

**DEVELOPING A MECHANISTIC UNDERSTANDING AND
OPTIMIZATION OF THE CANNIBAL PROCESS
PHASE II**

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Thesis submitted to the faculty of
The Virginia Polytechnic Institute and State University
in partial fulfillment of the requirement for the degree of

**Master of Science
in
Environmental Engineering**

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August 29, 2006
Blacksburg, Virginia

Key words:
Activated sludge, Hydraulic Retention Time (HRT), Interchange Rate, Solids Retention
Time (SRT), Solids Destruction, Anaerobic Bioreactor

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ABSTRACT

The Cannibal™ system, comprised of an activated sludge process integrated with a side stream anaerobic bioreactor, is capable of reducing excess sludge up to 60% compared to the conventional activated sludge process. The hydraulic retention time (HRT) in the Cannibal bioreactor and the interchange rate (the percent of sludge by mass interchanged between the activated sludge system and the bioreactor on daily basis) are the two important operational parameters in the optimization of the Cannibal process. This research was designed to investigate the effect of the Cannibal bioreactor hydraulic retention time and the interchange rate on the solids destruction in the system. The first phase of this study has looked at the effect of three different HRTs, 5 day, 7 day and 10 day. The interchange rate during phase I was 10%. The results showed that the 7 day HRT can be recommended as the minimum retention period for the Cannibal process. The 5 day HRT Cannibal system had settling problems and higher VFA production. The protein and polysaccharide tests showed that the Cannibal bioreactor is primarily involved in the release of biopolymers which are degraded in the aerobic environment.

The second part of this study focused on the effect of the interchange rate (IR) on the solids destruction in the system. The interchange rates that were applied in the system were 15%, 10%, 7%, 5% and 4%. The HRT in the Cannibal bioreactor was 7 day. The results showed that the 10% interchange rate gave maximum solids destruction than the other interchange rates. This implies that 10% is an optimum IR for the Cannibal system. Apart from higher solids wastage, the 4% and 5% IR Cannibal systems had higher volatile fatty acid production.

DEDICATION

In the ever-loving memory of my beloved grandmother, Ammani

ACKNOWLEDGEMENT

I sincerely acknowledge the valuable guidance and support I have received from Dr. John Novak throughout this research work and my graduate study. I am grateful to him for funding me and keeping me financially stable throughout my study at Virginia Tech. He was too patient in dealing with me in my hard times and without him I would have never been able to continue my research. I would also like to thank my committee members, Dr. Clifford Randall and Dr. Gregory Boardman, for their inputs and timely guidance.

This project was funded by US Filter/ Envirex. Their support for this research is greatly appreciated.

I would like to thank Julie Petruska and Jody Smiley for their instructions and patience for my laboratory work. Betty Wingate and Sherry Burke have been most co-operative and supportive in administrative issues and I duly acknowledge their help. I thank fellow researchers Dong Hyun, Chul Park and Christopher Muller for taking their time to teach me several analysis techniques and Fransisco Cubas, Yuan Fang, Christopher Wilson and Passkorn Khanthongthip for their help in the lab.

I am very grateful to my sister and brother-in-law for trusting me and providing an opportunity to do my graduate studies. I thank them for the financial and moral support they gave, to pursue my dreams. I sincerely thank my husband for his confidence in me and his timely inspirational guidance whenever I needed them. His encouragement has greatly helped me in my tough times. I am always thankful to my mother for her unconditional love throughout my life and for being my role model. I would like to express sincere gratitude to my parents-in-law for motivating me to study further. Last but not the least; I will always remember my grandmother for her sincere prayers.

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CHAPTER I:

LITERATURE REVIEW

INTRODUCTION:

Activated sludge process is employed as the major biological treatment method for municipal and industrial wastewaters. The process in which an activated mass of microorganisms is capable of stabilizing the organic materials in the wastewater is called the activated sludge process (Metcalf and Eddy, 2003). Activated sludge is an agglomeration of organic and inorganic particles bound together in a matrix of microorganisms, exocellular polymers and cations.

The basic activated-sludge system consists of a primary clarifier, aeration basin that aids biological processes and a secondary clarifier with a recycle system. The biological process involves the transformation of dissolved and suspended organic matter to biomass and evolved gases. Engineering innovation and technological advances have enhanced the performance of activated sludge process by incorporating nitrification and biological nitrogen and phosphorous removal mechanisms.

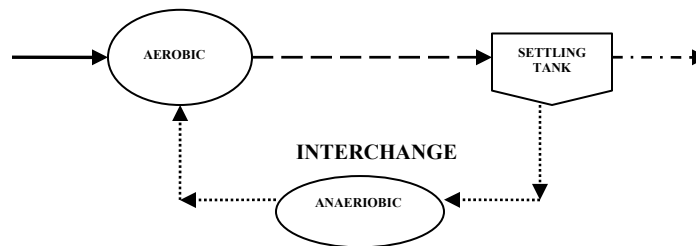
One main challenge that evolves from this process is the generation of solids waste, namely excess sludge. The treatment and disposal of the excess sludge accounts for 30-60% of the total operational cost (Horan, 1990). An alternative ideal approach would aim at reducing the excess sludge in the existing treatment process rather than the post treatment of the sludge produced. The approach should be cost effective and not affect the other treatment characteristics such as effluent quality and settling properties. Approaches that have been listed in the literature are mineralization or disintegration of excess sludge using ozonation (Yasui et al., 1994; Yasui et al., 1996), chlorination (Saby et al., 2002), heating (Canales et al., 1994), control of sludge growth by metabolic uncouplers (Low et al., 1999; Mayhew et al., 1998) and modification of the activated sludge process by introduction of an anaerobic tank with a recycle circuit (Chudoba et al., 1992; Novak et al., 2006) called the oxic-settling anaerobic process (OSA) or commercially termed “Cannibal Process”.

Research at Virginia Tech by Novak et al. (2006) has shown that the Cannibal™ process compared to the conventional activated sludge process is capable of reducing excess sludge up to 60%. The yield, defined as mg of VSS per mg of COD, in a conventional system is about three times the yield in the Cannibal™ system.

Cannibal Process- Description:

The Cannibal process consists of an aerobic activated sludge system integrated with an anaerobic reactor (Cannibal bioreactor) and a recycle circuit (figure I-1). The operation involves the interchange of biomass between the aerobic and the anaerobic zone on daily basis. The recycled biomass is held in the Cannibal bioreactor for the specified detention period. The biomass in the aerobic zone is allowed to settle before they are recycled to the Cannibal bioreactor.

Figure I-1: Simple Schematic Flow Chart of the Cannibal Process



Cannibal Process- Important Operational Parameters involved:

Several investigations have been conducted on the operational parameters of the conventional activated sludge process since its development. Since the Cannibal process is a modification of the activated sludge process, interests are focused on the operational parameters of the Cannibal bioreactor. Optimization of the Cannibal process can be defined as refinement of the design parameters and evaluation of the process. The operational parameters that are of interest towards the optimization of the Cannibal process are:

1. Oxidation Reduction Potential (ORP)
2. Hydraulic Retention Time (HRT)
3. Interchange Rate (IR)

Saby et al. (2002) have studied the effect of ORP in the oxic-settling anoxic process. According to their study the ORP level in the Cannibal bioreactor plays an important role in reducing the excess sludge. An ORP level at -250mV reduces excess sludge by 36% compared to that controlled at +100mV or by 58% compared to a conventional activated sludge process. The low ORP in the Cannibal bioreactor also helps to maintain a low SVI.

In any wastewater treatment system, both the aerobic and the anaerobic biochemical reactions depend on the solids retention time (SRT). The SRT has to be maintained above a minimum range for the proliferation and proper functioning of the microorganisms. Since the Cannibal bioreactor is a CSTR, the SRT is identical to the HRT. Hence the HRT in the Cannibal bioreactor is a critical operational parameter that needs to be studied. Similarly another operational parameter that needs consideration is the interchange rate (IR) employed in the Cannibal process. The IR is an important parameter because it is essential in achieving the required target of solids destruction in the system. Maintaining a higher IR during the operation will increase the operational cost and may reduce the degree of solids destruction in the system. Any information about the impact of the HRT and IR on the Cannibal system will help reduce the economic cost and optimize the operation. The goal of this research was to contribute information pertaining to this topic by determining the effect of the Cannibal bioreactor hydraulic retention time and interchange rate on the solids destruction in the system.

CANNIBAL PROCESS: MECHANISM

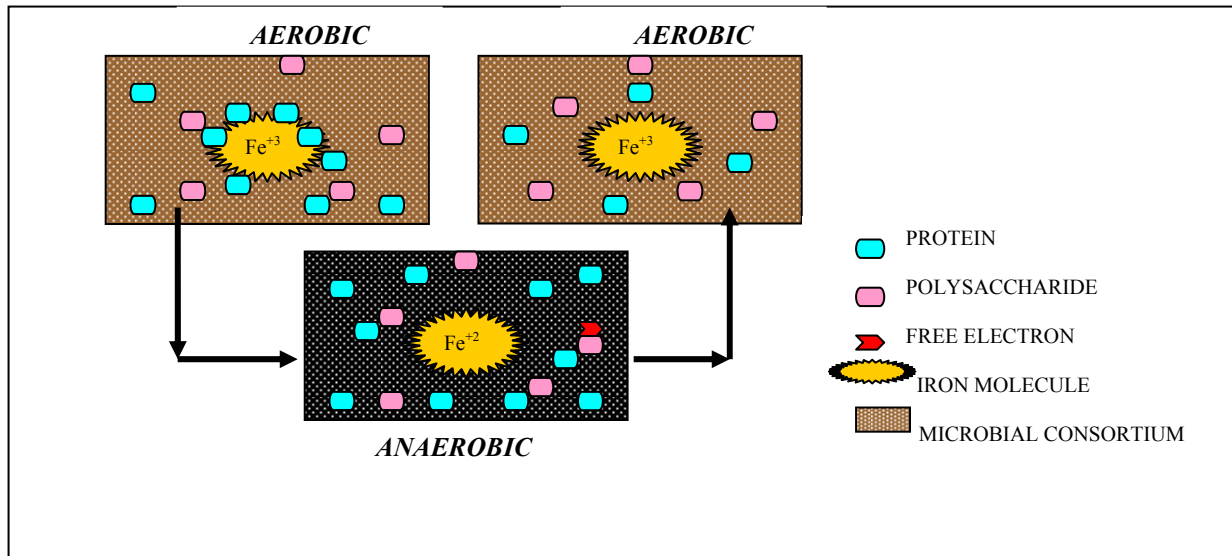
As mentioned previously, activated sludge is a conglomeration of organic and inorganic particles bound together in a matrix of micro-organisms, exo-cellular polymers and cations. Extra-cellular polymeric substances (EPS) in activated sludge consist mainly of humic substances, polysaccharides, proteins and DNA (Urbain *et al.*, 1993; Frølund *et al.*, 1995). The exo-cellular biopolymers act as a binding agent for the flocs in the activated sludge (Higgins and Novak, 1997a). Earlier studies by Bruss *et al.*, (1993) and Murthy *et al.*, (1999) have shown that biopolymers associated with activated sludge flocs are released into solution during aerobic and anaerobic digestion.

Research by Novak *et al.* (2003) proposes that different processes exist under aerobic and anaerobic condition with regard to biopolymer release and degradation. They determined that proteins and polysaccharides in the activated sludge flocs are associated with different cations in floc. One fraction of protein is associated with iron and the other lectin-like fraction is associated with divalent cations. Polysaccharides are thought to be linked with lectin-like compounds and are retained by divalent cations. In aerobic systems, the polysaccharide concentration in solution is approximately double that of proteins. This increase in polysaccharide concentration is accompanied with the increase in divalent cations. Under anaerobic condition, the release of protein is more extensive than the release of polysaccharide. But this release of protein in anaerobic systems has not been simultaneous with the result in an increase in divalent cations. This suggests that the protein released under anaerobic condition is not associated with the lectin-like biopolymer.

The existence of two types of biopolymer and their varied concentrations in aerobic and anaerobic systems suggest that degradation might be best accomplished by combining the two systems. Park *et al.* (2006) has proposed that the iron protein linkages are an important factor for observing higher concentration of protein under anaerobic conditions. During anaerobic digestion, iron is reduced from ferric to ferrous. This reduction promotes the release of protein into solution. In the Cannibal system, the organic matter (protein) released by the reduction of iron in the anaerobic bioreactor is

recycled to the aerobic activated sludge system and rapidly degraded. This is the proposed mechanism for the excess sludge reduction in the Cannibal process by Novak et al., (2006). The following figure I-2 represents the proposed mechanism.

Figure I-2: Proposed Mechanism for the Cannibal Process



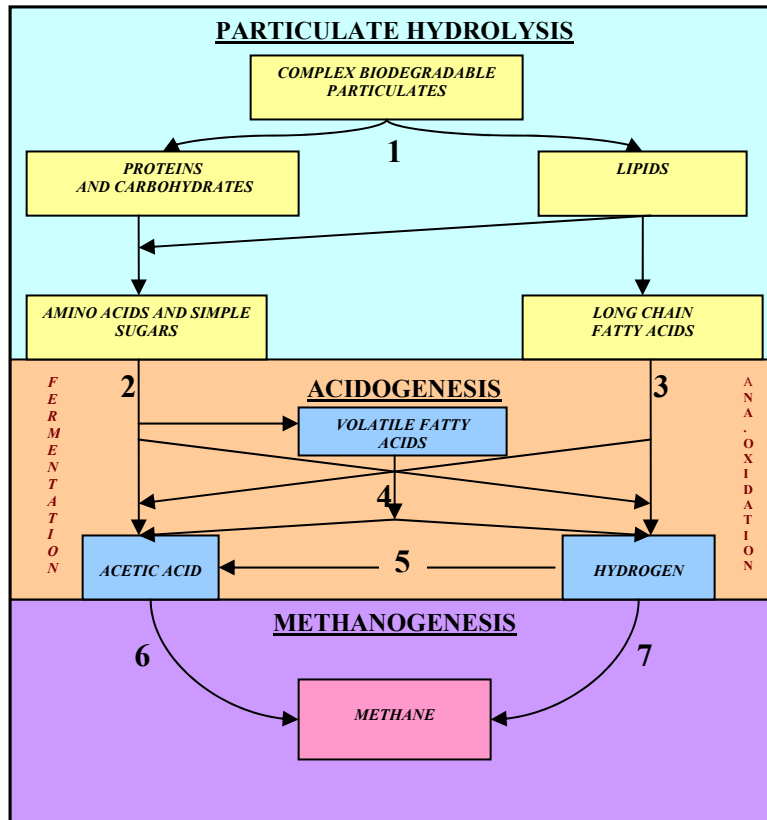
ANAEROBIC SYSTEM: FUNDAMENTAL BIOLOGICAL REACTIONS

An anaerobic system consists of a complex sequence of biological reactions, during which the end products of one group of microorganisms serve as substrates for another group of microorganisms. Under anaerobic conditions, biopolymers are degraded via hydrolysis, acidogenesis, acetogenesis (oxidation of fatty acids) and methanogenesis (Gallert et al., 2005; McInerney, 1988). The classification of the principle reaction sequence is shown in figure I-3.

The hydrolysis (reaction 1) reactions constitute the solubilization of the large organic molecules. The size reduction aids in the cell membrane transport and is catalyzed by extra-cellular enzymes (Fox et al., 1994; Beer et al., 1998). Reaction 2 involves the degradation of amino acids and sugars by fermentative reactions. The main byproducts of this reaction are fatty acids, acetic acid and hydrogen. The quantity of hydrogen produced by this reaction is small. The major percentage of hydrogen is produced from oxidation of fatty acids to acetic acids (reactions 3 and 4) through anaerobic oxidation. In the

anaerobic system, production of hydrogen through anaerobic oxidation is very critical because hydrogen is a major substrate for methane production (Grady et al., 1999).

Figure I-3: Sequence of Biological Reactions in Anaerobic System.



*-Reproduced from Grady et al., (1998)

Reaction 5 results in acetic acid production by combination of hydrogen and carbon dioxide. As mentioned earlier, the products of acidogenesis are used as substrates by the methanogens to produce methane. Reaction 6 involves breaking of acetic acid into methane and carbon dioxide by the acetoclastic methanogens. Reduction of carbon dioxide to methane by hydrogen oxidizing methanogens constitutes reaction 7. About two-thirds of the methane is derived from acetic acid and the remainder is derived from hydrogen and carbon dioxide. It should be noted that the methanogenesis and acidogenesis maintain a relationship called “obligate syntrophy” (Grady et al., 1999). The working of methanogens aid the production of acetic acids during acidogenesis and proper functioning of acidogenesis is required to provide the substrates for methanogens.

HYDRAULIC RETENTION TIME:

The Hydraulic Retention Time (HRT) is defined as the “average length of time that an element of fluid stays in the reactor of constant volume receiving constant flow rate of fluid with constant density” (Grady et al., 1999). The Cannibal bioreactor can be treated as a continuously stirred tank reactor in which the HRT and SRT are identical.

IMPORTANCE OF SOLIDS RETENTION TIME:

Solids Retention Time or the mean cell residence time is defined as the period that represents the average length of time the organic matter (biomass) resides in the reactor. The minimum SRT is described as the value below which microorganisms are unable to proliferate because they are wasted from the system before they could produce a stable population. Maintaining the SRT above the minimum value is therefore essential for any wastewater treatment system. The ratio of the operating SRT to the minimum SRT is known as the safety factor. In any treatment system, it is required to have a safety factor of 1.5 or above.

Activated Sludge System:

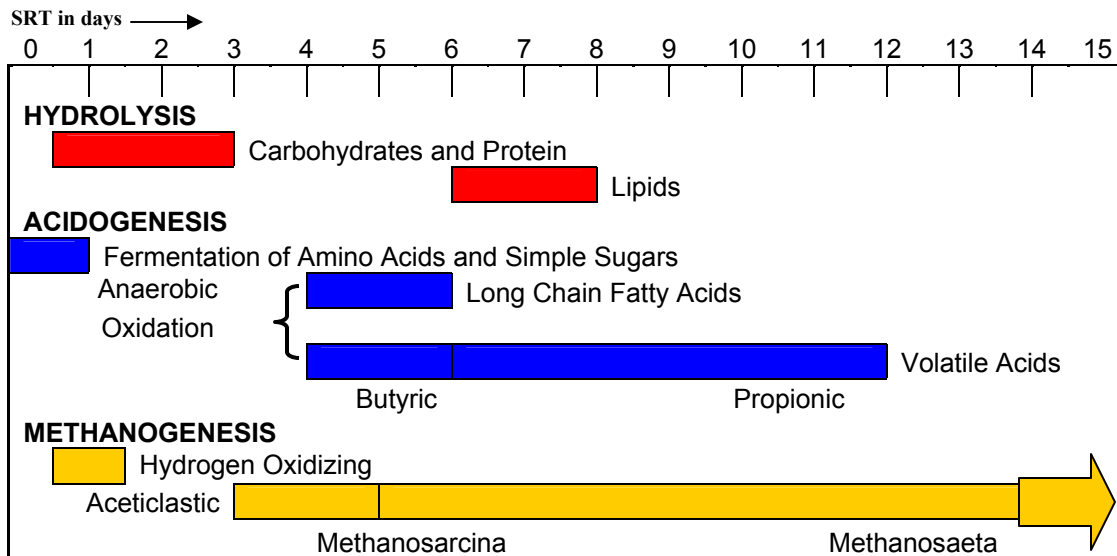
As the SRT is increased, the active fraction of the biomass decreases. Longer SRT produces excess inactive biomass that has to be accommodated with the active fraction since the active biomass and the debris cannot be separated (Grady et al., 1999). A lower yield is observed at longer SRTs because longer opportunity is given for the biomass to decay and greater maintenance energy is required. Furthermore, at longer SRTs excess biomass wastage will decrease due to increased decay. At steady state, the SRT is associated with the specific growth rate coefficient of the biomass. The specific growth rate controls the biodegradable substrate concentration in the reactor and its effluent. Microbial cell lysis can be increased by extending the SRT (Liu et al., 2001; Saunders et al. 1981). Murthy (1998) showed that an increase in the SRT resulted in increased polysaccharides in solution. The increase in effluent COD was directly proportional to the increase in protein and polysaccharide. According to Bisogni et al., (1970) settling properties can be expressed as a function of the SRT. At a lower SRT, dispersion of

bacterial flocs is observed leading to higher concentration of effluent suspended solids. The Sludge Volume Index (SVI) improves with increase in SRT above 4 days.

Anaerobic System:

The stability of the biochemical reactions depend on viable bacterial groups and the SRT is a significant factor in selecting the predominant species. Solids retention time controls the extent to which reactions occur in the anaerobic system by controlling the types of microorganisms. Hydrolysis of particulate carbohydrates and proteins occur at shorter SRTs while hydrolysis of lipids requires longer SRTs. The conversion of volatile fatty acids into acetic acid and hydrogen (anaerobic oxidation during acidogenesis, can be achieved only when sufficient retention period is given for the growth of the bacteria that aid in this conversion. Alternatively, fermentation of amino acids and sugar take place at shorter SRT. The effect of SRT is seen even among the group of methanogens. Hydrogen oxidizing methanogens proliferate at lower SRT while the aceticlastic methanogens need longer SRT to grow (Grady et al., 1999). The volatile acid produced can exceed its usage at lower retention periods, leading to failure of the anaerobic bioreactor (Ghosh, 1991). It has been proposed by Miron et al. (1999) that acidogenic conditions prevail at $SRT \leq 8$ days and methanogenic conditions prevail at $SRT \geq 10$ days. The range of SRT required for different processes within each biochemical reaction is shown in figure I-4.

Figure I-4: SRT Ranges for Biochemical Reactions in Anaerobic System



*-Reproduced from Grady et al., (1998)

EFFECT OF IRON AND ALUMINUM:

Iron and aluminum are used in wastewater treatment plants as coagulating and phosphorous –removing agents. These cations are often found in high concentrations in activated sludge (Park et al., 2006). It is thought that Fe and Al contribute to the physical stability of floc. Studies by Caccavo et al., (1996) and Nielsen et al., (1997) show that the turbidity in the solution of activated sludge increases when Fe is reduced, suggesting that Fe plays an important role in the floc structure. A study by Rasmussen et al., (1996) has demonstrated that 70-90% of Fe is present as Fe (III) in fresh activated sludge, and almost all Fe (II) and Fe (III) were associated with the sludge matrix. Novak et al., (2003) predict that a strong affinity between Fe (III) and protein exists under anaerobic condition and when the Fe (III) is reduced floc associated protein is released increasing the soluble proteins. Therefore the presence of iron in the floc is a critical requirement for the excess solids reduction in the Cannibal process.

In addition, iron can reduce the inhibitory effects of sulfide in an anaerobic system by reducing it. Unlike Fe, Al does not undergo oxidation-reduction. Studies by Park et al., (2006) suggest that selective binding between Al and polysaccharide might exist. Insufficient Fe and Al in the activated sludge floc result in poor binding of the biopolymer, poor effluent quality and high conditioning requirements. Determining the

optimum dose of Fe along with Al required for the target solids destruction in the Cannibal process was one was the objective of this research work.

VOLATILE FATTY ACIDS

Volatile fatty acids (VFA) are an important intermediate compounds in the metabolic pathway of methane fermentation. In an anaerobic bioreactor organic matter is first hydrolyzed and fermented into volatile fatty acids by acidogenic bacteria. Following their production the acetogenic bacteria oxidize the VFAs into acetate, molecular hydrogen and carbon dioxide that are substrates for methanogenic bacteria (Pavlostathis et al., 1991). VFAs exert microbial stress if present in higher concentrations (Buyukkamaci et al., 2004). VFAs are not detected under oxygen sufficient conditions. The observance of VFAs in any anaerobic system is important as it yields valuable information about the system's operational performance. For the better maintenance of the system, the VFAs should be maintained in the optimum concentrations. The increase in VFAs has a negative impact on the production of methane (Stafford, 1982). Volatile fatty acids are weak acids and are disassociated at neutral pH. It is thought that only the un-ionized form of the VFA is inhibitory (Andrews et al., 1965). The metabolic state of hydrogen producing acetogens and acetoclastic methanogens are indicated by the VFAs (Buyukkamaci et al., 2004). Studies show that the detention times have an effect on the total volatile fatty acid (TVFA) production. At lower hydraulic retention time the TVFA concentration is highest (Chu et al., 1996 and Colmenarejo et al., 2004).

SULFIDE IN THE ANAEROBIC SYSTEM: SOURCE AND EFFECTS

Sulfide is produced in the anaerobic system by the degradation of organic matter containing sulfur. Protein is one of the organic compounds that contain sulfur. It is also produced by the reduction of sulfate. Sulfate is reduced to sulfide which combines with hydrogen to form hydrogen sulfide. The hydrogen sulfide is sparingly soluble in water and hence collects as gas in the bioreactor headspace. It is gradually oxidized to corrosive sulfuric acid. Sulfate acts an inhibitory agent to the anaerobic processes and not to the anaerobic bacteria's. Sulfate inhibits the anaerobic processes by providing an electron acceptor that can be used by the sulfate reducing bacteria thus competing with the methanogens for available electrons. This results in reduced production of methane. The competition between the sulfur reducing bacteria and methanogens is very complex (Grady et al., 1999). Sulfide reacts with iron to form insoluble precipitates and it's the production of iron sulfide that gives a black color to the anaerobic solids. The hydrogen sulfide production can be minimized by the addition of iron which precipitates sulfide to iron sulfide. A study by Nielsen et al., (2005) showed that addition of Fe (III) in the presence of sulfide result in the immediate reduction of Fe (III) to Fe (II) associated with the oxidation of sulfide. The same study has confirmed that the stoichiometry for sulfide precipitation is 1 mole Fe per mole S. This information is very important to estimate the dosage of iron for sulfide control.

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CHAPTER II:

OPTIMIZATION OF THE CANNIBAL PROCESS: EFFECT OF HYDRAULIC RETENTION TIME AND SOLIDS INTERCHANGE RATE ON THE SOLIDS DESTRUCTION IN THE CANNIBAL™ SYSTEM

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ABSTRACT

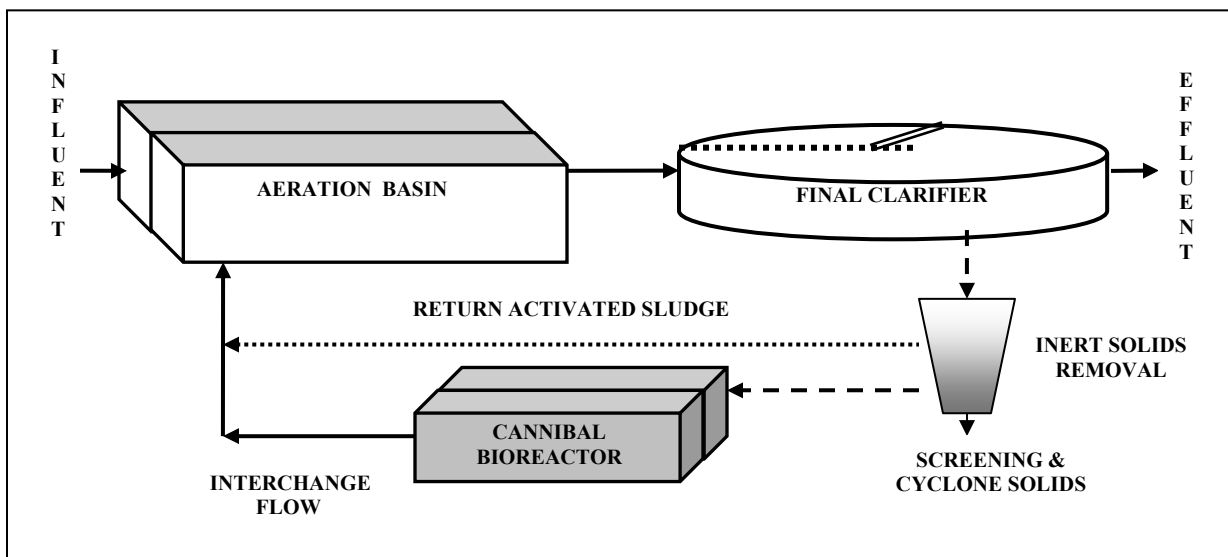
The Cannibal™ system, comprised of an activated sludge process integrated with a side stream anaerobic bioreactor, is capable of reducing excess sludge up to 60% compared to the conventional activated sludge process. The hydraulic retention time (HRT) in the Cannibal bioreactor and the interchange rate (the percent of sludge by mass interchanged between the activated sludge system and the bioreactor on daily basis) are the two important operational parameters in the optimization of the Cannibal process. This research was designed to investigate the effect of the Cannibal bioreactor hydraulic retention time and the interchange rate on the solids destruction in the system. The first phase of this study has looked at the effect of three different HRTs, 5 day, 7 day and 10 day. The interchange rate during phase I was 10%. The results showed that the 7 day HRT can be recommended as the minimum retention period for the Cannibal process. The 5 day HRT Cannibal system had some settling problems and high volatile fatty acid content compared to the 7 day HRT Cannibal system. The protein and polysaccharide tests showed that the Cannibal bioreactor is primarily involved in the release of biopolymers which are degraded in the aerobic environment.

The second part of this study focused on the effect of the interchange rate (IR) on the solids destruction in the system. The interchange rates that were applied in the system were 15%, 10%, 7%, 5% and 4%. The HRT in the Cannibal bioreactor was 7 day. The results showed that the 10% interchange rate gave maximum solids destruction than the other interchange rates. This implies that 10% is an optimum IR for the Cannibal system. Apart from higher solids wastage, the 4% and 5% IR Cannibal systems had higher volatile fatty acid production.

INTRODUCTION

The Cannibal™ process is an innovative wastewater treatment process that minimizes the excess sludge generation in a conventional activated sludge system. The Cannibal™ system is comprised of an activated sludge process integrated with a side-stream anaerobic bioreactor (Figure II-1). The actual operation involves an interchange flow of biomass between the activated sludge tank and the Cannibal (anaerobic) bioreactor. The biomass that enters the Cannibal bioreactor is retained for a specific retention period and recycled back to the activated sludge process. The Cannibal bioreactor is an anaerobic bioreactor in which a negative oxidation reduction potential (ORP) exists. The ORP plays a vital role in the sludge minimization in the Cannibal process (Saby et al., 2002).

Figure II-1- Schematic representation of the Cannibal process



(Source: <http://www.usfilter.com/NR/rdonlyres/D4F4BEE9-6226-47AB-8BFE-18E31DAD14EB/0/CannibalBrochure.pdf>)

Research at Virginia Tech by Novak et al. (2006) has shown that the Cannibal™ process compared to the conventional activated sludge process is capable of reducing excess sludge up to 60%. The yield, defined as mg of VSS per mg of COD, in the conventional system is about three times the yield in the Cannibal™ system.

The effect that the Solids Retention Time (SRT) exerts on the performance of the activated sludge system makes it a critical operational parameter. The minimum SRT is

described as the value below which microorganisms are unable to proliferate because they are wasted from the system before they can produce a stable population. Likewise, in an anaerobic system the biochemical operations of hydrolysis, acidogenesis and methanogenesis are affected in a unique way when the retention period is not maintained above the minimum range. The detention times of the activated sludge system and the Cannibal bioreactor are important parameters in the working of the Cannibal™ process. The initial research on the Cannibal process conducted at Virginia Tech employed a hydraulic retention time (HRT) of 2 days for the activated sludge system. This HRT was later reduced to 1.5 days. The HRT for the anaerobic bioreactor was maintained at 10 day (Chon, 2005). These retention periods were selected to be representative of the onsite operational parameters.

During the operation of the Cannibal system, a certain portion of thickened biomass is sent into the Cannibal bioreactor. The biomass is retained in the Cannibal bioreactor for the desired retention period. The percentage (by mass) of biomass from the activated sludge system recycled through the Cannibal bioreactor on daily basis is called the “Interchange Rate”. The interchange rate is an important parameter because it is important for achieving the required target of solids destruction in the system. Before the interchange of biomass, the biomass is allowed to settle and thicken in order to reduce the recycle volume and the volume of the Cannibal bioreactor. If the biomass were to be recycled without settling, the recycle volume and the Cannibal bioreactor volume would be 4-5 times larger. The interchange rate was maintained at 10% during the initial studies at Virginia Tech (Chon, 2005).

Research Objective:

The primary objectives of this study were:

To determine the effect of the Cannibal bioreactor Hydraulic Retention Time on the solids destruction in the system (*PHASE I*) and

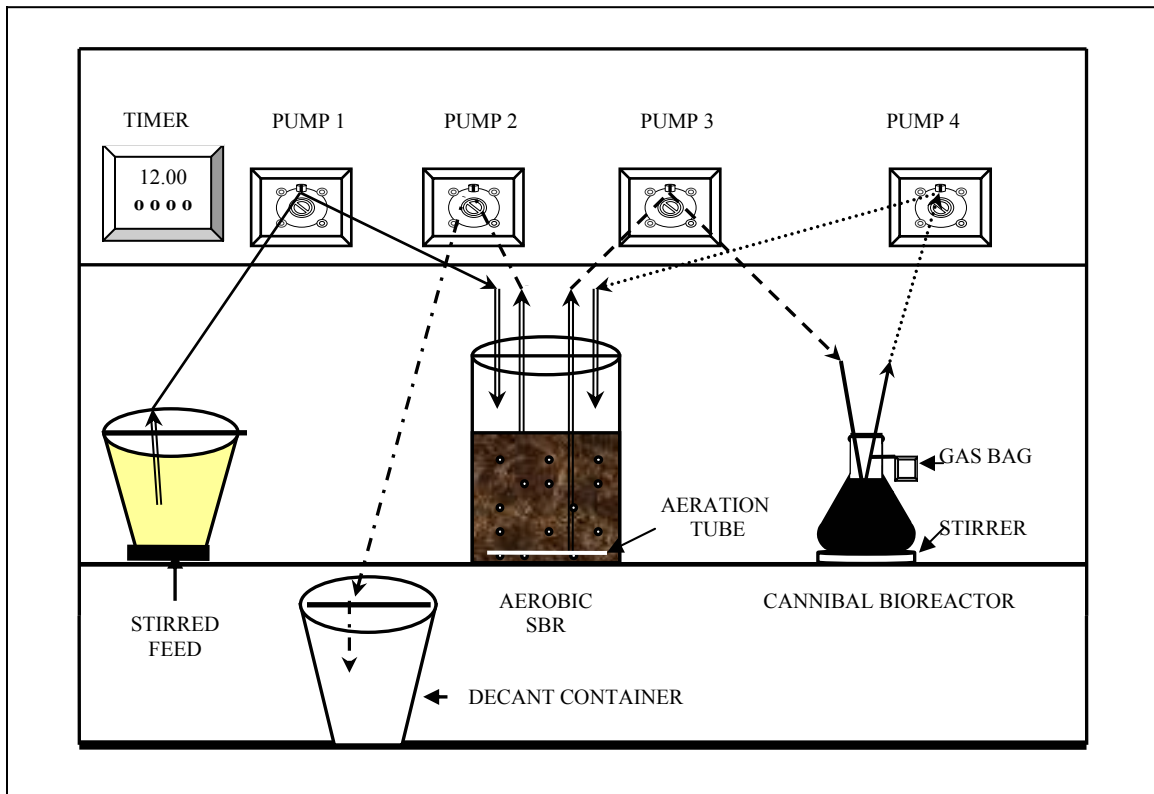
To determine the effect of Interchange Rate on the solids destruction in the system (*PHASE II*)

METHODS AND MATERIALS:

Laboratory Setup:

The laboratory reactors setup is shown in figure II-2.

Figure II-2: Laboratory setup of the Cannibal System



Operational Parameters:

The activated sludge system was operated as a Sequencing Batch Reactor (SBR). The SBR had four different steps that occurred in sequence. They were feed, aerate - react, settle and decant. The activated sludge used to seed the reactors was obtained from the Blacksburg Wastewater Treatment Plant. The biomass was kept in suspension and well aerated with aeration provided by compressed air. The HRT in the aerobic SBR was maintained at 1.5 days. The Cannibal bioreactor was an airtight container. The gases produced in the Cannibal bioreactor due to anaerobic reactions were collected in a Tedler gas bag. The volume of the anaerobic solids in the Cannibal bioreactor was periodically changed based on the settled volume to maintain the required Interchange Rate (IR)

during both phases. During phase I, a conventional activated sludge system was also operated. The conventional system, which served as a control, did not include an anaerobic bioreactor.

The anaerobic solids were continuously mixed with a magnetic stirrer to prevent settling. The effluent collected in the decant container was analyzed for solids concentration and COD. The operating steps of the SBR and the interchange between the Cannibal bioreactor and the aerobic system (SBR) were carried out on a 6 hour cycle or 4 cycles per day. Every cycle was automated with pumps running on timers. Each cycle consisted of 5 different processes. They were feeding the SBR, aeration of the biomass in the SBR, settling of the biomass in the SBR, decanting the effluent and interchange of solids between the aerobic system and treatment in the Cannibal bioreactor. The time for aeration during each cycle was 5 hours. The biomass was allowed to settle for 40 minutes in each cycle. The remaining 20 minutes in each cycle was used for the other 3 processes. The entire setup was maintained in a 20°C temperature- controlled room.

Feed Parameters:

Soluble synthetic feed was used in the process. BactoPeptone and sodium acetate provided the COD content of 400mg/l in the feed. The composition of the feed is shown in Tables 1 and 2. Allylthiourea was added to inhibit nitrification (Bond et al., 1999). Deionized water was used to prepare the feed and the solutions. The feed was continuously stirred to maintain homogeneity. All the systems operated during each cycle were fed from the same feed tank. The synthetic feed was prepared once every 48 hours. The feed tank was cleaned with chlorine bleach before the feed preparation. This was imperative to avoid microbial growth in the feed tank. The glass tubes used in the setup was washed with chlorine bleach every two weeks. Masterflex tubing and connectors were used for fluid circulation through the pumps. The feed composition was the same during phases I and II.

Table 1: Medium Composition

| NAME | FORMULA | CONCENTRATION(mg/l) |
|------------------------|---|---------------------|
| Bacto Peptone | - | 300mg COD/l |
| Sodium Acetate | CH ₃ COONa | 100mg COD/l |
| Ammonium Chloride | NH ₄ Cl | 57 |
| Ammonium Bicarbonate | NH ₄ HCO ₃ | 60 |
| Potassium Phosphate | KH ₂ PO ₄ | 44 |
| Potassium Bisulphate | KHSO ₄ | 34 |
| Sodium Bicarbonate | NaHCO ₃ | 394 |
| Calcium Chloride | CaCl ₂ .2H ₂ O | 220 |
| Magnesium Sulfate | MgSO ₄ .7H ₂ O | 150 |
| Ferric Chloride | FeCl ₃ | 20 |
| Alum | Al ₂ (SO ₄) ₃ .18H ₂ O | 20 |
| Allylthiourea | - | 1.4 |
| Trace Element Solution | - | 2ml/l |

Table 2: Trace Element Solution Composition

| NAME | FORMULA | CONCENTRATION(gm/l) |
|---|---|---------------------|
| Citric acid | - | 2.73 |
| Hippuric acid | - | 2 |
| Ethylene Diamine Tetraacetic Acid, trisodium salt | Na ₃ EDTA.4H ₂ O | 1.5 |
| Ferric Chloride | FeCl ₃ .6H ₂ O | 1.5 |
| Boric Acid | H ₃ BO ₃ | .25 |
| Zinc Sulphate | ZnSO ₄ .7H ₂ O | .15 |
| Manganese Chloride | MnCl ₂ .4H ₂ O | .12 |
| Copper (II) Sulphate | CuSO ₄ .5H ₂ O | .06 |
| Potassium Iodide | KI | .03 |
| Sodium Molybdate | Na ₂ MoO ₄ .2H ₂ O | .03 |
| Cobalt chloride | CoCl ₂ .6H ₂ O | .03 |
| Nickel (II) Chloride | NiCl ₂ .6H ₂ O | .03 |
| Sodium Tungstate | NaWO ₄ .2H ₂ O | .03 |

Analysis:

Tests were conducted on the mixed liquor suspended solids and effluent to determine total suspended solids (TSS) and volatile suspended solids (VSS), according to Standard Methods (APHA, 1995). The samples were filtered through 1.5µm binder-free glass micro-fiber filter. Other tests conducted were effluent soluble COD, sludge volume index and pH. The soluble protein concentration was measured by the Frølund et al. (1999) modification of Lowry method (1951) using bovine serum albumin as the standard. Soluble polysaccharide was measured by the Dubois et al. (1956) method using glucose as the standard. The samples tested for COD, protein and polysaccharide were filtered

through 0.45 μ m filter before measurement. Hence it is referred as “soluble”. The specific oxygen uptake rate (SOUR) was measured, using method 2710B from the “Standard Method for Examination of Water and Wastewater”, during phase I. Total iron and aluminum in the aerobic and anaerobic dried solids were measured during phase II. EPA method 3050B (acid digestion for metals analysis of soils, sediments and sludge’s) was used for iron and aluminum measurement. Volatile fatty acids (VFA) were determined, using Shimadzu Gas Chromatograph equipped with a Flame Ionization Detector (FID), to gain additional insight about the mechanism of the Cannibal process. The gases collected in the gas bag were tested to determine the percentage of gases present in the mixture. The gases were measured using Shimadzu Gas Chromatograph-14A with a Thermal Conductivity Detector (TCD). The primary interests were in hydrogen sulfide, carbon dioxide and methane.

Experimental Approach:

Phase I:

During the first phase of the study, the effect of HRT in the Cannibal bioreactor on solids destruction in the Cannibal system was investigated. A conventional system (without the Cannibal bioreactor) was run for comparison. The effects of 3 different HRTs were considered. The HRTs selected the Cannibal bioreactor were 10 day, 7 day and 5 day. The control system was run as a 10 day HRT bioreactor. Initially the study began with two Cannibal systems, one a 10 day HRT Cannibal system and the other a 7 day HRT Cannibal system. Thirty days after the start the 7 day HRT system was converted to a 5 days HRT system. Around 60 days from the start a conventional system was also started. After 70 days, the 10 day Cannibal HRT system was converted to 7 day Cannibal HRT system. A schematic representation of the systems that functioned during the operational period of phase I is shown in Table 3.

Table 3: Schematic Representation of the Operational Periods for the Systems in Phase I

| Operating Period Reactor Properties | 0 – 15 days | 16- 30 days | 31- 45 days | 46-60 days | 61-75 days | 76-90 days | 97 1-120 days |
|--|----------------|----------------|----------------|---------------|---------------|---------------|------------------|
| <i>10 days HRT</i> | ●—————● | | | | | | |
| <i>7 days HRT</i> | ●—————● | | ● | | ● | ●—————● | |
| <i>5 days HRT</i> | | | ● | ●—————● | | | |
| <i>Conventional</i> | | | | | ● | ●—————● | |

The volume of the SBR was maintained at 4 liters. The HRT in the sequencing batch reactor was 1.5 days. The volume of synthetic feed fed to the SBR was 2.6 liters per day. The same volume was decanted. The interchange rate (IR) in the Cannibal system was maintained around 10%. The IR was adjusted based on the settled volume of the aerobic solids. The volume of the Cannibal bioreactor solids was changed based on the settling characteristics of the sludge.

Phase II:

During phase II, the effect of the IR on solids destruction was determined. It may be recalled that the Interchange Rate is defined as the percentage (by mass) of biomass from the activated sludge system recycled through the Cannibal bioreactor, on daily basis. The effect of five different IR's was studied. The Interchange Rates used were 15%, 10%, 7%, 5%, and 4%. This phase was operated for a period of 125 days. Three cannibal systems (Figure II-2) were operated at a time. The 15%, 10% and 7% Interchange Rate (TOR) bioreactors were started initially. After 40 days of operation, the 15% IR bioreactor was changed to 5% IR bioreactor. The 10% IR bioreactor was changed to the 4% IR bioreactor 80 days from start. The Cannibal bioreactor HRT was maintained at 7 day. A schematic representation of the systems that functioned during the operational period of phase II is shown in Table 4.

Table 4: Schematic Representation of the Operational Periods for the Systems in Phase 11

| Operating Period Reactor Properties | 0-20 days | 21- 40 days | 41- 60 days | 61-80 days | 81-100 days | 101-125 days |
|--|--------------|----------------|----------------|---------------|----------------|-----------------|
| 15% IR | ●—————● | | ● | | | |
| 10% IR | ●—————● | | | ● | ● | |
| 7% IR | ●—————● | | | | ● | ● |
| 5% IR | | ● | ● | ● | ● | ● |
| 4% IR | | | | | ● | ● |

IR- Interchange Rate

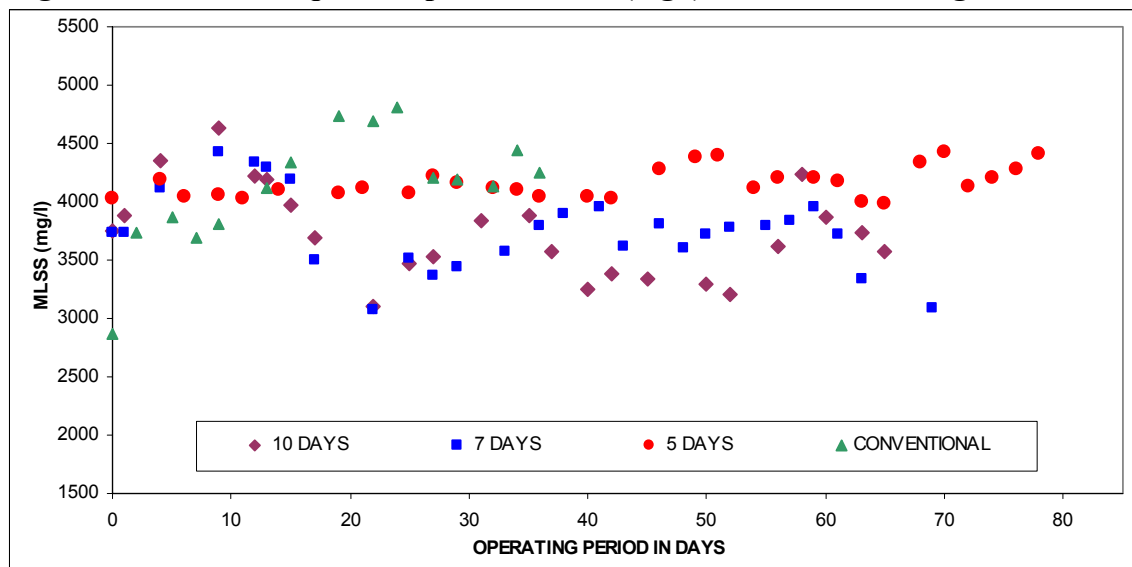
The activated sludge was recycled after settling for 40 minutes. The Hydraulic Retention Time (HRT) maintained in the Cannibal bioreactor was 7 day. The Hydraulic Retention Time (HRT) in the aerobic SBR was 1.5 days. The volume in the SBR was 3 liters.

RESULTS AND DISCUSSION:

Phase I:

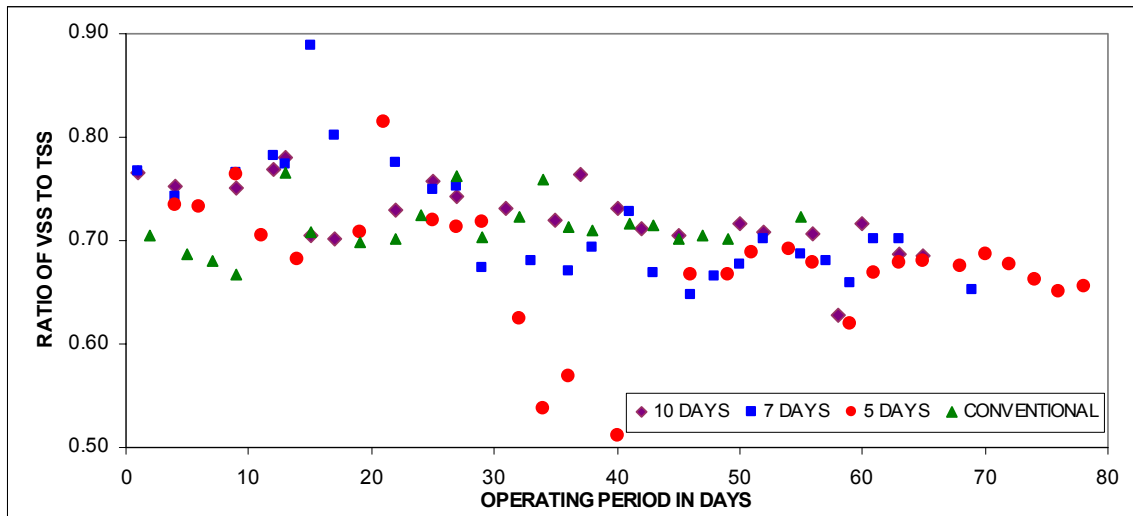
The objective of phase I was to determine the effect of the Hydraulic Retention Time in the Cannibal bioreactor on the solids destruction in the Cannibal system. The HRT's under study during this phase were 10 day, 7 day and 5 day. The mixed liquor suspended solids (MLSS) that was present in each of the aerobic SBRs is shown in figure II-3. The MLSS were maintained within a range of 3000 mg/l to 4500 mg/l.

Figure II-3: Mixed Liquor Suspended Solids (mg/l) in Reactors during Phase I



The ratio of VSS to TSS in the biomass is shown in figure II-4. The ratio gradually decreased and leveled off around 0.65 to 0.7. It can be seen that the ratios for each reactor leveled off at about 30 days of operation. The gradual decline in the ratios is likely due to the stabilization of the organic fraction in the reactors. The effect of Solids Retention Time (SRT) is also another factor to be considered. When the SRT is high, the active fraction of the biomass decreased due to the build up of biomass debris (Grady et al., 1997). During this study, the aerobic SBR's in both the Cannibal and the conventional system maintained a high SRT. Therefore, the solids retention time could be another cause for the lower volatile fraction in the systems.

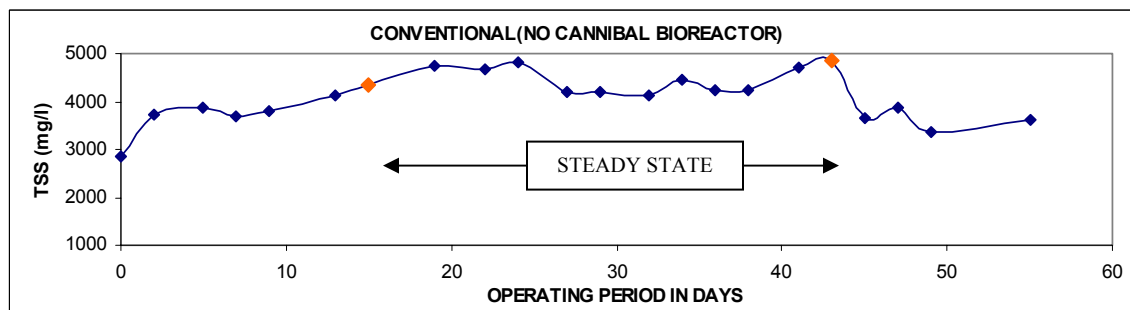
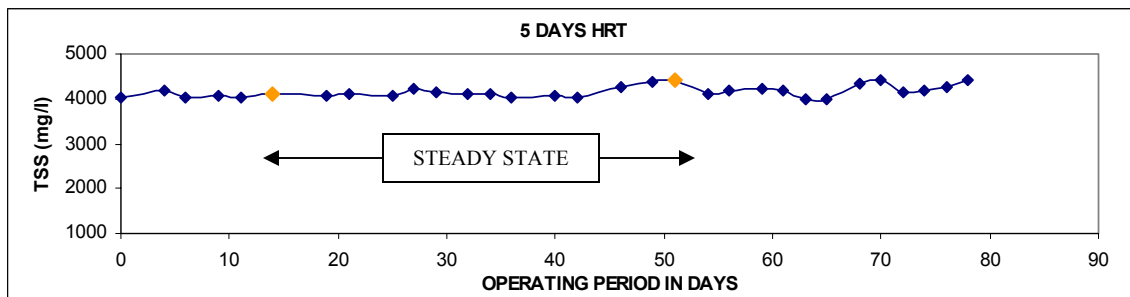
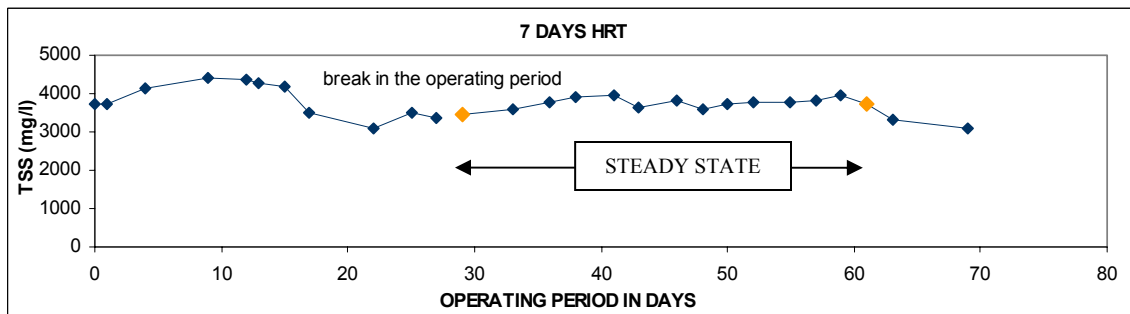
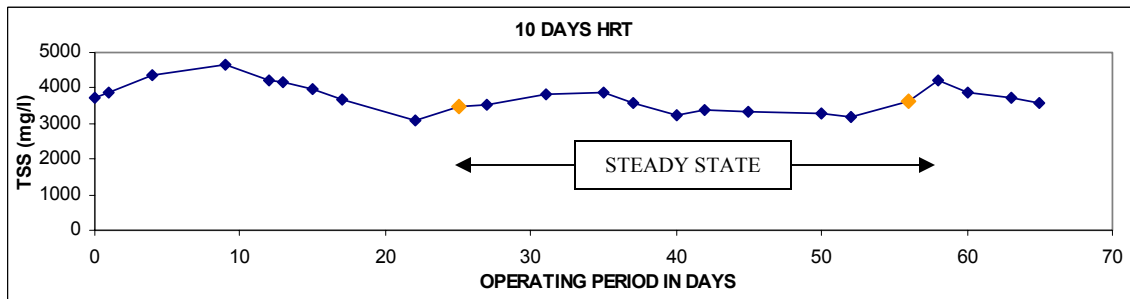
Figure II-4: Ratio of VSS to TSS in the Biomass during Phase I



The cumulative solids (TSS) wasted in each aerobic system during the operational period was used to evaluate the system's performance with regard to solids destruction. The solids wastage was inversely proportional to the solids destruction in the system. This means when the solids destruction was higher in the systems, less solids were wasted. The solids from the aerobic SBR's were wasted for three different reasons. They were wastage due to sampling, effluent wastage and intentional wasting (rarely done to maintain the TSS within specific range). One time intentional wasting was done from all the reactors, though at different times during the operation.

The cumulative solids wasted were plotted by two different methods. In method A, a steady state phase during the operational period was selected and the wastage during that specific phase was plotted. The steady state phase can be described as a phase during which the total suspended solids showed minimum variation in the system. The number of days that were considered for the steady state phase was different for each system. The wastage included the sampling wastage, effluent wastage, intentional wastage and the average biomass growth (or solids accumulation in the bioreactor) during the steady state period. The steady state period that was considered for the four systems is shown in figure II-5.

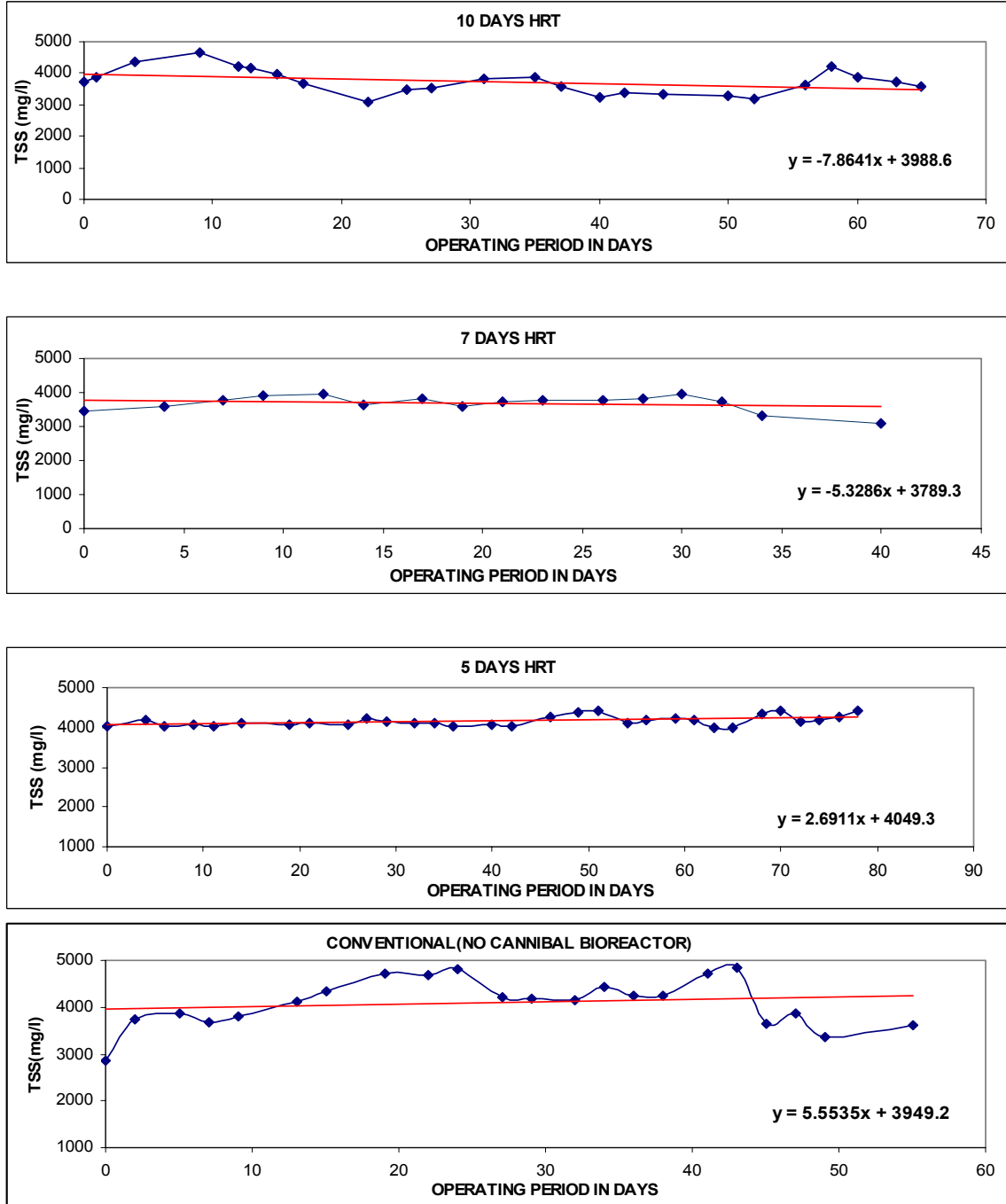
Figure II-5: Method A- Steady State Period for Phase I TSS



In Method B, a linear regression over the entire data set was used to estimate the change in biomass. The slope obtained from the equation was used as the average biomass growth in each system. As in Method A, the cumulative wastage was calculated from

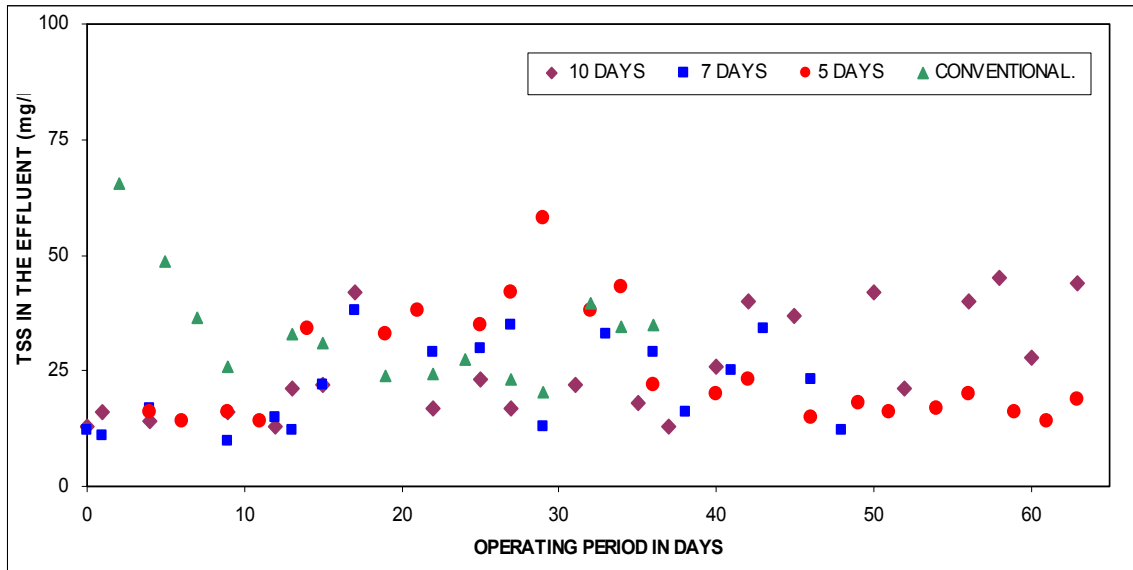
sampling wastage, effluent wastage, intentional wastage and average biomass growth. For the 7 day HRT system, only the second operating period (refer to Table 3) was considered. Figure II-6 gives the values of slopes that were used in the calculation.

Figure II-6: Method B – Linear Regression for Phase I TSS



The sampling wastage was calculated from the TSS values shown in figure II-3. The effluent wastage was based on the volume of effluent decanted per day and the Total Suspended Solids (TSS) present in the effluent. Figure II-7 shows the Total Suspended Solids that were present in the effluent from each system during the operational period.

Figure II-7: Total Suspended Solids (mg/l) in the Effluent during phase I



A one time intentional wastage was done from all the systems. Intentional wastage was done to maintain the Total Suspended Solids within a specific range. The mass of solids that were wasted from each system is shown in Table 5.

Table 5: Total Suspended Solids (mg) Wasted Intentionally during Phase I

| <i>SYSTEM CONFIGURATION</i> | 5 days HRT | 7 days HRT | 10 days HRT | Conventional |
|-----------------------------|----------------------|----------------------|----------------------|----------------------|
| <i>TSS WASTED(mg)</i> | 1584 | 2796 | 2217 | 3267 |
| <i>WASTAGE DONE ON</i> | 51 st day | 17 th day | 17 th day | 24 th day |

The cumulative solids wastage from each system that were calculated using Method A and B are shown in figure II-8 and figure II-9 respectively.

Figure II-8: Method A- Cumulative solids (TSS) wastage in Phase I

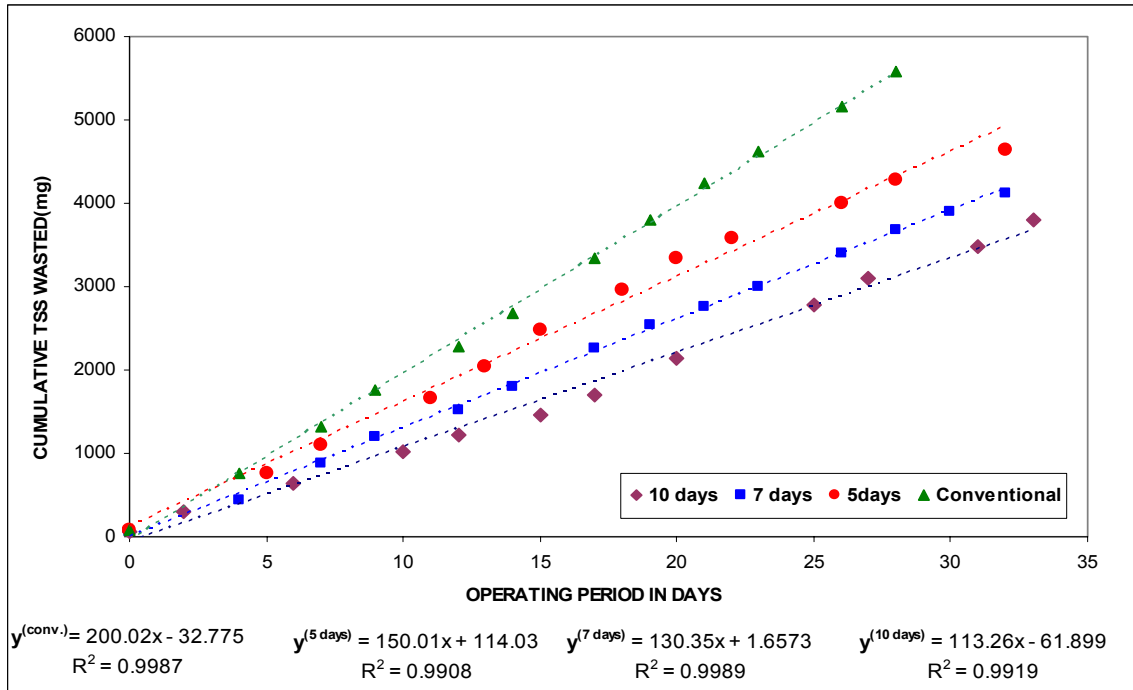
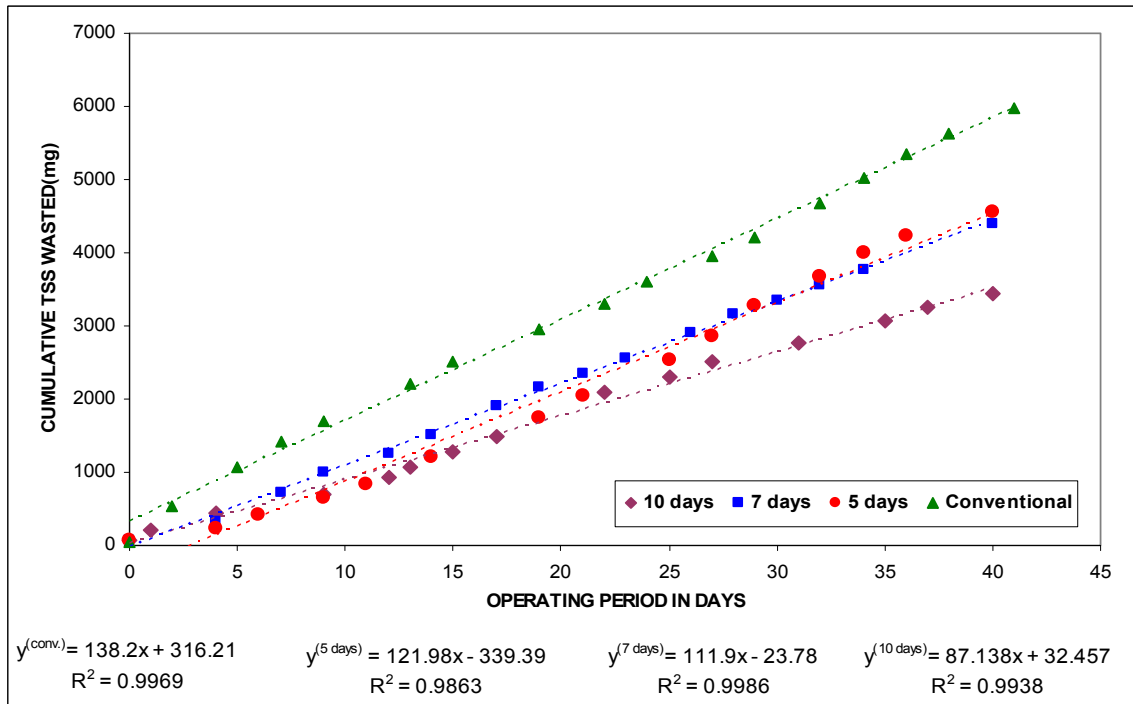


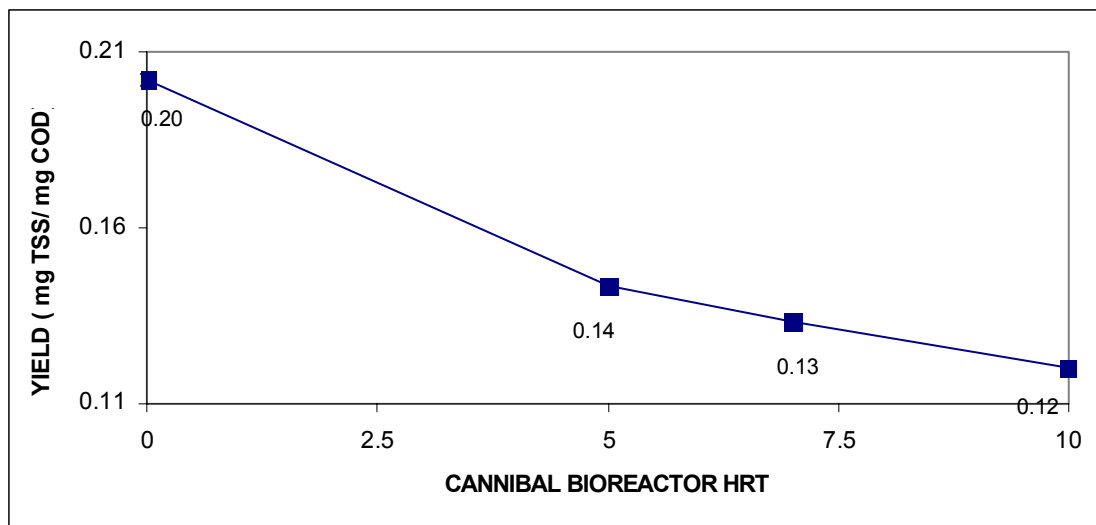
Figure II-9: Method B- Cumulative solids (TSS) wastage in Phase I



As can be seen from figure II-8 and figure II-9, the wastage from the Cannibal system is less than the conventional system. Though there is a difference in the quantity of solids wasted from the three Cannibal systems, they are all lower than the conventional system. The 10 day HRT system gave the maximum solids reduction. However, the 7 day HRT and the 5 day HRT systems had a much lower yield compared to the conventional system. Figure II-8 and figure II-9 shows that the Cannibal system can still work efficiently at solid retention time's lower than 10 day. This implies that onsite Cannibal systems will not fail if the solid retention period is less than optimum. However, the solids wastage may not be as low as desired.

It can be seen from Figures II-8 and II-9 that the 10 day HRT Cannibal system generated 35% to 40% less solids than the conventional system. The 7 day HRT Cannibal system and 5 day HRT Cannibal system generated between 25% to 35% less solids than the conventional system. The observed yield (mg TSS/mg COD) values are shown in figure II-10.

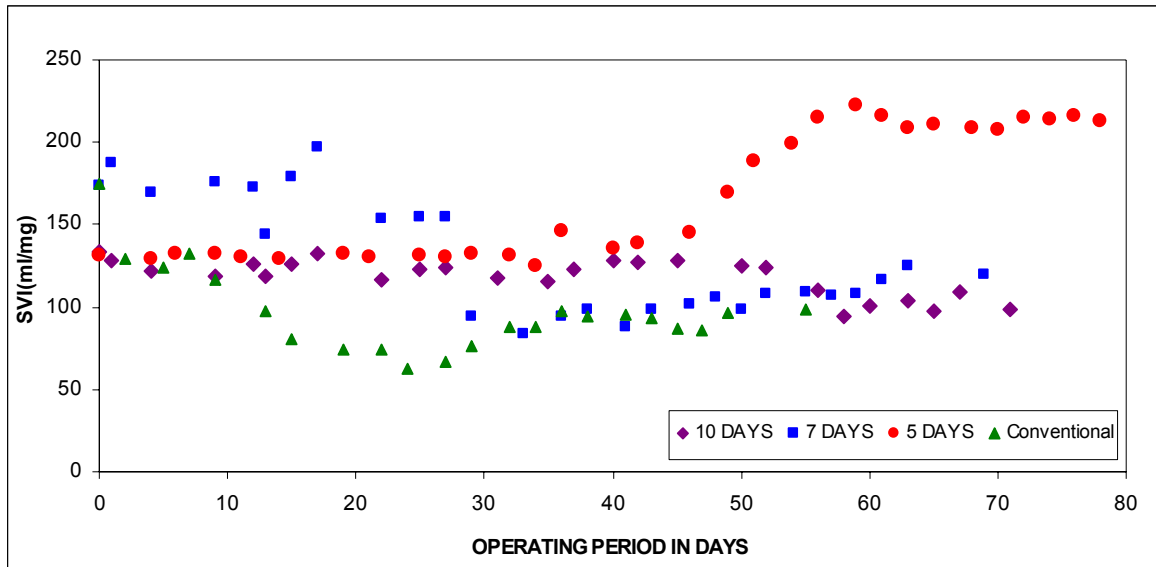
Figure II-10: Observed Yield (mg TSS/mg COD) in Phase I



Earlier research by Novak et al. (2006) on the Cannibal process showed that the yield in the conventional system was around 0.26 mg of VSS per mg of COD. The reason for the difference between this study and the earlier study is the difference in the SRTs. During the earlier studies, the SBR was operated with a SRT of around 20 days. During this

study, the SBR was operated with a SRT over 100 days. Though the 7 day HRT Cannibal system and the 5 day HRT Cannibal system showed similar results with regard to solids destruction, the SVI deteriorated in the 5 day HRT Cannibal system. The SVI for the 4 systems that were operated during phase I is shown in figure II-11.

Figure II-11: Sludge Volume Index (SVI)

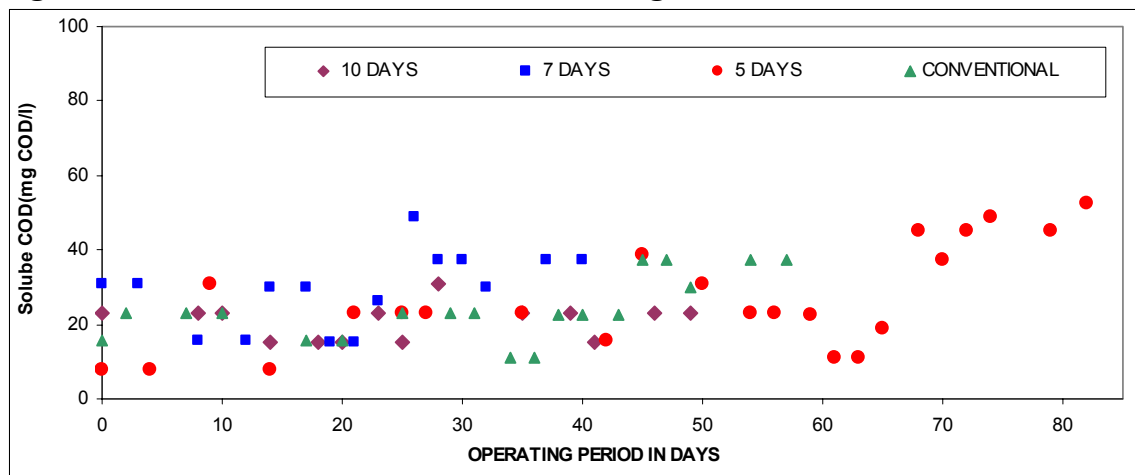


The SVI is considered as an important parameter in any wastewater treatment unit. For the Cannibal system, the settled (thickened) sludge is recycled from the aerobic SBR into the Cannibal bioreactor. Therefore the settling volume is directly proportional to the recycle volume and the volume of the Cannibal bioreactor. The conventional system and 10 and 7 day HRT Cannibal systems showed good settling properties throughout the operational period. However the 5 day HRT Cannibal system had an SVI at steady state exceeding 200ml/gm.

Settling characteristics can be altered by presence of filamentous microorganisms (Grady et al., 1997), exocellular polymer production (Urbain et al., 1993) and cation concentrations (Higgins and Novak, 1997b). Microscopic observations of the biomass from the 5 day HRT Cannibal system eliminated filamentous growth as a cause for the SVI deterioration. Further studies are required to determine the exact cause of the poor settling.

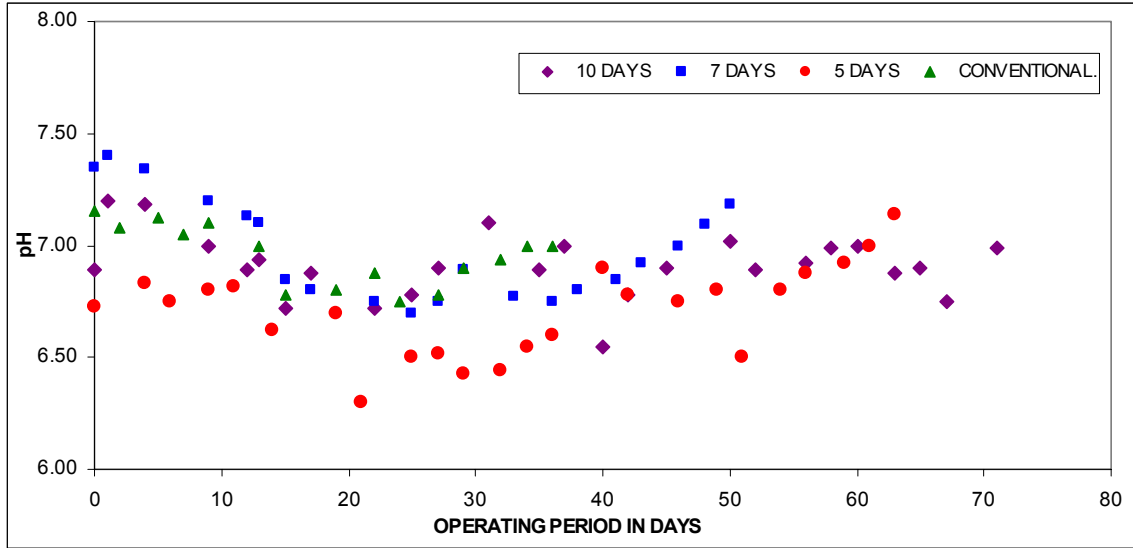
The Cannibal process effluent characteristics, namely soluble COD and pH, during phase I were studied. The chemical oxygen demand decreases with the production of methane in the anaerobic system. Minimum COD is reduced when methane is not produced and it is associated with hydrogen gas formation (Grady et al., 1999). Thus COD stabilization in the Cannibal bioreactor is directly related to methane production. The soluble COD in the effluent during phase I is shown in figure II-12. The 10 day HRT Cannibal system had the maximum COD reduction. The 5day HRT Cannibal system had the least COD reduction. The 10 day HRT Cannibal system had higher methane formation than the 5 days HRT Cannibal system as shown in figure II-19.

Figure II-12: Soluble COD in the effluent during Phase I



The pH in the effluent from any wastewater treatment plant should be in a range of 6.5 to 8.5 (Metcalf and Eddy, 2003). The effluent collected from the reactors during phase I were tested for their pH values. The Cannibal systems and the conventional system operated in an acceptable pH range. The pH in the effluents during phase I is shown in figure II-13.

Figure II-13: Hydrogen-ion concentration (pH), in the effluent during Phase I



Specific Oxygen Uptake Rate (SOUR) Test:

SOUR tests were conducted on samples of the Cannibal bioreactor supernatant and the aerobic biomass mixed together. The anaerobic solids were centrifuged and the supernatant was added to the aerobic biomass (both cannibal and conventional) to determine the SOUR. Similarly, tap water was added to the aerobic biomass for comparison. The aerobic thickened sludge was well aerated before the Cannibal bioreactor supernatant was added. The oxygen uptake rate curve reflects the kinetics of aerobic biodegradation of substrates by activated sludge (Orupold et al., 1999). Figure II-14 and II-15 shows the SOUR test results for the 7 and 5 day HRT systems.

Figure II-14: SOUR Test for 7 days HRT Cannibal System and the Conventional System

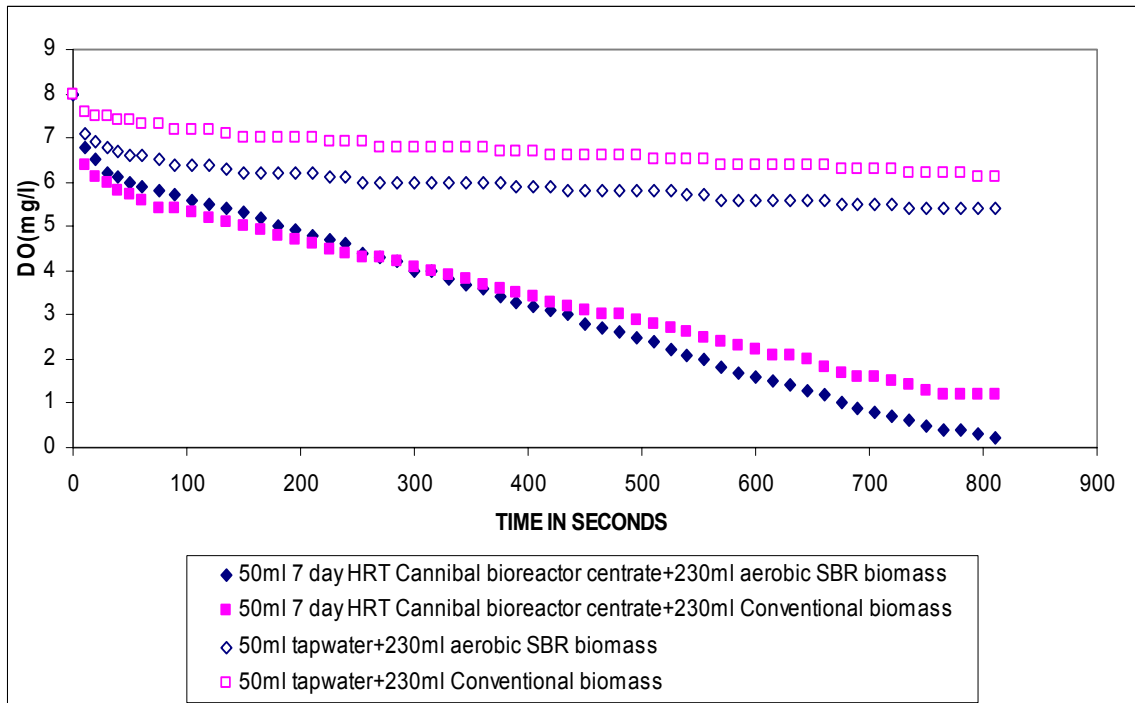
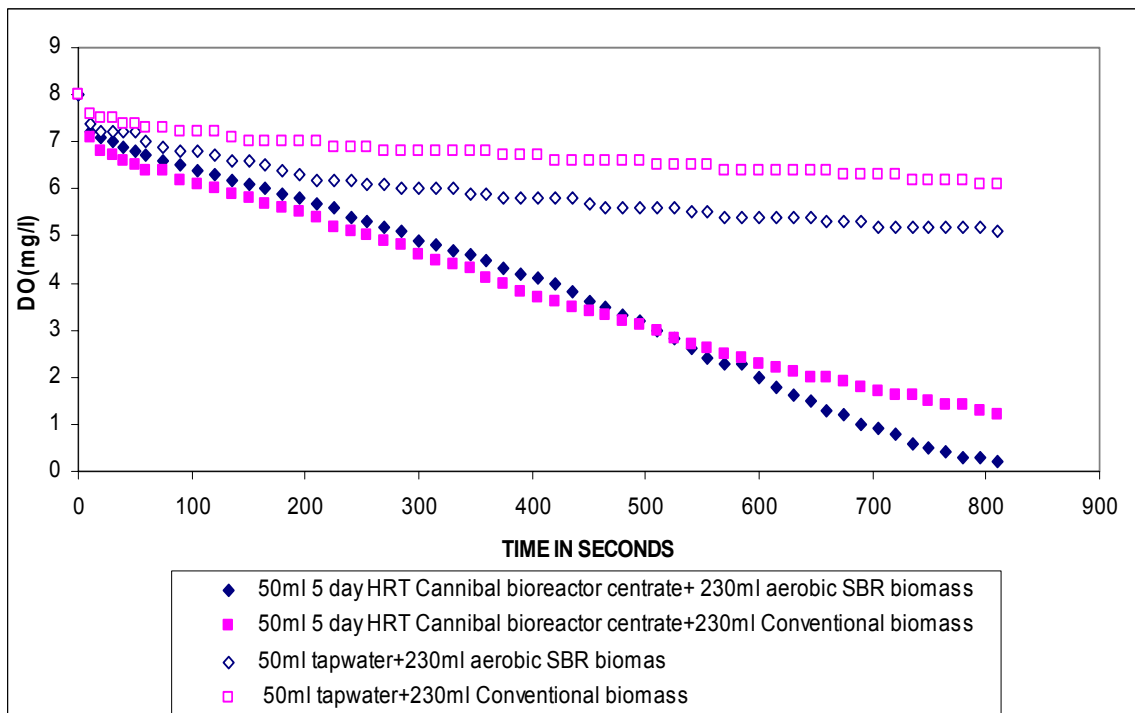


Figure II-15: SOUR Test for 5 days HRT Cannibal System and the Conventional System



The results from figure II-14 and II-15 show us that the behavior of the Cannibal system is different from the conventional system. In the Cannibal bioreactor, biodegradable materials that are not available to microorganisms in the aerobic SBR are released. When the released biodegradable materials are made available to the microorganisms they are readily digested in the aerobic SBR. The difference in the oxygen uptake is well noted when the Cannibal bioreactor supernatant and tap water are added to the aerobic biomass. Table 6 gives the SOUR of the 7 day HRT and 5 day HRT solids.

Table 6: Oxygen Uptake Rate (mg O₂/ hr/ gm of TSS)

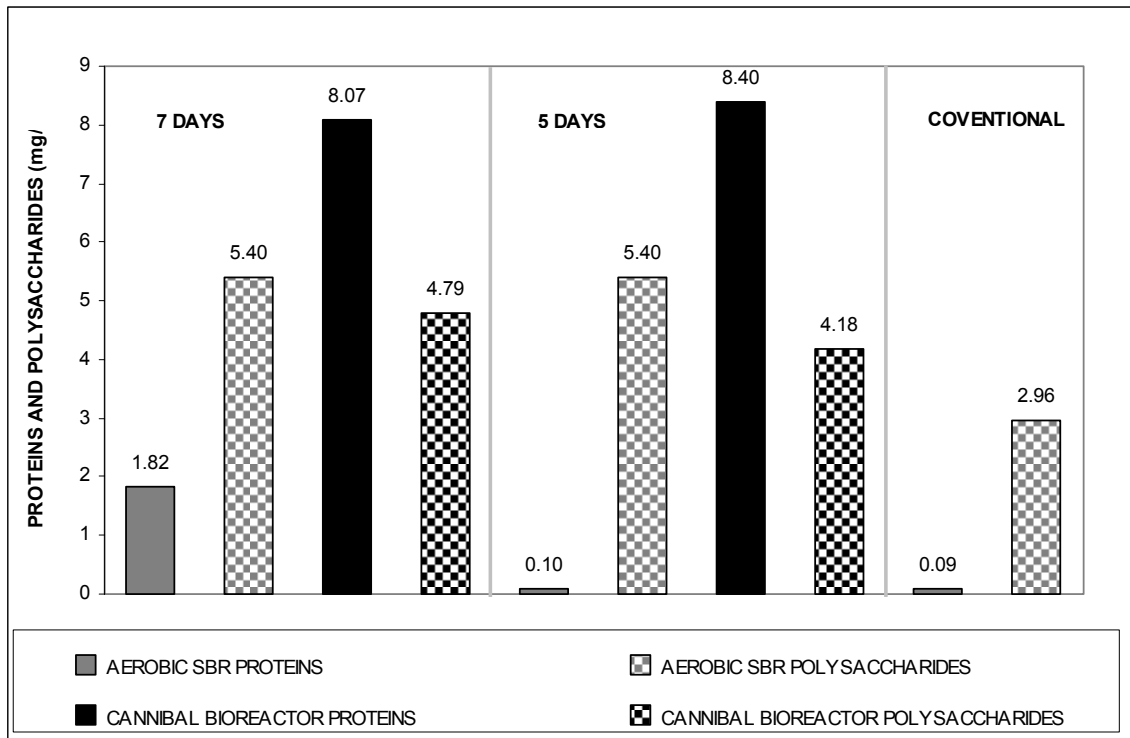
| | 230ml aerobic SBR biomass | 230 ml conventional biomass |
|--|----------------------------------|------------------------------------|
| 7 days HRT Cannibal bioreactor centrate | 0.14 | 0.10 |
| 5 days HRT Cannibal bioreactor centrate | 0.12 | 0.11 |

As can be seen from table 6, the difference between the 7 day HRT and the 5 day HRT Cannibal system is minimum. They show similar behavior except for the deterioration of SVI in the 5 day HRT Cannibal system.

Protein and Polysaccharide Test:

According to studies done by Novak et al. (2003), the concentration of protein released under anaerobic conditions is more than the amount of polysaccharide that is released. It is thought that the released biopolymer under anaerobic conditions is linked with reduced iron. The same study showed that the concentration of polysaccharide is higher than protein in the aerobic environment. The released polysaccharides are associated with divalent cations. Similar results with regard to proteins and polysaccharides concentration were obtained from the tests conducted on the phase I solids. The results are shown in figure II-16.

Figure II-16: Proteins and Polysaccharides in Phase I



The release of proteins, most likely associated with the reduced iron, is more in the anaerobic Cannibal bioreactor. It is proposed that when these released proteins are recycled to the aerobic SBR, they are easily degraded. Polysaccharides are also degraded but not as much as proteins. This suggests that the primary function of the Cannibal bioreactor is to release biopolymer, primarily proteins, into solution which are then biodegraded by the aerobic microorganisms.

Volatile Fatty Acids:

Volatile Fatty acids (VFA), an important intermediate compounds in the metabolic pathway of methane fermentation (Buyukkamaci et al., 2003), were measured in the Cannibal bioreactor to gain insight into the mechanisms responsible for solids loss in the Cannibal system. Research by Rubia et al. (2005) has shown that the retention time in the anaerobic bioreactor has a considerable effect on the population levels of methanogens and on the production of VFAs. Measurements of individual VFAs and total VFAs in the Cannibal bioreactors maintained at different HRTs are shown in figure II-17 and II-18 respectively.

Figure II-17: Volatile Fatty Acid Concentration in the Cannibal Bioreactors

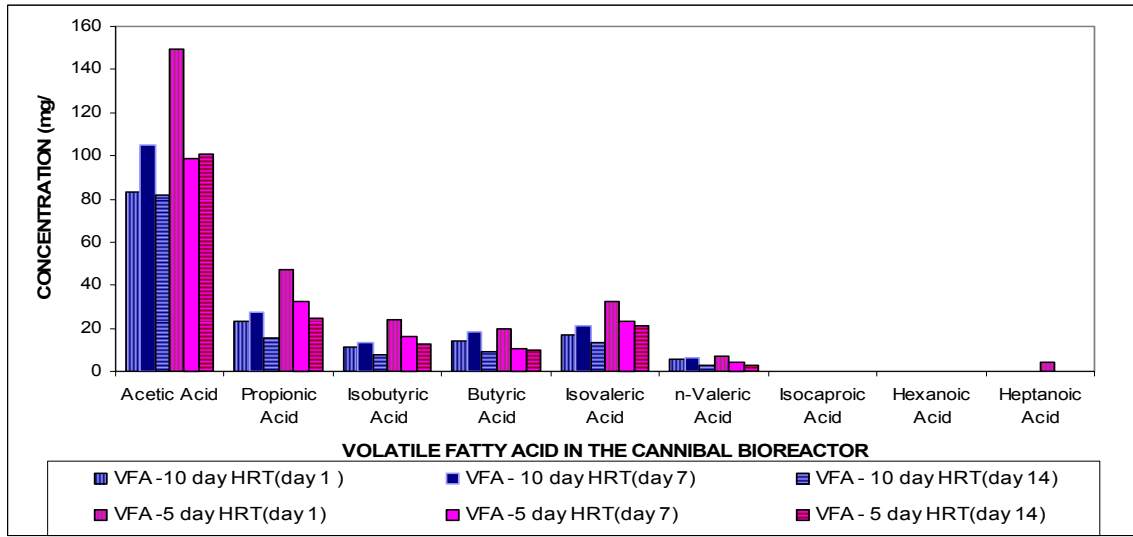
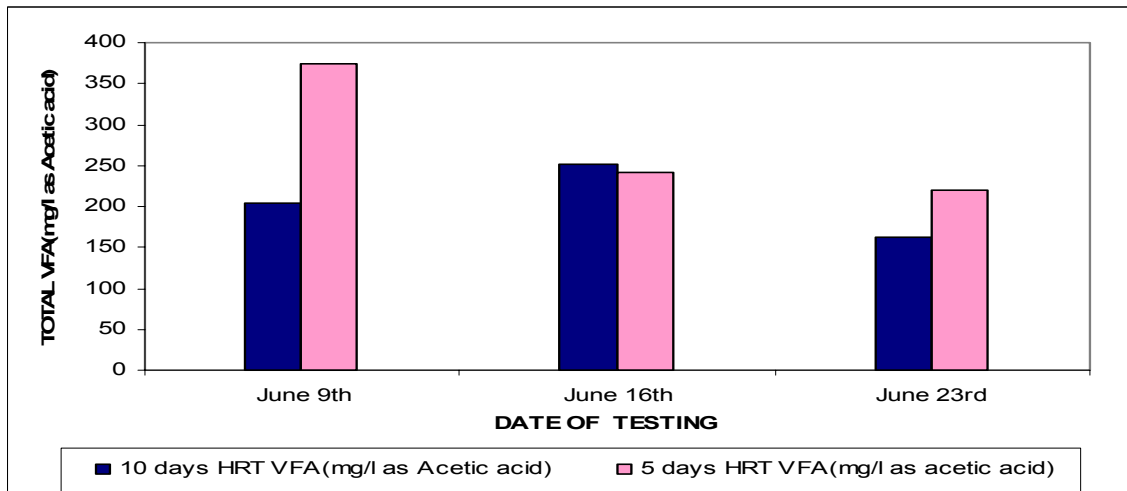


Figure II-18: Total Volatile Fatty Acids in the Cannibal Bioreactor

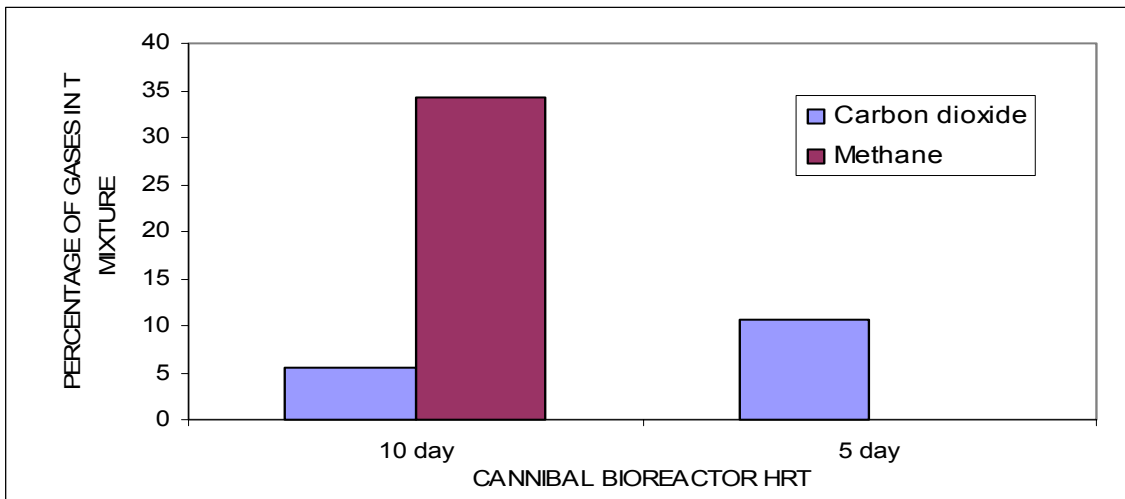


It can be seen from figures II-17 and II-18 that as the Cannibal HRT decreases the VFA accumulation increases. The VFA production and accumulation in the different HRTs Cannibal bioreactor require further investigation.

Biogas Production:

Gas bags were attached to the Cannibal bioreactors to prevent buildup of pressure in the bioreactors. The composition of gases was measured to get an insight into the relationship between the gas production and HRT.

Figure II-19: Percentage of Carbon Dioxide and Methane in the Gas Mixture



The data provide an idea about the methanogenic and acidogenic activity in the bioreactors. The absence of methane in the 5 day HRT is because the operational HRT was low. According to Grady et al. (1999), at lower SRT and temperature of 20°C, washout of methanogens occurs, preventing the formation of methane. In the 10 day SRT reactor, methane was generated and this corresponds to lower VFAs in the 10 day Cannibal reactor. It can be concluded from both the gas and VFA measurements that the loss of solids by the Cannibal system is not primarily due to degradation in the Cannibal bioreactor. The Cannibal bioreactor solubilizes organic matter from the flow which can then be biodegraded when the biomass is returned to the aerobic reactor.

SUMMARY

Phase I:

Phase I of this research has provided important results about the effect of HRT on the solids reduction in the system. The data clearly show that the wastage from the Cannibal system is less than the conventional system. Although there is a difference in the quantity of solids that has been wasted from the three cannibal systems, they are all lower than the conventional system. The 10 day HRT system gave the maximum solids reduction among the three cannibal systems that were operated in the laboratory. But, the 7 day HRT and the 5 day HRT did not show much difference from the 10 day HRT system. This research determined that the Cannibal system can still work efficiently at HRTs lower than 10 day. But, it should be understood that the solids destruction in a Cannibal system operated at 7 day or 5 day will not produce the same yield that a 10 day HRT Cannibal system would produce. This implies that onsite Cannibal systems will not fail if the HRT goes down due to unexpected operational troubles.

The 10 day HRT Cannibal system generated 35% to 40% less solids than the conventional system. The 7 day HRT Cannibal system and 5 day HRT Cannibal system generated between 25% to 35% less solids than the conventional system. Initial studies at Virginia Tech by Novak et al., (2006) showed that the Cannibal process generated 60% less solids than the conventional system. Compared to the present study, the earlier study had a higher yield in the conventional system. The difference in the yield values of the conventional system lies in the fact that the system HRT was highly different. In the earlier studies, the conventional SBR was maintained at an SRT of about 20 day. In this current study, the conventional SBR was maintained at a SRT over 100 days. At higher SRTs the decay of biomass is prolonged and the yield value decreases.

The SOUR data showed that the mechanism of solids destruction in the 7 day HRT Cannibal system and the 5 day HRT Cannibal system was the same. Though the 7 day HRT and 5 day HRT Cannibal system showed the same degree of solids destruction, the 5 day HRT Cannibal system had other complications. Important among them was the deterioration of the settled volume index. Also, compared to the other systems the

accumulation of VFAs in the 5 day HRT Cannibal system was higher. This can inhibit the proper functioning of the Cannibal bioreactor.

SPECIFIC CONCLUSIONS

Phase I:

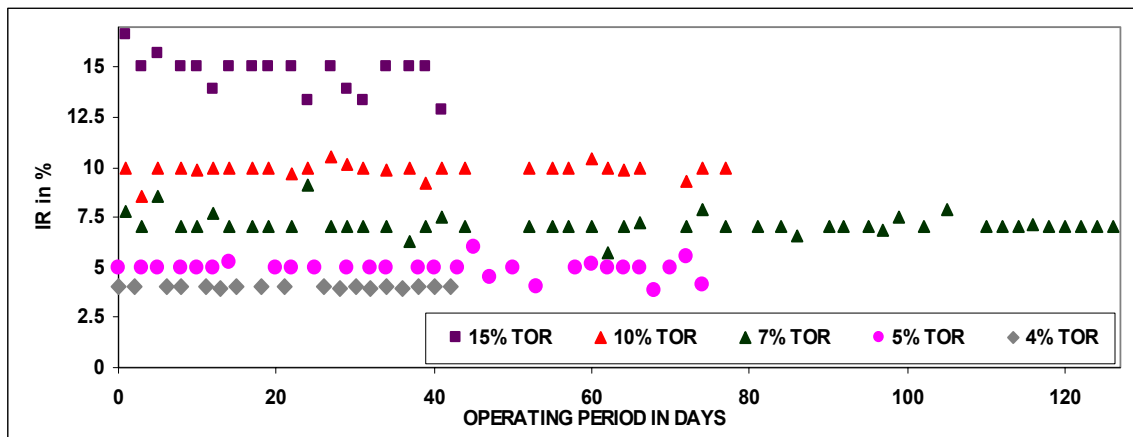
1. The 10 day HRT Cannibal system had the greatest solids destruction than the 7 day and 5 day HRT Cannibal system.
2. As the Cannibal HRT increases from 5 day to 10 day, the yield decreases by 25% to 35% for the 5 day HRT and 7 day HRT and by 35% to 40% for the 10 day HRT, compared to the conventional system.
3. From the protein and polysaccharide test, it was shown that the Cannibal bioreactor is involved in the release of biopolymers, primarily proteins, which are then degraded in the aerobic environment.
4. The Saturated Oxygen Uptake Rate was comparable for the 7 day HRT and the 5 day HRT system. The results strengthened the conclusion (Novak et al., 2006) about the release of organic matter in the Cannibal bioreactor

RESULTS AND DISCUSSION:

Phase II

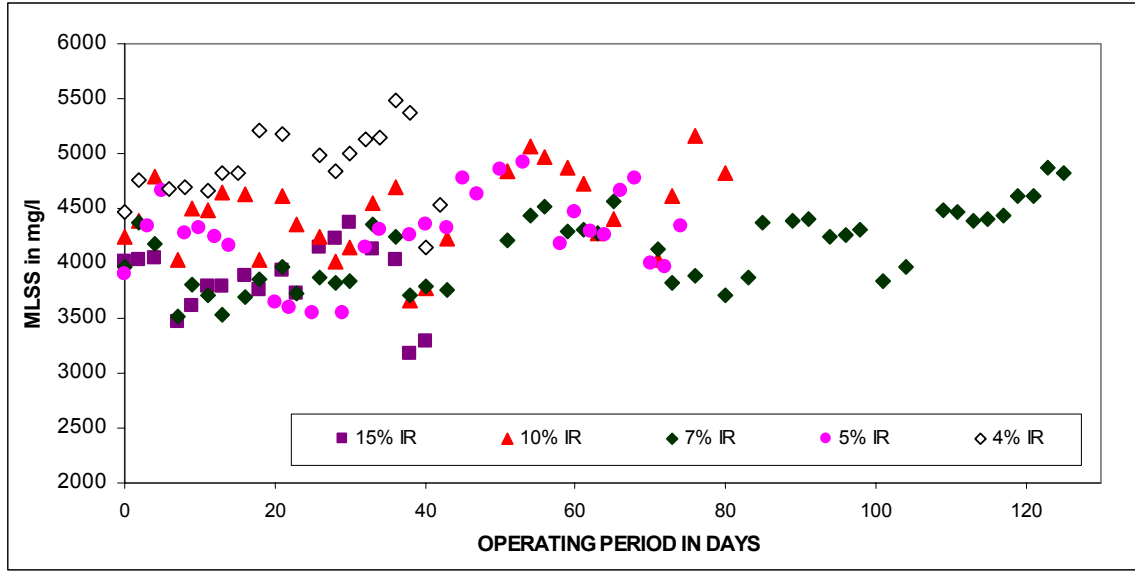
The objective of phase II was to vary the Interchange Rate and observe its effect on the solids destruction in the Cannibal system. The Interchange Rate is defined as the percentage (by mass) of biomass from the activated sludge system recycled through the Cannibal bioreactor, on a daily basis. The interchange rates under study during this phase were 15%, 10%, 7%, 5% and 4%. The settling volume of the aerobic solids in the SBR controlled the volume that was recycled to maintain the IR. Therefore the recycle volume was adjusted, based on the settling volume, three times a week to maintain the IR. The interchange rate that was maintained in the Cannibal system is shown in Figure II-20.

Figure II-20: Interchange Rate in the Cannibal Systems during Phase II



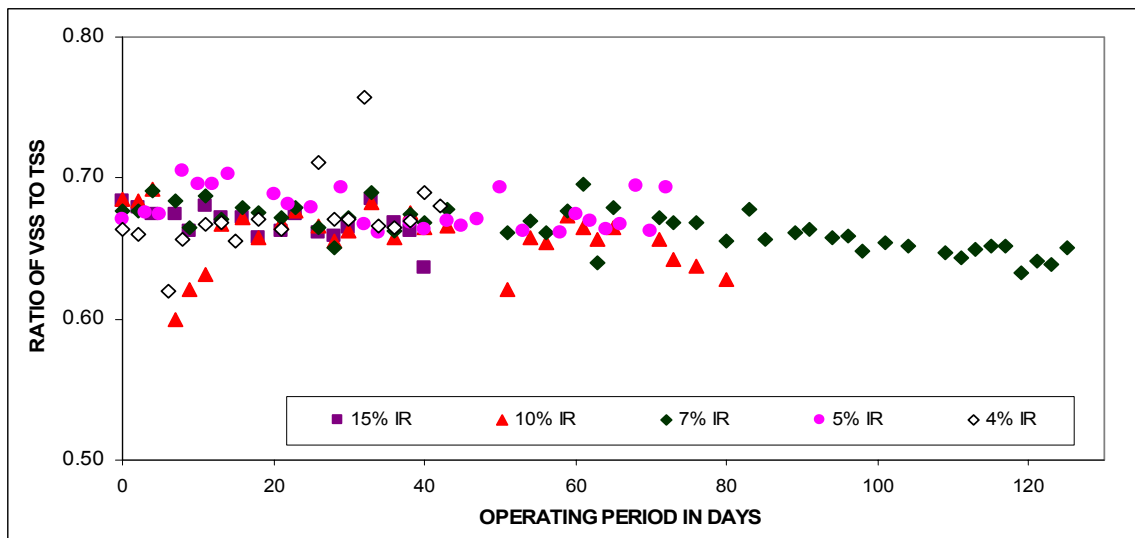
The Mixed Liquor Suspended Solids (MLSS) that was present in each of the aerobic SBR that were operated is shown in figure II-21. The hydraulic retention time maintained in the Cannibal bioreactor during this phase was 7 day. The hydraulic retention time maintained in the aerobic SBR was 1.5 days.

Figure II-21: Mixed Liquor Suspended Solids (mg/l) in reactors during Phase II



From figure II-21, it can be seen that the suspended solids begin to increase in the 4% IR Cannibal system quite early in the operating period. This indicates that very low interchange rates did not destroy solids to the same extent as the higher interchange rates. The ratio of VSS to TSS in the biomass during phase II is shown in figure II-22. The ratios were between 0.63 and 0.7. Variation in the ratios among the different IR Cannibal systems did not differ significantly probably because the solids retention time was the same for all the reactors.

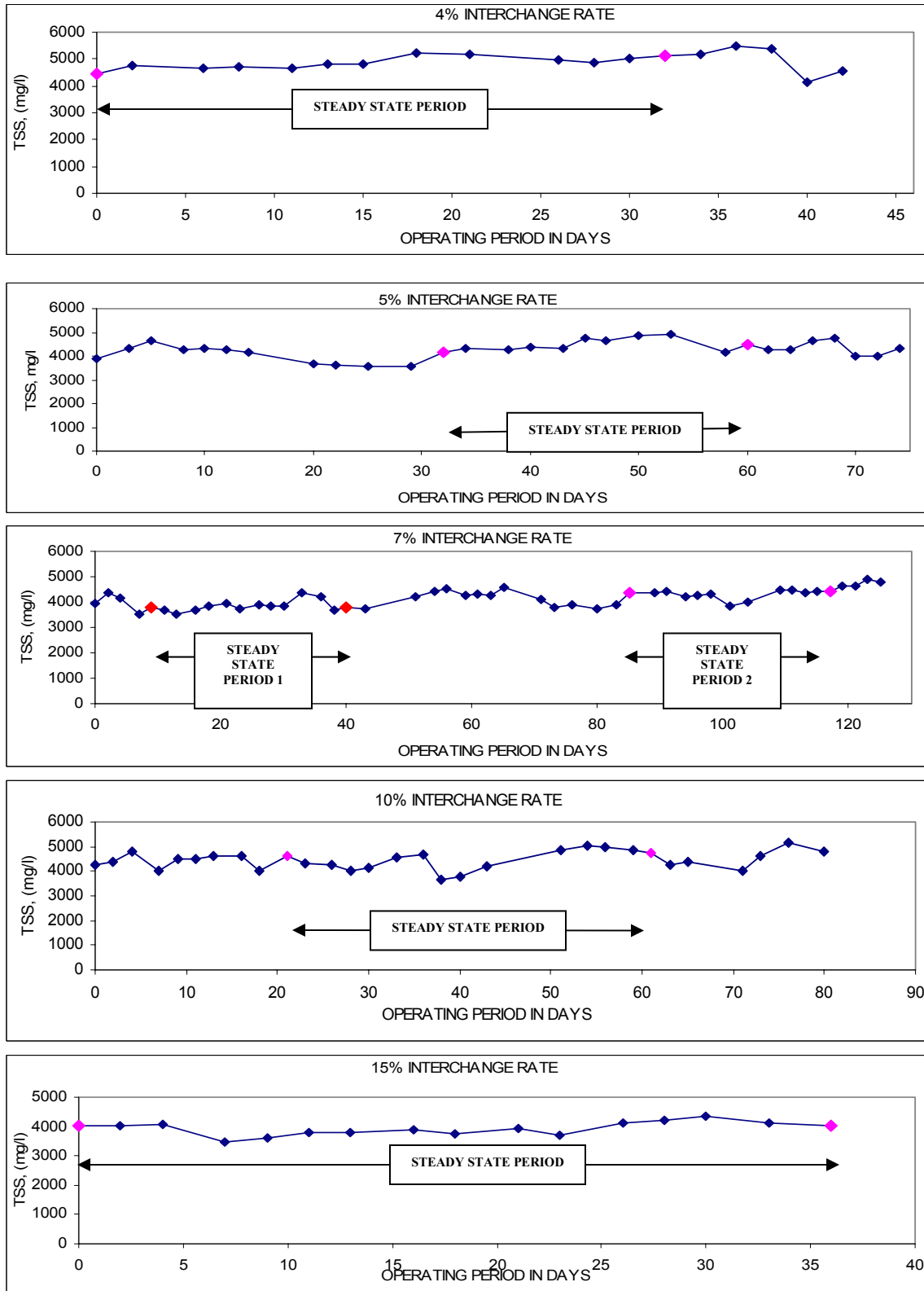
Figure II-22: Ratio of VSS to TSS in the Biomass during Phase II



As in phase I, the cumulative solids (TSS) wasted in each aerobic system during the operational period were used to predict the system's performance with regard to solids destruction. The solids from the aerobic SBR's were wasted due to sampling, effluent wastage and intentional wasting. One time intentional wasting was done from all the reactors, though at different times during the operational period.

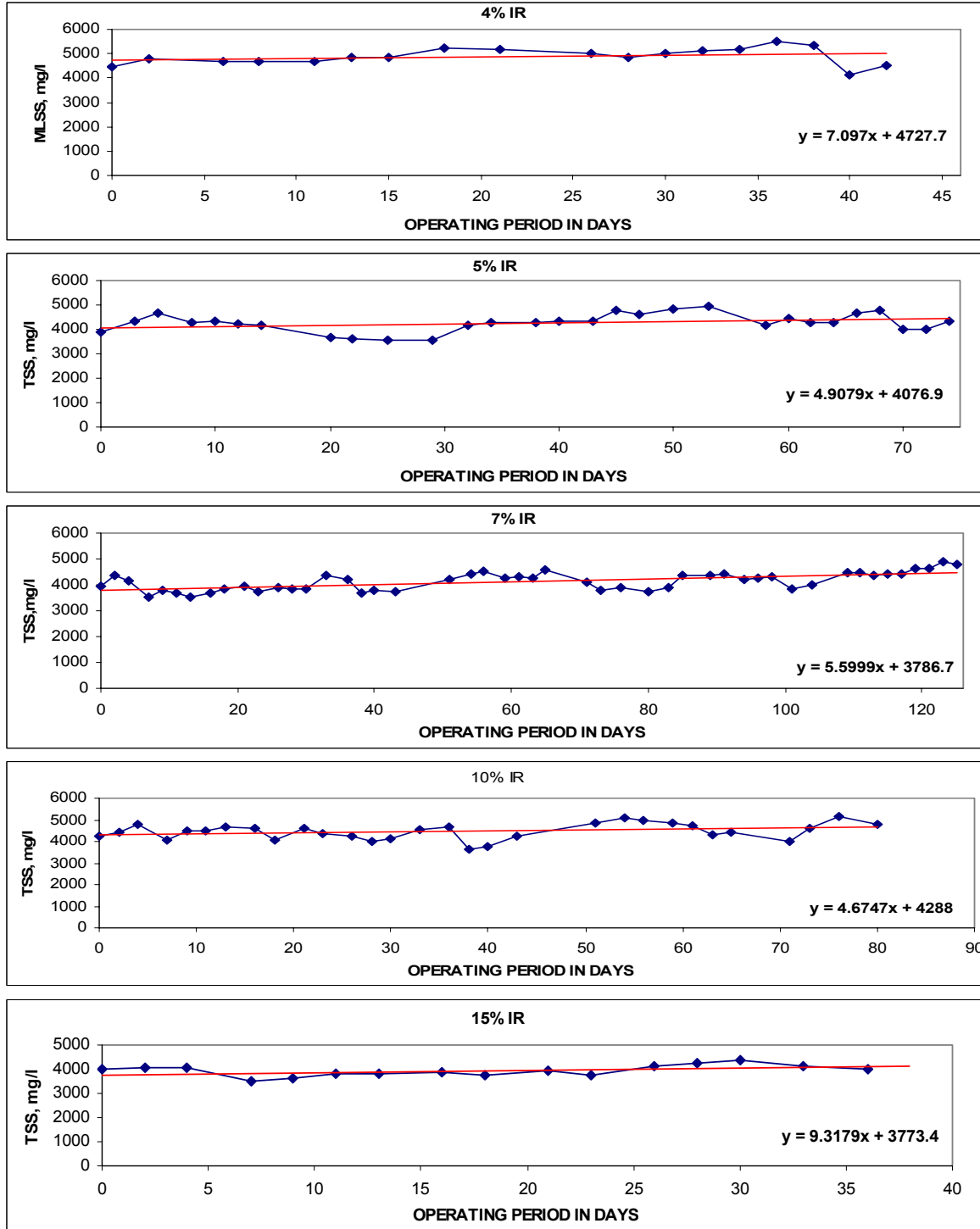
As in phase I, the cumulative solids were plotted using Method A and Method B. In method A, a steady state phase during the operational period was selected and the wastage during that specific phase was used to calculate the yield. The steady state period that was considered for the five systems is shown in figure II-23. For the 7% IR reactor two steady state periods were considered as noted in figure II-22. The period of operation for the 7% IR Cannibal system was long, but two periods were relatively steady, and these were used to determine the solids accumulation.

Figure II-23: Method A- Steady State Period for Phase II TSS



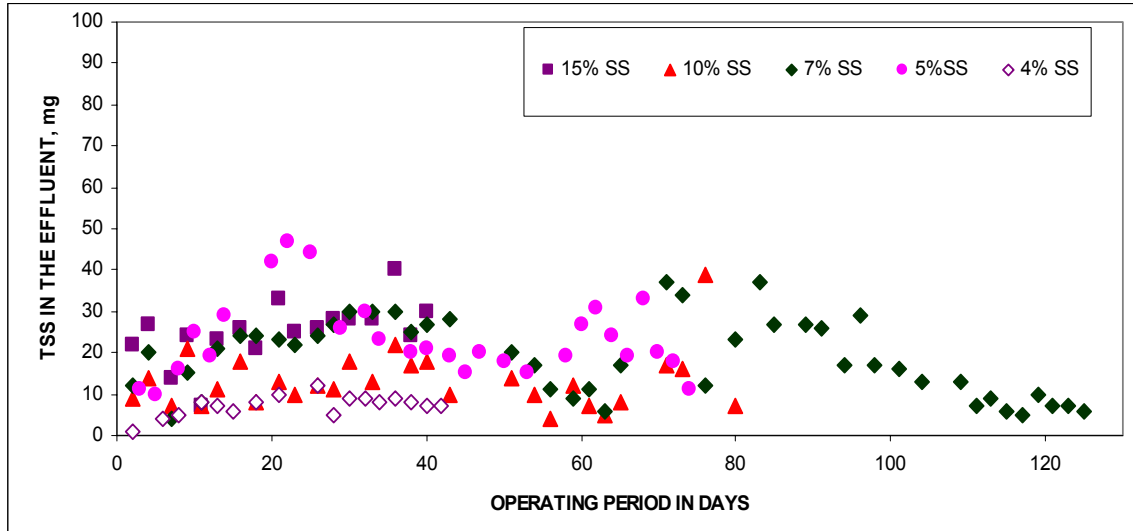
As described earlier, in Method B a linear regression for the entire set of data was considered. The slope obtained from the equation was used as the average biomass growth in each system. Figure II-24 shows the values of slopes that were used.

Figure II-24: Method B- Linear Regression for Phase II TSS



The solids wastage included the sampling wastage, effluent wastage, intentional wastage and average biomass growth. For the effluent wastage calculation the TSS shown in figure II-25 was used. The volume of effluent decanted each day was 2 liters.

Figure II-25: Total Suspended Solids (mg/l) in the Effluent in Phase II



As in phase I, a one time intentional wastage was done from all the reactors. This time biomass removed was used for iron and aluminum analysis. The mass of solids wasted from each system is shown in table 7

Table 7: Total Suspended Solids (mg) Wasted Intentionally During Phase II

| SYSTEM CONFIGURATION | 4% IR | 5% IR | 7% IR | 10%IR | 15% IR |
|----------------------|----------------------|----------------------|---------------------|----------------------|---------------------|
| TSS WASTED(mg) | 2683 | 2390 | 2088 | 2313 | 2028 |
| WASTAGE DONE ON | 36 th day | 68 th day | 4 th day | 16 th day | 4 th day |

The cumulative solids wasted from each system as calculated by Method A and B is shown in figures II-26 and II-27, respectively.

Figure II-26: Method A- Cumulative Solids (TSS) Wastage in Phase II

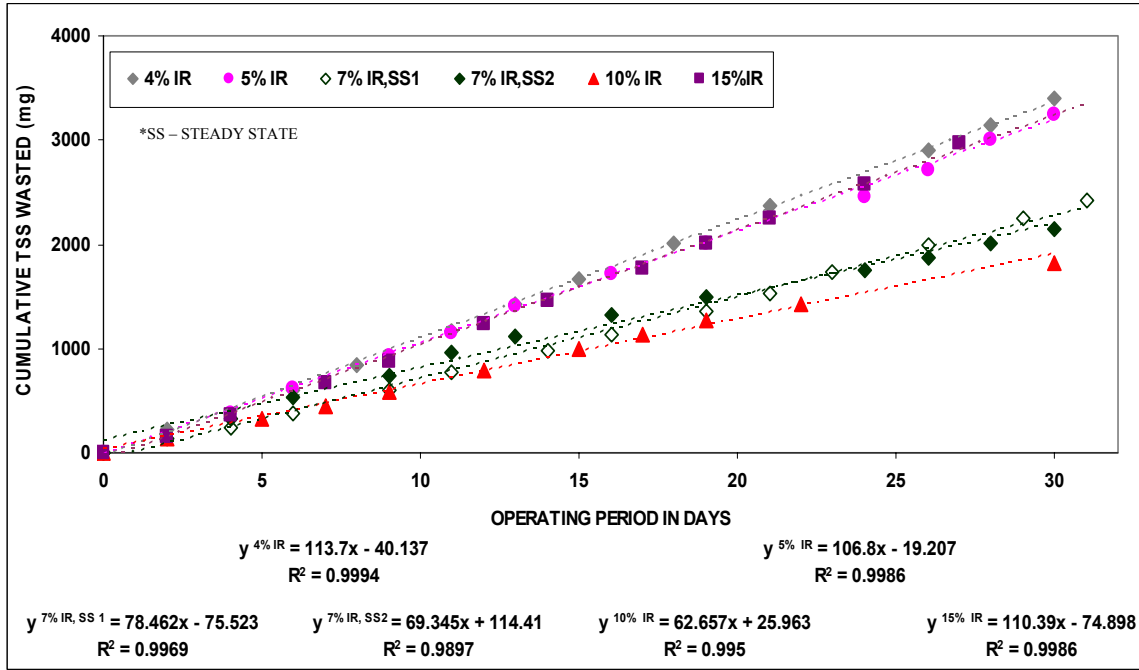
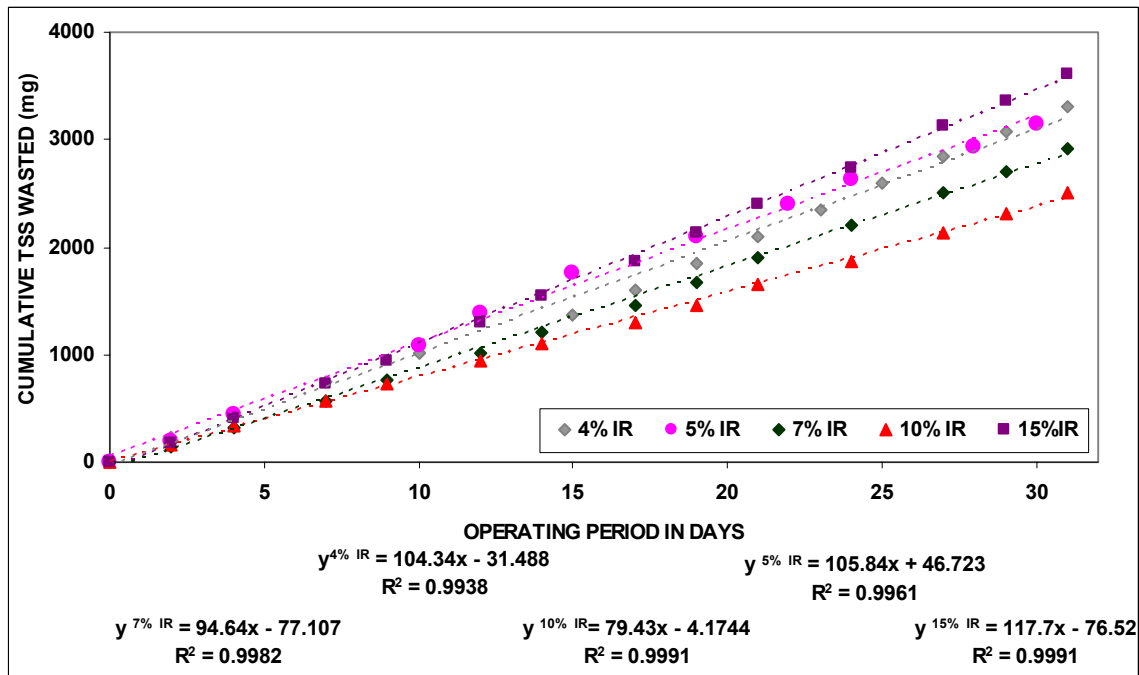


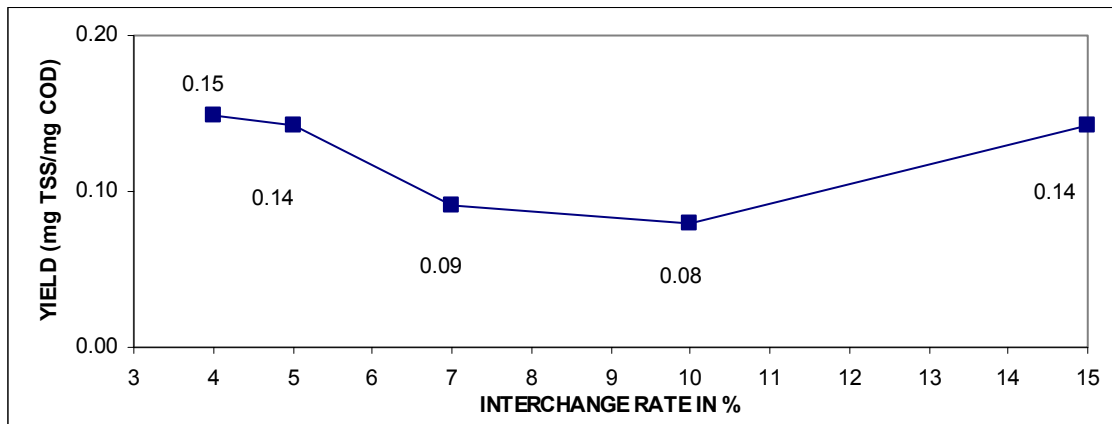
Figure II-27: Method B- Cumulative Solids (TSS) Wastage in Phase II



The 10% IR Cannibal system showed the maximum solids reduction compared to the other systems. However, the 7% IR Cannibal system did not show much difference from the 10% IR system. The 7% IR Cannibal system gave a similar performance with regard

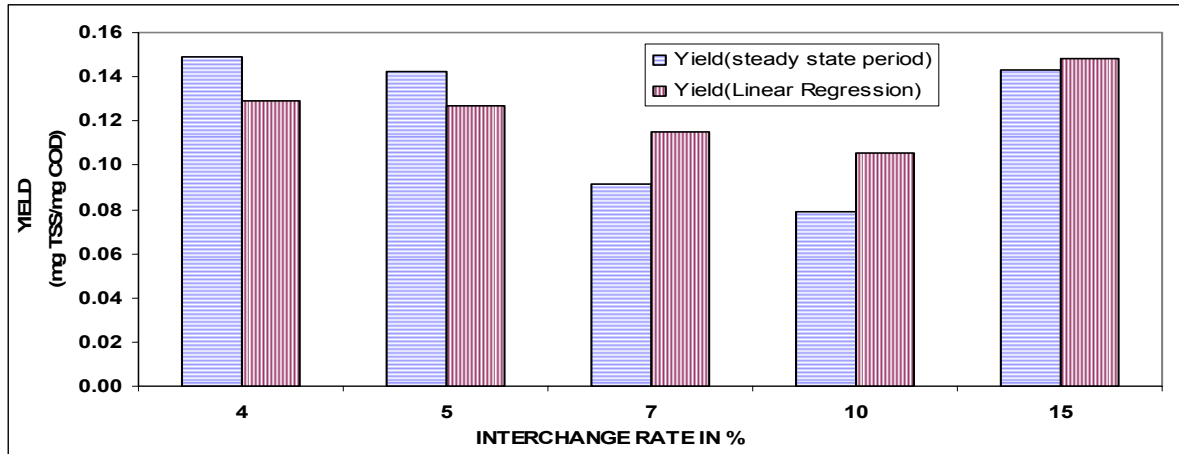
to solids destruction as the 10% IR Cannibal system. The 4% IR and the 5% IR Cannibal system showed similar slopes which indicated that their efficiencies in reducing the excess sludge was nearly the same but neither had a yield as low as the 7% and 10% IR as indicated in figure II-26 and II-27. The performance of the 15% IR Cannibal system was highly erratic. Different steady states gave very different solids production rates. In general, from figure II-24 it can be seen that the solids were gradually rising in the system and the linear regression slope was higher than that of the 10% IR Cannibal system. The results from this study show that 15% IR does not give better performance than the 10% IR. However, to clearly understand the performance of the 15% IR, further study is suggested. As far as the lowest interchange rate that is feasible for a Cannibal system, 7% IR would be recommended. It should although be noted that the yield would not be the same for the 10% IR and 7% IR. The observed yield values obtained through Method A is shown in figure II-28.

Figure II-28: Observed Yield (mg TSS/mg COD) from Method A



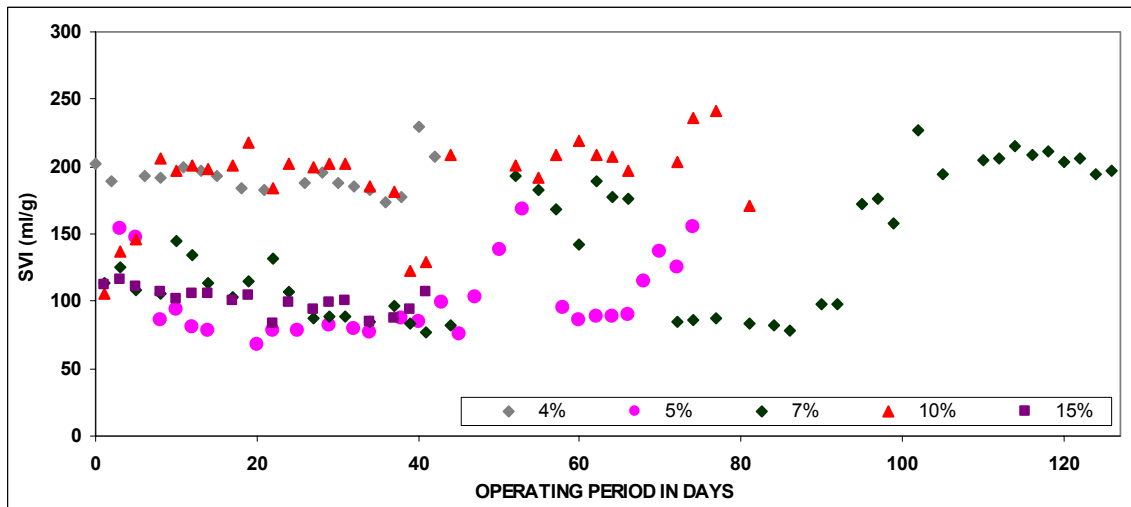
The yield value obtained through methods A and B are shown in figure 29.

Figure II-29: Observed Yield in Phase II from Method A and Method B



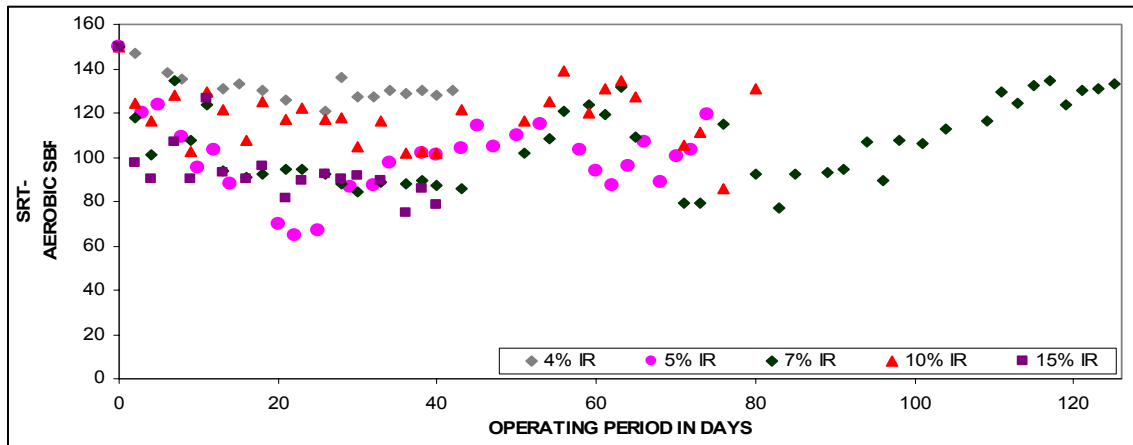
The sludge volume index during phase II is shown in figure II-30.

Figure II-30: Sludge Volume Index (SVI) during phase II



The reason for adjusting the recycle volume based on the settling volume three times in a week can be understood from figure II-30. The settling properties of the solids were not uniform and had a wide variation. Though the 15% IR Cannibal system had higher solids wastage, its floc characteristics were different from the others. This system had pin point floc with excellent settling properties. As in phase I, filamentous micro-organisms were not noticeable in any reactors. It is thought that the solids retention time in the aerobic SBR had an influence on the settling properties of the activated sludge (Bisogni et al., 1970, Andreadakis, 1993). The SRT in the SBR's were above 75 days as can be seen in figure II-31.

Figure II-31: Solid Retention Time in the Sequencing Batch Reactors during Phase II



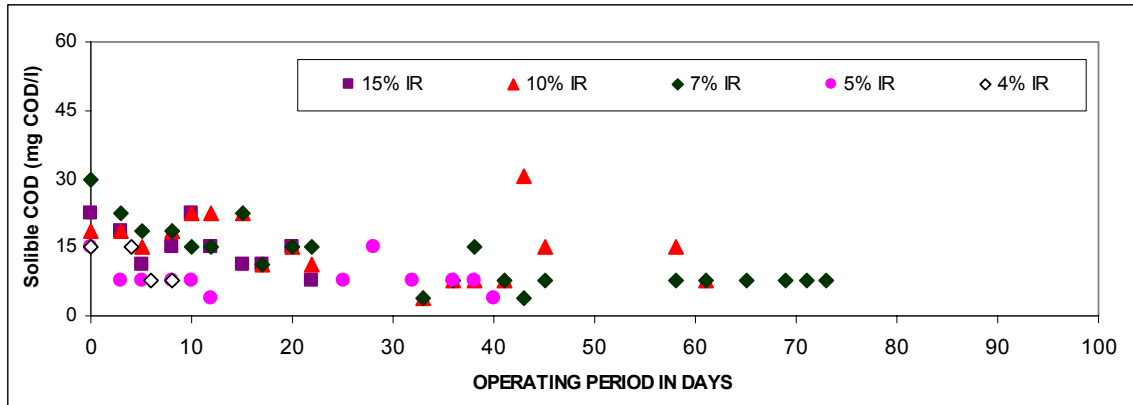
Nielsen et al. (1997) has shown that the presence of sulfide may have a deteriorating effect on the activated sludge floc structure by reducing Fe (III) to Fe (II). Since different IR's were used, the introduction of different percentages of sulfide from the Cannibal reactor into the SBR's could have been possible. But, further studies are required to confidently state this reason. The increase in the SVI (refer figure II-30) in the 5%, 7%, and 10% IR Cannibal system during certain phase of the operating period appeared to be due to the occurrence of red worms (figure II-32) in the aerobic SBR's. The occurrence of these worms was baffling and posed a lot of difficulty in the operation of the SBR's. They gradually disappeared in the reactors except the 7% IR Cannibal system where they appeared twice.

Figure II-32: Red Worms that Appeared in the Aerobic SBR



The soluble COD in the effluent during Phase II is shown in figure II-33.

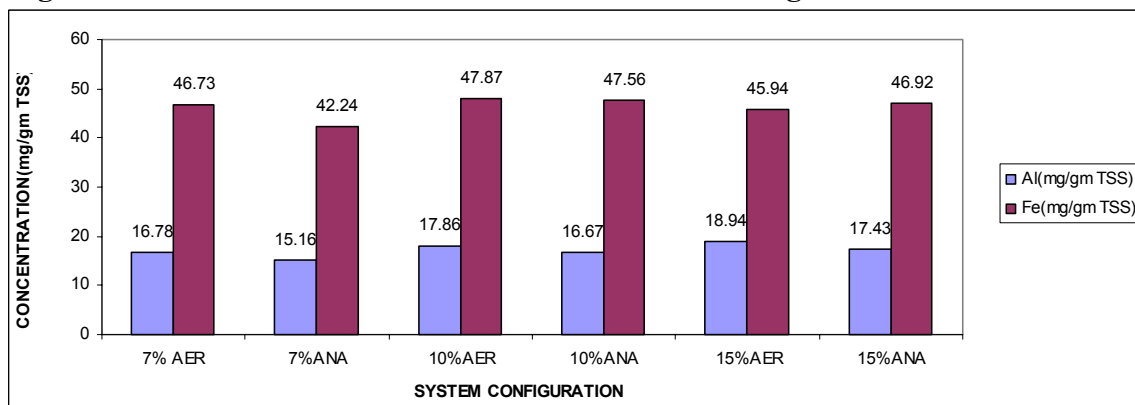
Figure II-33: Soluble COD in the effluent during Phase II



Iron and Aluminum:

Research by Park et al. (2006) showed that iron and aluminum have significant impacts on the characteristics of activated sludge. Although extensive studies have not been done on the role of Al and Fe on floc structure, they are used in WWTP’s as coagulating and phosphorus-removing agents. In this study, 20mg/l of Alum and Ferric Chloride was added to the feed. This is equivalent to 1.6mg/l of Al and 6.9mg/l of Fe, respectively. The accumulation of Al and Fe in the aerobic and anaerobic bio-solids was measured. Figure II-34 shows the iron and aluminum present in the 3 Cannibal systems.

Figure II-34: Aluminum and Iron in the Bio-Solids during Phase II



Volatile Fatty Acids:

Initial measurements of individual VFA and total VFA in the Cannibal bioreactors maintained during phase II are shown in figures II-35 and II-36, respectively.

Figure II-35: Volatile Fatty Acids Concentration in the Cannibal Bioreactors

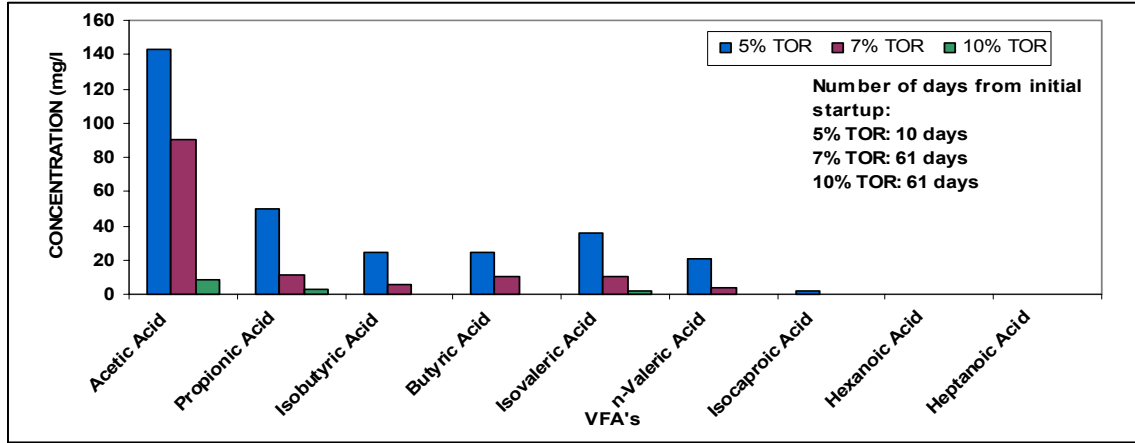
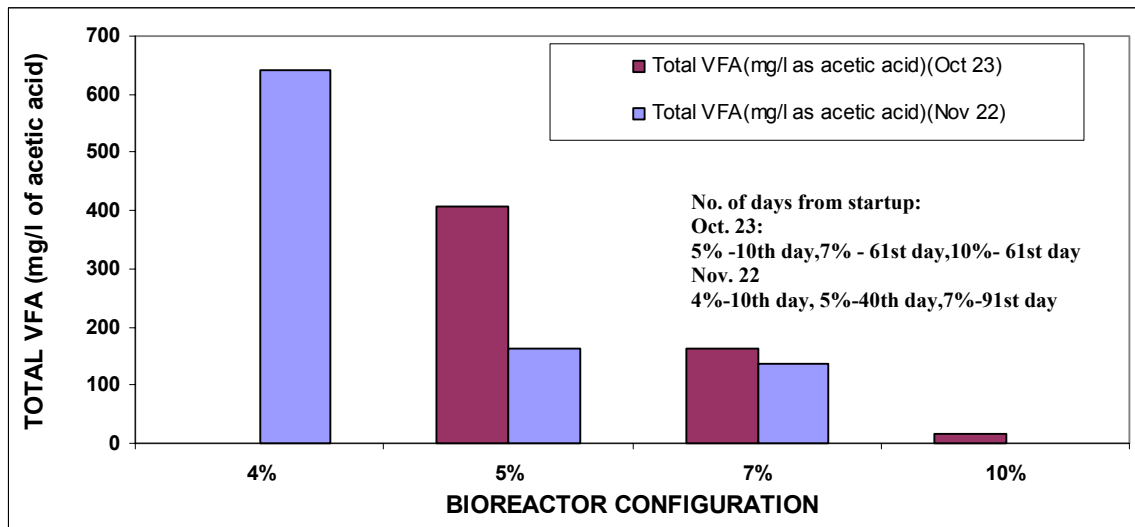


Figure II-36: Total Volatile Fatty acids in the Cannibal Bioreactors



From figure II-35 and II-36, it is thought that the Cannibal systems operating at lower interchange rates (below 10% IR) produce more VFA than the others. But it is not clear if very high IR (above 10% IR) will produce more or less VFA. Due to the limited literature on the Cannibal process, it is quite difficult to compare these results with previous relevant studies. The IR's can be looked at as different organic loadings to the Cannibal bioreactor maintained at the same detention time.

SUMMARY

Phase II:

Phase II of this study primarily focused on the effect of “Interchange Rate” on the solids destruction in the system. The effects of 4%, 5%, 7%, 10% and 15% IR were studied. From figure II-26 and II-27, it is understood that the 10% IR Cannibal system showed the maximum solids reduction compared to the other systems. However, the 7% IR Cannibal system did not show much difference from the 10% IR Cannibal system. The 4% IR and the 5% IR Cannibal system showed similar slopes which indicated that their efficiencies in reducing the excess solids were on the same level. The 4% IR and 5% IR Cannibal system had higher solids wastage when compared to 7% IR and 10% IR Cannibal system. The performance of the 15% IR Cannibal system was not very comprehensible. In general, from figure II-24 it can be seen that the solids were gradually rising in the system and the linear regression slope was higher than that of the 10% IR Cannibal system. The advantage of this system was the pin point floc structure with excellent settling characteristics. This study proposes that 15% IR does not give better performance than the 10% IR. It is clearly seen that optimization of the Cannibal process is very important from the above results. Since the volume of recycle is directly proportional to the volume of the Cannibal bioreactor, a lower interchange rate would be cost effective. As far as the lowest interchange rate that is feasible for a Cannibal system, 7% IR would be recommended. It should although be noted that the yield would not be the same for the 10% IR and 7% IR. The yield in the 10% IR Cannibal system was 13% lower than the yield in the 7% IR Cannibal system which in turn was lower than the yield in the 4% and 5% IR Cannibal system by 35%.

The settling volume of the aerobic bio-solids was not uniform during phase II. The possible reasons that could explain the irregularity in the SVI are variation of solids retention time, sulfide production and occurrence of red worms. The performance of the aerobic SBR's was highly disturbed by the red worms. The origin and propagation of the red worms was not traceable.

Initial measurement of VFA in the bioreactors predicted that the Cannibal bioreactors with interchange rates lower than 10% produced more VFA. To gather information about production of VFA in Cannibal system with interchange rates higher than 10%, further studies are required. In this study, VFA measurement was done as a supplementary measurement and hence it was not monitored on a regular basis. Also due to the limitation of literature on the variation of VFA with different IR, it is difficult to arrive on a reasonable conclusion. Measurement of iron and aluminum was done to gain insight about the accumulation of these in the bio-solids. The results showed that the presence of iron and aluminum in the 7% IR, 10% IR and 15% IR Cannibal system bio-solids were similar.

SPECIFIC CONCLUSIONS

Phase II:

1. The 10% IR Cannibal system had the greatest solids destruction.
2. The yield decreased from 4% IR to 10% IR and increased at 15%. This implies that an optimum IR is essential for the Cannibal process.
3. Apart from higher solids wastage the 4% IR and the 5% IR Cannibal systems had higher VFA production compared to the others.

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