	6100	27875	2250
27-Sep	6375	20000	1500	6375	22000	1200
7-Oct	6844	18969	3500	6844	28750	5878
14-Oct	6000	15813	3500	6563	20750	3500
22-Oct	6750	16156	2875	6562	27125	2875
25-Oct	3500	17500	2625	5000	24000	4500
1-Nov	7500	19250	2750	7500	22500	3750
8-Nov	10500	15160	5500	6000	24375	5200
15-Nov	13690	18125	2500	5750	21000	5500
22-Nov	9440	17750	2875	7070	21375	2125
29-Nov	11812	18500	3000	9250	32100	3925
16-Dec	9000	13500	3250	3500	31000	1800
24-Dec	8125	12000	1950	4350	35000	1075
6-Jan	11250	16000	2500	3750	26375	2875
13-Jan	6250	12500	2125	2125	27500	2500
19-Feb	7125	13500	2500	4250	24550	2650
5-Mar	8000	13000	3000	6370	19500	4875
12-Mar	10500	14250	2250	5750	14250	3250
7-Apr	5700	13800	2375	4500	9000	3125
16-Apr	6250	17500	2375	4375	7750	2875
24-Apr	6000	10000	2100	4750	9000	3875

* All values in mg/l

Table A 11: Total Ammonia Nitrogen of the two systems

Date	System 1			System 2		
	Feed 1	Reactor1	Effluent 1	Feed 2	Reactor 2	Effluent 2
1-Nov			31		105	83
10-Nov	39	64	53	107	152	125
15-Nov	50	63	33	89	123	107
2-Dec	14.5	18.2	7.7	59	96	75
16-Dec	12	16.4	4.6	39	57	40
24-Dec	1.09	2.4	1.5	32	49	29
6-Jan	8	11	3	78	110	88
13-Jan	9	12	3	78	127	97
19-Feb	35	41	12	109	165	115
12-Mar	44	51	34	104	153	130
7-Apr	23	28	18	67	109	86
24-Apr	1.1	1.8	1.7	29	54	50

* All values in mg/l

Table A 12: TKN of the two systems

Date	System 1			System 2		
	Feed 1	Reactor1	Effluent 1	Feed 2	Reactor 2	Effluent 2
25-Oct	208	777	156	284	956	186
1-Nov	224	597	124	318	741	218
10-Nov	265	433	132	285	930	412
15-Nov	227	608	142	279	791	338
2-Dec	160	417	102	191	936	187
16-Dec	80	309	77	131	814	118
24-Dec	126	310	71	143	793	95
6-Jan	175	428	130	225	708	169
13-Jan	170	397	101	260	705	205
19-Feb	205	422	187	325	704	288
12-Mar	199	373	136	281	597	278
7-Apr	86	320	105	190	391	213
24-Apr	105	352	121	248	485	287

* All values in mg/l

Table A 13: TKN Balance

Runs	Reactor 1		Reactor 2	
	IN (mg/day)	OUT (mg/day)	IN (mg/day)	OUT (mg/day)
2	618	402	782	816
3	195	147	248	248
4	299	252	437	422
5	154	196	350	412

APPENDIX B

Various Conversion factors

Conversion Factors for VFAs

Parameter	Molecular Weight	mg VFA/mg HAc
Acetic	60.05	1.000
Propionic	74.08	0.817
Butyric	88.10	0.682
Valeric	102.13	0.588

Conversion Factors for CODs

Parameter	Conversion Factor	Basis
Acetic Acid COD	1.067 mg/mg Acid	Acetic Acid
Propionic Acid COD	1.514 mg/mg Acid	Propionic Acid
Butyric Acid COD	1.818 mg/mg Acid	Butyric Acid
Valeric Acid COD	2.039 mg/mg Acid	Valeric Acid