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SMALL PILOT SCALE STUDY FOR NEW WASTEWATER TREATMENT PROCESS: HyVAB

(HYBRID VERTICAL ANAEROBIC BIOFILM)

María del Mar Batista Seguí

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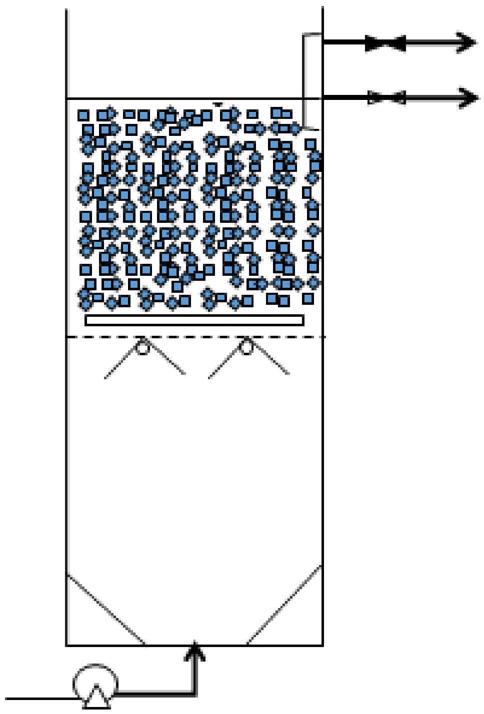

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ABSTRACT

Due to strict pollutant discharge limits the wastewater industry faces the challenges to find more effective treatments but without increasing energy, space requirements or operational cost, especially for industrial wastewater with high amount of pollutants, such as chemical oxygen demand (COD). Conventional biological treatments have shown good treatment efficiency for this type of industrial wastewater, but these systems have operational limitations (large space requirements, no possibility of biogas collection or long retention times). High rate integrated bioreactors are able to overcome these limitations. This type of reactor combines wastewater processes in a single bioreactor unit that are normally done in separate steps.

The objective of this study is to investigate the start-up and the treatment performance of the novel high rate aerobic–anaerobic reactor called the Hybrid Vertical Anaerobic Biofilm (HyVAB). The reactor operates as a single treatment unit consisting in two chambers connected vertically. The upper chamber is working using Continuous Flow Intermittent Cleaning (CFIC®) system, which is a technology developed by Biowater AS, and the lower chamber incorporates the Up Flow Anaerobic Sludge Blanket (USAB) technology. HyVAB offers important improvements for biological wastewater treatment systems. These are: less space requirements, lower sludge production and biogas collection without compromising the COD removal treatment efficiency. The biogas can be used as a renewable source of energy.

The study was carried out with two different sized pilot scale reactors placed in different locations treating high strength wastewater (COD >10.000 mg/L) sourced from Norsk Spesialolje (NSO), Kambo (Norway). The main findings are that the start-up was accomplished in only 20 days. During the 20 days, HyVAB exhibited treatment efficiencies with an average of 82% COD removal and attaining 97% after three months of operation. The reactor also recovered fast after periods of organic overloads The results make this reactor a worthy candidate for further studies of economic feasibility and in steady state operations.

SAMMENDRAG

På grunn av strengere utslippskrav står avløpsbransjen overfor utfordringen med å finne mer effektive behandlingsprosesser, men uten å øke energi, plassbehov eller operasjonelle kostnader, spesielt for industrielt avløpsvann med høyt innhold av forurensende stoffer (det vil si, med høy kjemisk oksygenforbruk, KOF). Konvensjonelle biologiske behandlinger har vist god renseeffekt for denne typen av industrielt avløpsvann, men disse systemene har vanligvis operasjonelle begrensninger (store plassbehov, ingen mulighet for biogass samling eller lang oppholdstid). *High rate integrated* bioreaktorer er i stand til å unngå disse ulemper. Denne type reaktor kombinerer flere vanlige avløpsrensingprosesser som normalt utføres i separate trinn i en enkel enhet.

Målet med denne studien er å undersøke oppstart og utførelsen av den nye høy aerob - anaerob reaktoren nevnt *Hybrid Vertikal Anaerob Biofilm* (HyVAB). Reaktoren opererer som en enkelt behandlingsenhet som består i to kameer som er koblet vertikalt. Det øvre kammeret fungerer ved hjelp av *Continuous Flow Intermittent Cleaning* (CFIC®) system, som er en teknologi utviklet av *Biowater AS*. Det nedre kammeret inkorporerer *Up Flow Anaerobic Sludge Blanket* (USAB) teknologi. HyVAB tilbyr viktige forbedringer for biologisk avløpsrensingsystemer: mindre plassbehov, lavere slamproduksjon og samling av biogass uten å redusere renseeffekten (KOF fjerning). I tillegg kan biogass brukes som en fornybar energikilde.

Studien ble utført med to pilotskala-reaktorer med ulike størrelse som var plassert på forskjellige steder. Begge to behandlet høyforurenset avløpsvann (KOF > 10,000 mg/L) hentet fra Norsk Spesialolje (NSO), Kambo (Norge). Hovedfunnene er at oppstarten ble oppnådd på bare 20 dager. I løpet av disse 20 dagene, oppnådde HyVAB behandlingseffektiviteter med et gjennomsnitt på 82 % KOF fjerning og 97 % etter tre måneders drift. Reaktoren utvant også raskt etter perioder med organiske overbelastning.. Resultatene gjør denne reaktoren til en god kandidat for videre studier av økonomisk gjennomførbarhet og rensingeffektivitet i *steady-state* avløpsvannbehandling.

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LIST OF ACRONYMS AND ABBREVIATIONS

HyVAB	Hybrid Vertical Anaerobic Biofilm
CFIC	Continuous Flow Intermittent Cleaning
BOD	Biochemical Oxygen Demand
CH_4	Methane
CO_2	Carbon Dioxide
UASB	Upflow Anaerobic Sludge Blanket
EU	European Union
GHG	Greenhouse Gas
CDM	Clean Development Mechanism
COD	Chemical Oxygen Demand
TSS	Total Suspended Solids
VSS	Volatile Suspended Solids
TS	Total Solids
VS	Volatile Solids
TN	Total Nitrogen
TP	Total Phosphorous
OiW	Oil in Water
RBC	Rotating Biological Contactors
MBBR	Moving Bed Biofilm Reactor
VFA	Volatile Fatty Acids
$NaHCO_3$	Sodium bicarbonate
VHL	Volumetric Hydraulic Load
HRT	Hydraulic Retention Time
OLR	Organic loading rate
DO	Dissolved Oxygen
NSO	Norsk Spesialolje
SP	Sampling Point
POME	Palm oil mill effluent

APPENDIX: TABLES OF RESULTS

1 INTRODUCTION

Trends in municipal and industrial wastewater management at the global level have changed in the last century. The main drivers for these changes are the scarcity and pollution of natural fresh water supplies due to the continued population growth and industrialization (Chan et al. 2009). The pollution is produced by the discharge of inadequately treated water from the municipality (households, hospitals, schools, etc.) and industries. This inadequately treated water can contain contaminants that can be naturally treated by ecosystems but not if the amount of discharge is high (over 1000 mg/L). There are some industries that produce wastewater with high levels of pollutants (oil and food processing, textile or pulp and paper); hence, these industries' effluent treatment face special challenges regarding cost effectiveness.

Combating this threat of pollution and water scarcity is a significant environmental priority for many governments. For example, the European Union has developed strict pollutant discharge requirements in their environmental policies, also international organizations have stringent regulations about luxury ocean cruise and passenger ships where zero discharge is compulsory (Phattaranawik & TorOve 2010). However, the industries that produce the contaminants perceive these requirements to be a burden leading to additional costs because more treatment means more space requirements and energy consumption. Moreover, the instability in energy prices has encouraged wastewater treatment systems to use sustainable technology that provides renewable energy, low operation and maintenance costs with small space requirements but without compromising the quality of the effluent (Phattaranawik & Leiknes 2011).

To have a successful treatment process it is important to choose the right combination and sequence of treatment methods. Anaerobic- aerobic treatments have shown great performance during last decades, but these conventional systems have some operational limitations (big space requirements, difficulties in biogas collection or long retention times). These limitations can be addressed with the use of high rate integrated bioreactors, which are considered a promising sustainable wastewater treatment technology. The main characteristic of this type of reactor is the combination of wastewater processes in a single bioreactor unit that are normally done in separate steps (Chan et al. 2009).

A single reactor unit with the combination of anaerobic-aerobic treatment can enhance the overall efficiency of the system plus be cost effective and efficient with small footprint (Chan et al. 2012). In addition, biogas produced in the digestion can potentially be collected and used as a renewable source of energy (Tauseef et al. 2013). However, there is a lack of evaluation of these reactors in large-scale implementation. Further improvements on biogas collection and the use of suspended media are considered essential (Chan et al. 2009).

The treatment potential for such reactors must be examined and optimized through new scientific investigations. The objective of this research is to propose a new combined aerobic –anaerobic reactor configuration that operates as a single treatment unit, called the Hybrid Vertical Anaerobic Biofilm (HyVAB). The innovation of this reactor is that includes a new technology called Continuous Flow Intermittent Cleaning (CFIC) in the aerobic stage. In this thesis, the design, start up and steady state performance treating high organic strength industrial wastewater are investigated.

1.1 Wastewater treatment for industrial wastewater

Industrial and urban wastewaters have different characteristics not only in the components but also in the ranges of pollutants (Table 1). Industrial wastewater with pollutant limits within municipal wastewater can be discharged to the municipal sewer system and be treated by the municipality. However, industrial wastewater with high levels of contaminants must be pre-treated before discharge either to the municipality sewage system or directly to the environment. For example, the organic content of industrial wastewater can be within 5-20 times greater that urban wastewater and if the treatment plant is not designed to treat these water characteristics it would result in a treatment process failure. The treatment of industrial wastewater with high levels of certain compounds have specific challenges that must be taken into account to achieve a successful treatment (Hammer & Hammer 2004).

Table 1 Average characteristics of selected wastewaters, (Hammer & Hammer 2004) and (Latif et al. 2011)

Type of water	BOD (mg/L)	Total solids (mg/L)	Suspended solids (mg/L)	Nitrogen (mg/L)	Phosphorous (mg/L)
Urban wastewater	200	800	240	35	7
Milk processing	1000	1600	300	50	12
Meat packing	1400	3300	1000	150	16
Synthetic textile	1500	8000	2000	30	0
Palm oil mill effluent (POME)	11000-30000	43635	9000-25000	500-900	-
Dairy wastewater	1940	1560	830	51	22

1.2 Biological treatments for wastewater

Wastewater treatment must be designed for a specific project after defining the treatment objectives. These treatment objectives have to be established according to the international, state and local regulations. Afterwards, the treatment degree will be determined by comparing the influent characteristics with the effluent characteristics. To achieve this treatment degree a number of different methods can be used depending on the principle involved: physical, chemical and biological (Metcalf & Eddy, Inc. 1991). This research focuses on biological treatment processes because they are used to remove biodegradable organic substances.

Biological treatments are derived from processes that occur on nature carried out by microorganisms. Microorganisms transform the contaminants into gases that are released into the atmosphere as well biological cell tissue that can be easily removed from wastewater by settling. By controlling the environment of these microorganisms, the process can be sped up to obtain greater efficiency in the cleaning process.

The biological processes used for wastewater treatment can be divided in five major groups, depending on the environment characteristics: aerobic, anoxic, anaerobic, combined and ponds. They can be subdivided depending on where the microbial activity takes place: suspended, attached or combined growth systems. Biological treatment systems are usually applied to the removal of carbonaceous organic matter, nitrification, denitrification, phosphorous removal and waste stabilization (Metcalf & Eddy, Inc 1991). The most common biological treatments processes are anaerobic and aerobic. Anaerobic treatment is the degradation of waste into a variety of products in the absence of oxygen, including methane (CH_4) and carbon dioxide (CO_2). Conversely, aerobic treatment uses free or dissolved oxygen by microorganisms, which it converts into biomass and CO_2.

1.3 Biogas production

As mentioned previously, aerobic processes have the potential of producing methane gas that can be collected and used as a renewable source of energy. The goal of the European Union (EU) is that 20% of the overall energy consumption of the EU has to come from renewable energy by 2020; however, nowadays this percentage is around 9%. Biogas can help to achieve this goal because it can be used for energy production. Moreover, biogas production can also help to achieve another 2020 EU goal: reducing the deposition of biodegradable municipal wastewater into landfills to 50% by reducing of sludge during aerobic digestion (Havukainen et al. 2014). Due to this priority, the production and improvement of biogas has gained importance in the recent years among researchers.

There are different ways of producing biogas: manure, landfills and digestion of wastewater sludge. Anaerobic digestion of sludge, in addition of the traditional role in the wastewater treatment, has the possibility of contributing to reduction of greenhouse gas (GHG) emissions by capturing the methane that otherwise will be released to the atmosphere. Biogas production can also be used as a secondary source of income by taking advantage of the Clean Development Mechanism (CDM) under the Kyoto Protocol by shortening the payback time of investments related with the technology (Chan et al. 2009). Not implementing technologies to take advantage of biogas production would result in a clear waste of possibilities towards achieving less costly and more sustainable treatment processes.

1.4 Combined aerobic-anaerobic reactors

Each treatment process has strengths and weaknesses (Table 2), such as the energy requirement or the sludge production or the start-up time.

Table 2 Comparison of aerobic and anaerobic treatment (Chan et al. 2009)

Feature	Aerobic	Anaerobic
Organic removal efficiency	High	High
Effluent quality	Excellent	Moderate to poor
Organic loading rate	Moderate	High
Sludge production	High	Low
Nutrient requirement	High	Low
Alkalinity requirement	Low	High for certain industrial water
Energy requirement	High	Low to moderate
Temperature sensitivity	Low	High
Start-up time	2-4 weeks	2-4 months
Odour	Less opportunity odours	Potential odours problems
Bioenergy and nutrient recovering	No	Yes
Mode of treatment	Total (depending on feedstock characteristics)	Essentially pre-treatment

When anaerobic and aerobic processes alone do not accomplish the treatment efficiency required, combined treatments can be implemented and they are promising in terms of high organic matter removal efficiency, smaller sludge production and no pH correction. The benefits of integrated anaerobic-aerobic processes have been summarized by Chan et al., (2009, page 2):

- Great potential of resource recovery: biogas production by anaerobic digestion of the organic pollutants.
- High overall treatment efficiency: the aerobic treatment after the anaerobic on results in very high overall treatment efficiencies while smoothes out the fluctuation quality in the anaerobic treatment.
- Less disposal of sludge: by digesting the excess of aerobic sludge in the anaerobic tank.

- Low energy consumption: anaerobic pre-treatment as an equalization tank of the influent, which means that the daily quality fluctuations are balanced with the consequence reduction in oxygen demand and aeration needs in the tank.

In the simplest anaerobic-aerobic treatments, for example stabilizations ponds and natural or artificial wetlands, aerobic processes take place in the upper part of the reactor and anaerobic in the bottom. These simple treatment processes need a long retention time, low organic loads and large treatment areas and they normally achieve low treatment efficiencies. To overcome these disadvantages, new technologies using high rate anaerobic-aerobic bioreactors have been developed and nowadays a wide range of these bioreactors are available such as the upflow anaerobic sludge blanket (UASB), fluidized bed reactor, membrane bioreactor, etc. These reactors can achieve high quality discharge effluent while being economically viable and sustainable through resource recovery. A further treatment technology is to combine both zones in one within single bioreactor with or without physical separation (Chan et al. 2009).

The reactor tested in this investigation was designed using a process technology combining both zones within a single reactor. Its is called the Hybrid Vertical Anaerobic Biofilm reactor (HyVAB) and it is under development by Biowater Technology AS. HyVAB removes organic matter from high strength industrial wastewater to produce effluent suitable for discharge while also producing methane gas as a source of renewable energy. Less space is required and it has lower costs than current biological treatments processes.

1.5 Objectives

The objective of this study is to investigate the treatment performance of the novel high rate integrated anaerobic-aerobic reactor Hybrid Vertical Anaerobic Biofilm Bioreactor (HyVAB) through a small-scale pilot study. This research investigates the overall performance, treatment efficiencies and biogas production under different treatment conditions. The specific objectives of the study are:

- Study the start-up process of the reactor.
- Determine the effect of the influent temperature in the chemical oxygen demand (COD) removal efficiency.
- Determine the effect of the organic loading in the COD removal efficiency.
- Study the sludge production.
- Study the biogas production.

2 LITERATURE REVIEW

Industrial wastewater treatment has specific challenges compared with urban wastewater treatment. While urban wastewater effluents have stable characteristics, industrial wastewater processes have to deal with changes in influent properties depending on the process. Moreover, they can experience flow variations because of operational issues and consequently, waste streams can be periodic in nature. There are some industries that discharge wastewater with high levels of pollutants; this wastewater is called high strength industrial wastewater.

High strength industrial wastewater is difficult to define. It is called such because it contains large amounts of components like chemical oxygen demand (COD), ammonium or total suspended solids (TSS) (Mutamim et al. 2012). Some of these industries with high COD, oil and grease effluents face big challenges to discharge with acceptable levels. Usually, treatments solutions for this special wastewater require long hydraulic retention times, large areas to place the treatments and difficulties in methane collection (Chan et al. 2012). However, meeting the discharge requirements does not necessary lead into additional costs if the right technology is used as for example biological treatments in integrated aerobic-anaerobic reactors.

2.1 Biological processes for wastewater treatment

As mentioned before, biological treatments are processes where microorganisms are involved in the degradation of organic matter. They are natural processes where microorganisms use organic compounds as a carbon and energy source to produce various gases and cell tissue (biomass). Afterwards, the cell tissue produced will settle due to greater specific gravity than water and can be easily removed. There are some basic conditions that should take place to optimize the process. First, the microorganisms have some nutritional requirements to reproduce and function, the most important are: carbon, energy source and nutrients (major: N, S, P, K, Mg, Ca, Fe, Na and Cl and minor: Zn, Mn, Mo, Se, Co. Cu, Ni, V and W). Secondly, there are also environmental requirements that have an important role in survival and bacterial growth; the most important are pH and temperature. Every group of microorganisms has an optimum range of temperature and pH; the most common are 25-40ºC for temperature and 6 -8 for pH.

The biological processes used for wastewater treatment can be divided in five major groups depending on the environment characteristics: aerobic, anoxic, anaerobic, combined and pond processes. A further subdivision can be done depending on where the microbial activity takes place: suspended, attached or combined growth systems (Metcalf & Eddy, Inc 1991). The HyVAB design is based on anaerobic suspended-growth and aerobic-attached treatment processes.

2.1.1 Anaerobic suspended- growth treatment processes

The anaerobic digestion involves the decomposition of organic and inorganic matter in the absence of molecular oxygen in a multistep process. The process consists of the breakdown of long chain organic compounds into organic acids and some gas by-products of CO_2, CH_4 and HS^-. Afterwards, the organic acids are converted into methane and CO_2. This process is carried out by acid-splitting methane forming bacteria. A good balance of these two steps will result in a successful digestion process (Hammer & Hammer 2004). Anaerobic treatment systems present clear advantages compared with other biological process: low construction costs, small land requirements, low sludge production and easy operation and maintenance requirements. Anaerobic processes offer the possibility to generate biogas production. Additionally, anaerobic treatment is stable in terms of COD removal efficiency, pH and recovery time (Latif et al. 2011).

Many different types of reactors have been developed to operate anaerobic processes. The Upflow Anaerobic Sludge-Blanket Process (UASB) (Figure 1) is one of them and it has been successfully investigated in treating different types of wastewater (slaughterhouse, food processing, olive mill residues, pulp-bleaching, manure or brewery) (Puyol et al. 2011). The operating procedure of the reactor consists of the influent flowing from the bottom to the top of the reactor. The cleaning process takes place in a the dense sludge bed formed by the accumulation of suspended solids and bacteria growth (Latif et al. 2011) and the sludge blanket is formed by the upflow velocity. Gas collection happens when the gas bubble that is attached to the substrate flows upwards until it hits the top of the reactor where the collector is. Here, the gas will be released and the flocks will fall back to the sludge blanket in suspension.

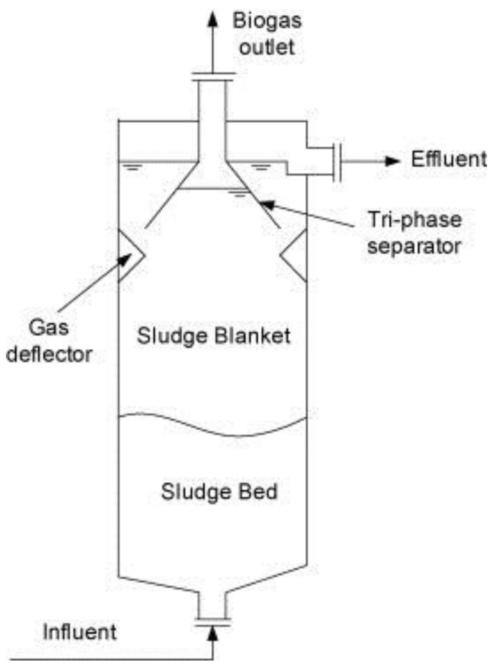


Figure 1: Schematic representation of an UASB reactor (Von Sperling & de Lemos Chernicharo 2005)

One of the main advantages of the UASB reactors is that in UASB reactors there is no need of mixing because the flow of the gas produced and with the upflow will reproduce the mixing effect., Therefore no mixing needs makes the process less energy consuming. Another advantage of this technology is that the granulation of the sludge that occurs from the process retains a high concentration of active sludge, which allowing for higher organic loads. Also, and achieves COD removal efficiencies are around 65-75%. In addition, the UASB reactor is compact, ; it has low constructions and operation costs, and, with good sludge production that can be easily dewatered. However, the reactor also presents some disadvantages: it can cause bad odors, it is does not good perform welling when toxic compounds are load present, it requires a long start up if there is not seed sludge and in most cases the need of post-treatment in most of the cases is needed (Von Sperling & de Lemos Chernicharo 2005).

2.1.2 Aerobic attach-growth treatment processes

The processes based on attached biofilm have recently been favoured over activated sludge processes. The main reason is that they require less space, the process is less influenced by biomass separation and the attached biomass becomes more specialized (Ødegaard 2006b). There are many biofilm systems: trickling filters, rotating biological contactors (RBC), fixed media submerged biofilters, granular media biofilters, fluidized bed reactors, etc. However, all of them present advantages and disadvantages.

The moving bed reactor (MBBR) is one of these treatments. It uses the whole volume of the tank to operate. Contrary to the activated sludge reactor, it does not need any recycling (Fig. 2). The reason behind this is because the MBBR processes biomass growth on carriers that move freely all over the reactor and only the surplus biomass has to be separated. The reactor can be used for both, aerobic and anaerobic processes. The MBBR process has been used for many different applications (nitrogen removal and organic matter removal). Advanced technologies like CFIC® based on MBBR are being researched to improve the benefits.

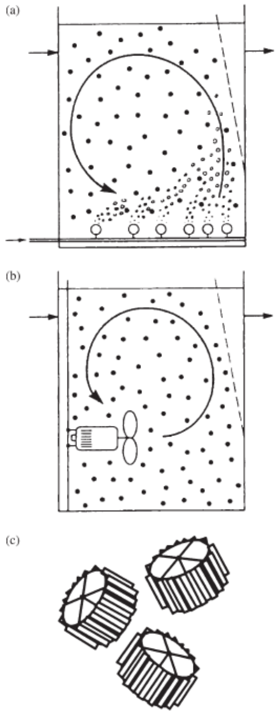
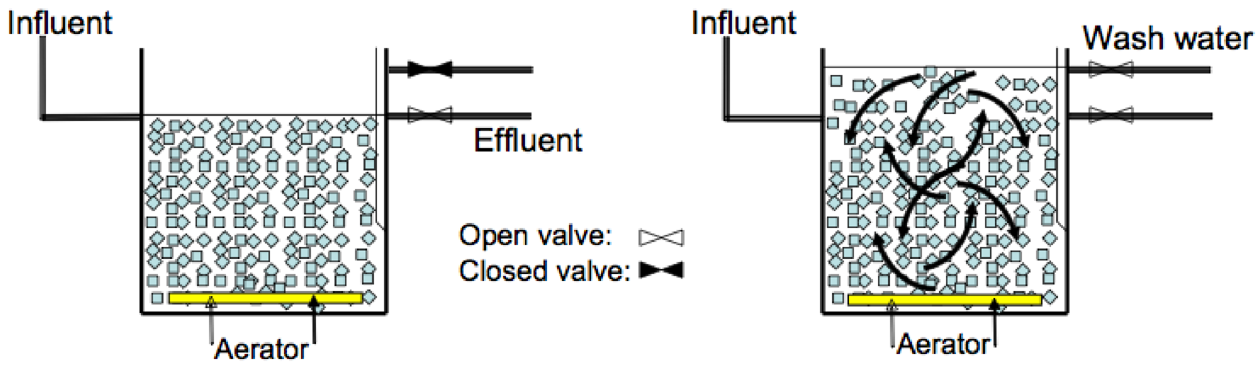


Figure 2 Principle of the MBBR and shape of the original biofilm carrier (K1). (a) Aerobic reactor; (b) Anoxic and anaerobic reactor; (c) The biofilm carrier (K1) (Ødegaard 2006a)

The CFIC® process is a new technology developed by Biowater Technology with the help of external R&D institutions and it is expected to be the next generation of biofilms reactors. It consists of a two-step process. First, highly packed biofilm carriers (90-99% bulk volumetric fill) in the reactor prevent biocarriers from free movement. These conditions create high carbon and nutrient gradients inside the biofilm. If the reactor is aerated, the efficiency of the oxygen transfer will be increased since the air bubbles have to travel though the compact biocarriers. This means that there are longer retention times until the bubble reaches the surface, thus creating a “filter” to reduce solids in the effluent. Secondly, cleaning cycles where the level of the reactor is elevated slightly provides free movement to the carriers

(Fig.3). This condition will wash out the excess of biomass removed from the carriers due to the turbulences and collisions inside the reactor (Rusten et al. 2011).



a) Normal operation b) Cleaning cycle

Figure 3 The CFIC® during a) normal operation, and during b) the cleaning cycle. Rusten et al, 2011.

Biowater Tecbnology tested the treatment efficiency in parallel with MBBR process and results showed that the produced influent had lower FCOD and TSS concentrations than MBBR, even at higher biofilm surface area, loading rates and significantly higher volumetric loading rates. The cleaning process removed accumulated biomass from the biofilm carriers by cleaning once a day (Rusten et al. 2011).

2.2 Operational parameters in integrated anaerobic-aerobic reactors.

Anaerobic-aerobic treatments can be a feasible solution when anaerobic or aerobic processes alone do not accomplish the required treatment efficiencies. In many treatment plants they have been used to combine economic and operational advantages of both treatment systems. However, the use of both systems in integrated reactors, in which anaerobic and aerobic zones share the same treatment unit, is a new way to overcome the disadvantages of anaerobic and aerobic treatments alone. The design is based on certain operational parameters that command the performance of the reactor.

2.2.1 Temperature

Temperature is the most important factor affecting biological processes. Microorganisms cannot control internal temperature so the ambient temperature determines their temperature. There are three temperature ranges for bacterial growth: psysophylic (4-15ºC), mesophilic (20-40ºC) and thermophilic (45-70ºC). Each range of temperature has a minimum, optimum and maximum for bacterial growth.

Mesophilic and thermophilic reactors are associated with better anaerobic digestion. Although, thermophilic reactors use to performance better after start up periods, they are more unstable and the extra energy consumption needed to reach the necessary temperature make it a disadvantageous process (Latif et al. 2011). It is important to maintain uniform temperatures because anaerobic processes are sensitive to changes and it will cause process failure (Von Sperling & de Lemos Chernicharo 2005).

2.2.2 Alkalinity, pH and volatile acids

Alkalinity, pH and volatile acids are closely related in the operation of anaerobic processes. Microorganisms have an optimum growth at pH levels between 6 and 8; levels below 4 and above 9.5 are not tolerated since they inhibit the growth of methanogenic microorganisms (Latif et al. 2011; Von Sperling & de Lemos Chernicharo 2005). This pH dependence has a practical implication. The acid-producing bacteria are less sensitive to pH changes than the methanogenic microorganisms. That implies that low pH in the reactor will produce acids but not methane. The pH can be affected in an anaerobic reactor by volatile fatty acids (VFA). Their accumulation will cause a pH drop and consequently a reactor failure by inhibiting the methanogenesis. For this reason, pH in the influent and VFA should be closely motorized. In order to control pH, alkalinity can be maintained by the addition of alkalinity supplements like NaOH or $NaHCO_3$.

VFA are fatty acids with a carbon chain of six or fewer, such as acetic, propionic, i-butyric, n-butyric, i-valeric and n-valeric. They are intermediate products of the anaerobic digestion. The measurement of VFA concentration is commonly used as a control test for anaerobic digestion since a VFA accumulation reflects a kinetic disequilibrium between the acids producers and the acids consumers (Switzembaum et al., 1990) and is an indicator of process destabilization.

2.2.3 Nutrients

Biological treatments are based in microorganism activity, so the necessary nutrients should be supplied to provide an adequate environment for optimum bacterial growth. Depending on the source of wastewater, it may or may not contain the basic nutrients. Usually, domestic water contains the main elements but industrial wastewater does not. In this case, they can be added as supplement in to the wastewater. The main nutrients that microorganism need are:

nitrogen, sulphur, phosphorus, iron, cobalt, nickel, molybdenum, selenium, riboflavin and vitamin B12 (Von Sperling & de Lemos Chernicharo 2005).

2.2.4 Volumetric hydraulic load, hydraulic retention time organic loading rate.

The volumetric hydraulic load is the amount (volume) of wastewater applied daily to the reactor per unit of volume:

$$VHL = \frac{Q}{V}$$

VHL = volumetric hydraulic load ($m^3/m^3 \cdot d$)

Q = flow rate (m^3/d)

V = total volume of the reactor (m^3)

The hydraulic retention time is the reciprocal of the volumetric hydraulic load:

$$HRT = \frac{V}{Q}$$

HRT = hydraulic retention time

Q = flow rate (m^3/d)

V = total volume of the reactor (m^3)

Organic loading rate is the mass of organic matter applied daily to the biofilter, per unit volume of the packing medium and expressed in mg COD/day.

$$OLR = \frac{QxCOD}{V}$$

OLR = organic loading rate

Q = flow rate (m^3/d)

V = total volume of the reactor (m^3)

COD= Chemical oxygen demand (mg/L)

In CFIC processes, the aeration plays a double role: adequate supply of oxygen for the microbial oxidation and improving the turbulence in the chamber to fluidized the bacterial biofilm. The selection of the aeration mode it is important for the efficiency of the treatment systems (Li et al. 2011). The Dissolved Oxygen (DO) in the aerobic reactor should not be less than 2 mg/L to maintain a good microbial growth and activity.

2.3 Biogas potential production from high strength wastewater

An increasing interest on renewable energy sources such as biogas from waste has resulted in an increase of research activities in this field. High strength industrial wastewater has a high organic content, making it suitable for biogas production. For example, the POME industry in Malaysia has a great potential of producing valuable biogas from adequate treating of their wastewater with an anaerobic digester instead of ponding systems. (Chin et al. 2013) reported that if the 57 million of generated POME in 2011 in Malaysia had been treated anaerobically, more than 50k tones of methane could have been produced. This could have supported about 700.000 households in Malaysia in 2011.

However, there are special challenges in producing biogas from high industrial wastewater. The most significant are the setup of adapted microorganisms to specific wastewater composition and flow alterations due to operational changes.

2.3.1 Process microbiology

Anaerobic digestion consists of three complex biochemical reactions phases (Fig.4). The first phase is hydrolysis, which is when organic compounds are transformed by enzymes into compounds suitable for use as a source of energy and cell carbon. Secondly, in acidogenesis, bacteria convert the products of the hydrolysis into hydrogen, formate, acetate and higher molecular-weight VFAs. In the third step, methanogesis, intermediate compounds (hydrogen) are converted into simpler end products (methane and carbon dioxide).

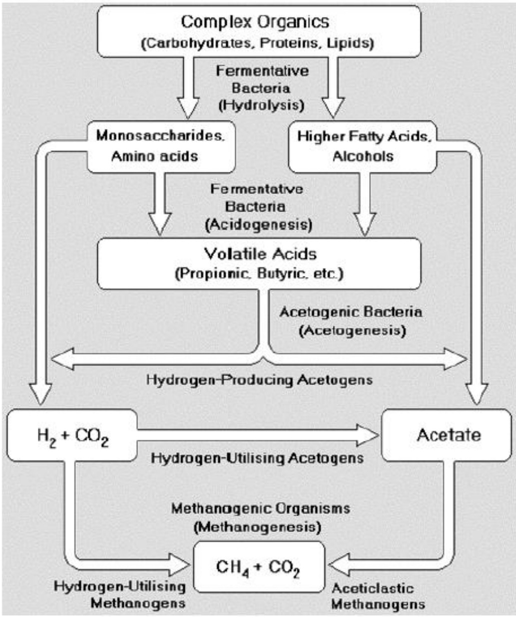


Figure 4 Metabolic pathways and microbial groups involved in anaerobic digestion (Lemos Chernicharo 2007)

In order to maintain and equilibrium between nonmethanogenic and methanogenic bacteria in the sludge digestion, some characteristics should be present in the anaerobic reactor such as avoiding dissolved oxygen, heavy metals and sulphides; keeping the pH level between 6.6 and 7.6; and providing enough alkalinity to avoid drops in pH. Methane bacteria do not function under 6.2 pH levels. In addition, alkalinity levels around 1000 to 5000 mg/L and VFA levels less than 250 mg/l result in digestion proceeding well. Organic (nitrogen and phosphorus) and inorganic nutrients should be present to ensure a proper growth of bacteria. Finally, a optimum temperature should be present in the reactor. For the mesophilic range, temperature should be between 30-38ºC and between 49-57ºC for the thermophilic range (Metcalf & Eddy, Inc 1991).

2.3.2 Process challenges

The main challenge is stabilizing the process without sudden changes in organic loading or rises in temperatures. In either case, an accumulation of organic acids will occur and the methanogenesis bacteria will not be able to assimilate all the acids produced. This imbalance will result in a decrease of the biogas production and eventually drop of the pH (Hammer & Hammer 2004). There are some preemptive strategies that can help avoid failure, like monitoring levels of the volatile acids concentration before and during the aerobic digestion. They should be stable at a given loading rate and temperature.

2.4 Start–ups strategies for combined reactors

In an anaerobic-aerobic reactor the start-up process must be watched carefully. The start-up process of the anaerobic stage is particularly important to have a successful performance of the reactor. The objective of the start-up period in high rate anaerobic reactors is to grow, build up and retain a sufficient concentration of active and well-balanced biomass (Chan et al. 2012). The start-up period differs from process to process, but it usually takes long time. It is a delicate operation procedure depending on many operational parameters, hence it is crucial to know how these factors affects the process (Cresson et al. 2006). Consequently, reducing start-up periods will lead to economic competitiveness of the wastewater treatment process (Escudié et al. 2011).

The start-up process in biological reactor can be divided in to two main steps: the inoculation and the period until it reaches a steady state. In the inoculation process, the quality and characteristics of the seed sludge are vital. During the start period of a UASB, the biomass tends to make aggregate forming granules and the development of these granules is essential to the success of this operation. It is important for granules to settle against the upflow influent. This is the reason why it has been a common practice to seed new reactors with pre-granulated sludge, as results from Goodwin et al. (1992) confirm.

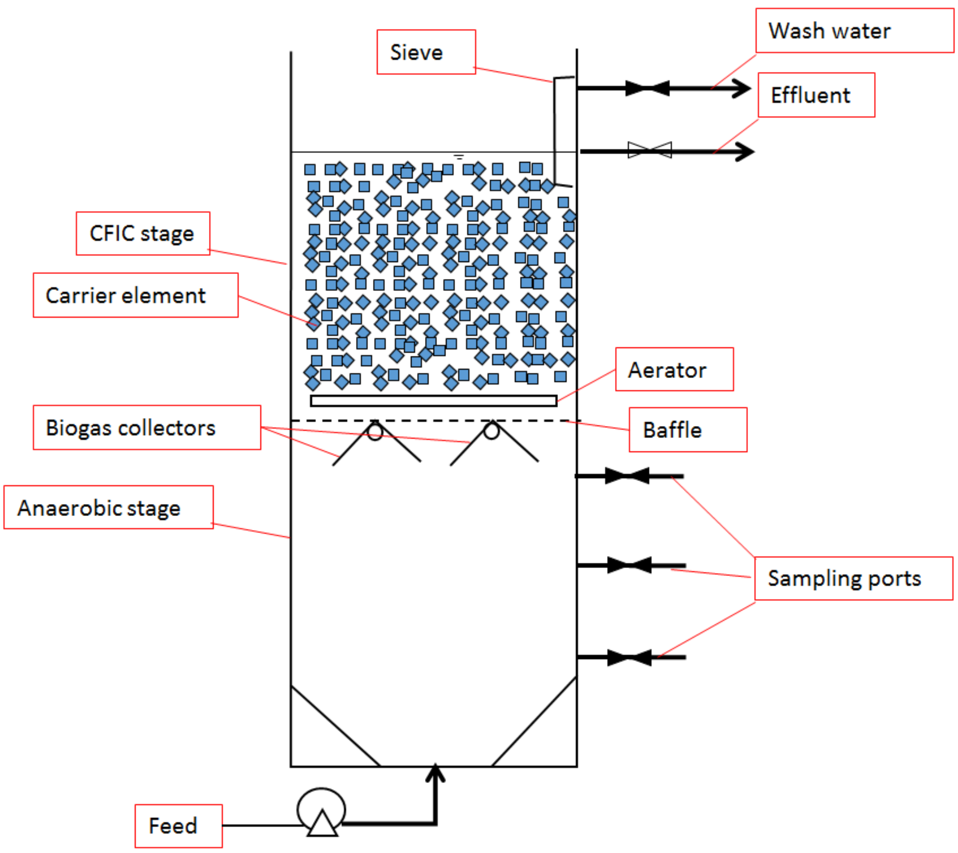
The second step is the progressive increase of the organic loading rate to stimulate the microbial adaptation and growth. The incremental loading in the organic load is crucial – the overloading of the system must be avoided because it will result in a failure of the system by inhibition of methanogenesis. Different strategies can be applied: one is to increase the loading rate by increasing the influent flow rate while keeping constant the COD concentration of the influent. Another strategy is to reduce the organic influent by diluting the influent while keeping constant the influent flow rate. The flow rate or the COD concentration can be progressively increased when the effluent reaches constant values of COD removal (80-85%). Chan et al. (2012) and Najafpour et al. (2006) reported rapid start-up (26 days) by decreasing the influent dilution in UASB treating palm oil. The excellent performance was because of good contact between the substrate and the sludge.

3 MATERIALS AND METHODS

3.1 General description of the reactor

Two different pilot scale HyVABs were used in the experiments. One was placed at NSO (Moss) and other was placed at Biowater's laboratory (Tønsberg). The HyVAB (Fig.5) reactor is a high rate bioreactor with a vertical combination of anaerobic sludge and aerobic biofilm with no physical separation. The HyVAB consists of two chambers connected vertically. The upper chamber is working as a CFIC® biofilm reactor and the lower incorporates UASB technology. A baffle is located in between the anaerobic and aerobic stage to separate the biocarriers from the anaerobic stage. A roof-like shape collector collects the generated biogas.The pilot situated in Kambo brings the biogas out from the reactor from two biogas collectors placed in the side of the reactor (Fig 5). The Tønsberg pilot collects the biogas from a pipe on top on the reactor.

a) Normal operation



b) Washing cycle

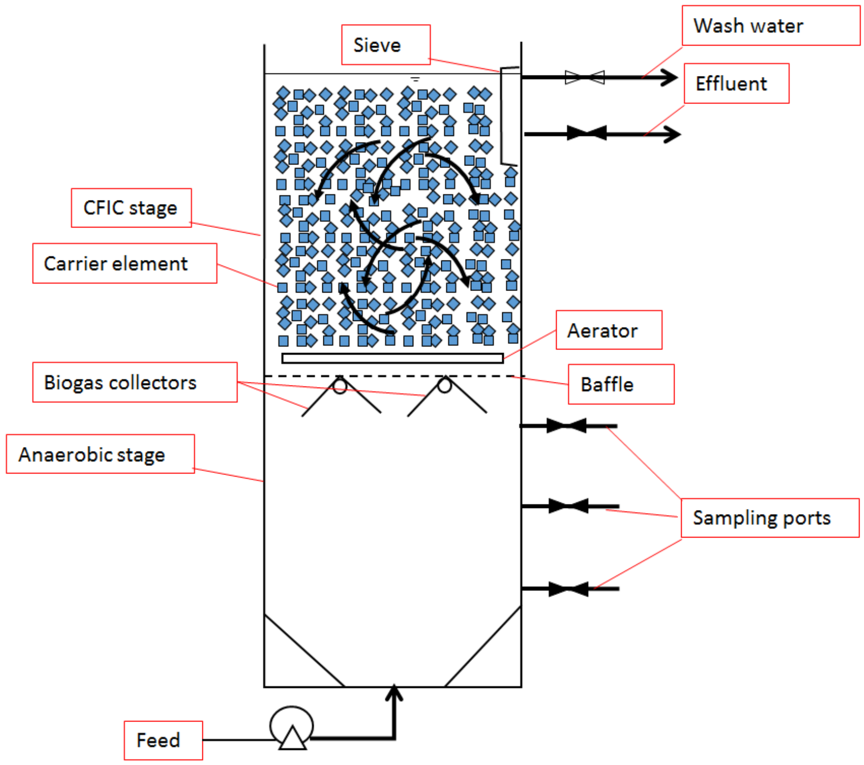


Figure 5 Systematic diagram for HyVAB reactor

The design parameters (Table 3) of both the reactors are:

Table 3 Design parameters of pilot scales HyVAB reactors

		Moss pilot	**Tønsberg pilot**
Parameter	**Unit**	**Value**	**Value**
Design flow	L/h	3,72	0,42
Design COD concentration	mg/L	10000	10000
Design COD loading	g/h	37,2	4,2
Design temperature	^{o}C	20	20
Anaerobic stage			
Volume	L	120	13,6
Water depth	m	0,8	0,60
Cross-sectional area	m^2	0,16	0,023

		Moss pilot	Tønsberg pilot
Parameter	**Unit**	**Value**	**Value**
Upflow velocity	cm/h	2,3	1,85
Hydraulic retention time	h	32	32
Design volumetric COD loading	kg/h/m^3	0,31	0,30
Design volumetric COD loading	kg/d/m^3	7,44	7,4
Expected COD removal efficiency	%	80	80
CFIC stage			
Working volume	L	60	6,8
Water depth-normal	m	0,36	0,30
Cross-sectional area	m^2	0,16	0,023
Type of media		BWTS	BTWS
Filling rate-normal*	%	92	95
Design volumetric COD loading	kg/d/m^3	2,98	2,96
Design biofilm COD loading	g/d/m^2	5,0	5,0
Hydraulic retention time-aerobic	h	16	16
Washing volume	L	70,656	8,34
Water depth-washing	m	0,44	0,37
Filling rate-washing	%	75	75

3.1.1 Wastewater preparation

The wastewater was source from Norsk Spesialolje (NSO) Kambo, Norway. NSO bases its business model in collection and cleaning of used oil (not lubricants) and oil-contaminated water. About 70% of the collected oil in Norway is treated in the Moss plant. Up to 50% of this waste is suitable for refining, around 30-35x10^6 kg per year. The cleaning process is based on the use of thermal heating to separate oil from water of the used oil. Then, the water extracted from this process is treated along with the externally received oil-contaminated

* Filling rate : bulk volumetric filled

water (Fig.6). Through this cleaning process NSO reduces the contaminated masses up to 97%, which is pumped into the sea, the other 3% of waste is retained and sent into destruction.

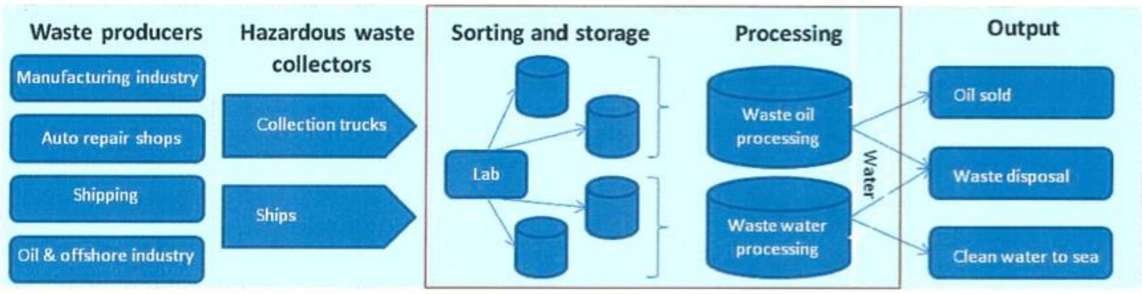


Figure 6 Processing diagram in NSO

The wastewater used in the study comes from the distillation carried out during the cleaning process and before any chemical or biological process is conducted. Its characteristics are presented below (Table 4). Due to the nature of the wastewater, some chemical additions were required to maintain a neutral pH and fulfill nutrient requirements in the anaerobic stage. The following chemicals were added to the wastewater before feeding the reactor. Dosages where calculated for an influent design flow of 100 L/day and influent COD of 10.000 mg/L (Table 5):

- Alkalinity for maintaining neutral pH: $NaHCO_3$.
- Phosphorous as bacteria nutrient: KH_2PO_4.
- Trace minerals, especially iron, cobalt, nickel and zinc for stimulating methanogenesis activities: Bloming.

Table 4 Characteristics of wastewater NSO (after adding chemicals)

Parameter	Units	Average	Range	Standard deviation
pH	-	7,89	9.5-6	3.261
COD	mg/L	12855	59640-3830	8183.8
TSS	mg/L	763	3610-130	3271.7
TN	mg/L	190	477-72	106.8
TP	mg/L	73	148-0.42	35.34
Oil in water	mg/L	434	>2000- 3.1	
Conductivity	µS/cm	520	1880-2.2	847.4

Table 5 Required chemical dosage for HyVAB with a design flow of 100 L/day and influent COD of 10000 mg/L

Chemical	Form	Required in feed water (mg/L)	Concentration in feed water (mg/L)	Dosage per 1000 L feed water
$NaHCO_3$	Powder	2000 mg/L as CaCO3	0	2.6 kg
KH_2PO_4	Powder	100 mg P/L	0	0.22 kg
Bloming (trace minerals)*	Liquid	-	0	1.455 L
Ferric Sulphate (PIX-113)**	Liquid	40 mg Fe/L	0	0.242 L

3.1.2 Operating conditions and procedure

The process flow diagram (Figure 7) was equal in both pilots. Wastewater was continuously fed from the feed tank to the anaerobic compartment using a Cole-Palmer Master Flex L/S feeding pump delivering an average of 85 L/day in Moss and 9 L/day in Tønsberg. The wastewater flowed upwards and overflowed into the aerobic compartment for further aerobic degradation. Air was supplied to the aerobic compartment through a blowing system. Six sampling ports where (SP1-SP6) were placed in all critical points. SP1 was placed in the EQ, SP2 after the feeding pump, SP3-SP4-SP5 were placed at suitable distances along the anaerobic compartment for sampling the sludge and an effluent sampling point was placed as SP6. Two extra gas-sampling ports were installed to determine the amount and composition of the biogas production.

The feed tank was filled up once a week with wastewater and chemicals in Moss and twice a week in Tønsberg. The flow rate of the feed line was manually set up by trial and error. The obtained volume was measured in a volumetric cylinder after pumping, the rotating rate was set up in the required flow rate, and the flow rate was checked weekly. The washing mode of the aerobic stage was operated once a week manually over a 16-hour period. The inlet temperature was controlled in Moss with an aquarium heater after the pump occurred since there was no possibility of room temperature control and with room heaters in Tønsberg. The aeration system was cleaned once a week to prevent clogging with pressured air. The feeding

* Bloming contains P, K, Cu, Fe, Zn, Mo and Mn. But does not contain Co and Ni,
** Active contents 177g Fe/L and 167 g S/L

tube was changed when clogging problems were detected. The pilot was operating with continuous flow for 24 hours.

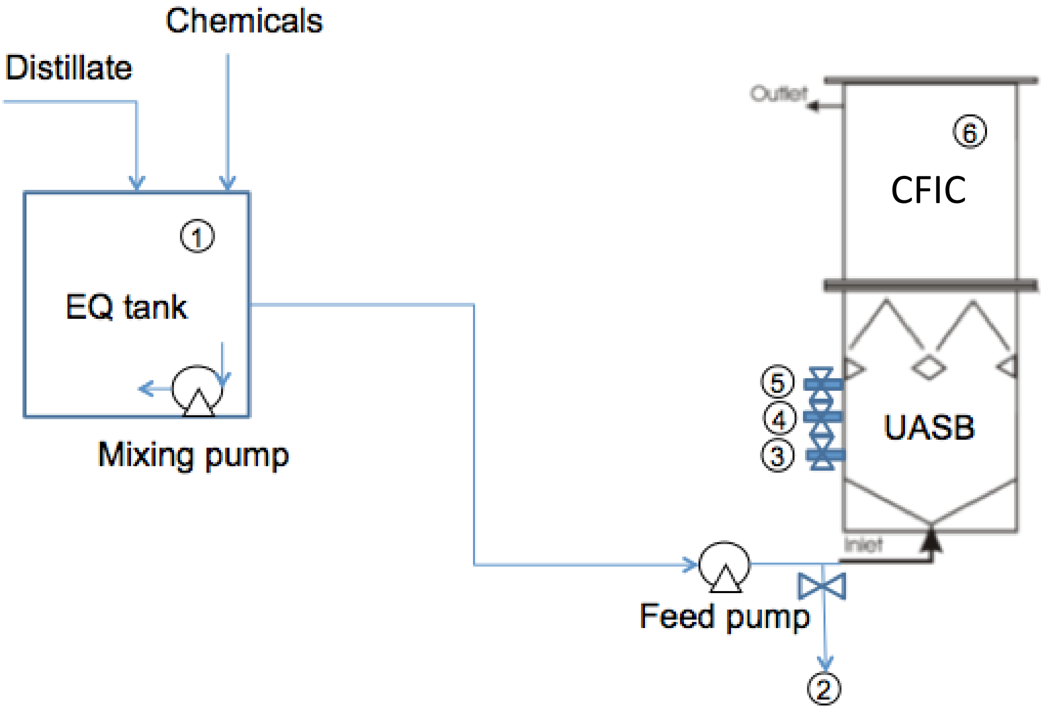


Figure 7 Process flow diagram of the wastewater treatment using HyVAB pilot plant.

Operation parameters

Main parameters monitored in this study and calculation methods are presented in Table 6, where Q_{in} is the influent flow rate (L/day), V is the volume of the bioreactor (L), $COD_{out,an}$ is the COD concentration of anaerobically treated wastewater, COD_{in} is the influent COD concentration (mg/L), COD_{out} is the treated effluent COD concentration (mg/L), TSS_{in} is the influent TSS concentration (mg/L), and TSS_{out} is the treated effluent TSS concentration (mg/L).

Table 6 Main parameters monitored in the present study

Symbol	Unit	Description	Equation
%COD	%	COD removal efficiency	$\frac{(Total\ CODin - Soluble\ CODout)x100}{Total\ CODin}$
OLR_{an}	g COD/day	OLR for anaerobic process	$\frac{QinXCODin}{Van}$
OLR_a	g COD/day	OLR for aerobic process	$\frac{QinXCODoutan}{Va}$

3.1.3 Sampling location, frequency and analyses

The volume deducted from the EQ and the flow measurements were used to determine the average flow to the reactor. Sampling (Table 7) was carried three times a week from sample ports (SP) 2-3-4-5-6 (Fig 6). For all the measurements, grab samples were withdrawn from the sampling ports using disposable tubes. For filtered samples a 0.45µm surfactant-free cellulose acetate (SFCA) filters were used with the disposal syringes. If the samples were not analyzed immediately, they were stored at 4ºC before analysis.

Table 7 Sampling location, frequency and analysis**.**

	Sampling point				
Measurements	Influent (SP2)	Bottom of the anaerobic zone (SP3)	Middle of the anaerobic zone (SP4)	Top of the anaerobic zone (SP5)	Effluent (SP6)
TCOD	3	3	-	3	3
SCOD	3	3	-	3	3
TSS	2	-	-	2	2
VSS	2	-	-	2	2
TS	-	1	-	-	-
VS	-	1	-	-	-
VFA	-	1	1	1	-
Alkalinity	1	1	-	-	-
Biomass on carriers	-	-	-	-	1

Legend: 1-Once a week, 2- twice a week, 3- three times per week

3.1.4 Seed sludge

The anaerobic chamber in Kambo was inoculated with anaerobic sludge taken from an industrial facility in Sweden where high strength oily wastewater is being treated with an anaerobic process. In Tønsberg the reactor was inoculated with new granule sludge from pulp and paper factory in Nederland.

3.1.5 Bioreactor start up

The pilot scale reactor placed in Kambo was started before this research was conducted. On the contrary, the start-up of Tønsberg's pilot was closely controlled. The anaerobic reactor was inoculated with 5 L of seed sludge. In order to acclimatize the sludge the reactor was fed with diluted wastewater during the start-up until it reached the designated COD concentration of 10000 mg /L. During the process the aerobic chamber was operated in MBBR mode. COD reduction, mass balance, pH, temperature, methane production and VFA concentration were monitored.

3.2 Analytical methods

Analytical determination of TSS, VSS, TS and VS were carried out in concordance with the Standard Methods for the Examination of Water and Wastewater. For determining TSS, samples of 5-10 mL were vacuum filtered through 47µm glass microfiber filters (Whatman Cat No 1822-047), the residue retained on the filter was dried in a 105°C oven for 1 hour before final weighing. VSS was determined by ashing the dry sample in a 550°C muffled furnace for 15 minutes. TS were measured by placing the sample in an aluminium disc (tare) and dried overnight in a 105ºC oven. VS analysis was carried out afterwards by drying the sample in a 550ªC muffled furnace for 15 minutes. The analysis for COD (LCK 314, LCK 514 & LCK 014), alkalinity (LCK 362) and VFA (LCK 365) were all conducted using testing kits from Hach. The cuvette samples were digested using the Hach Lange Thermostat HT200S, and final values were determined using the Hach Lange DR 2800 spectrophotometer. The pH and temperature measurement of grab samples were conducted using the pH electrode Sentix 41 and DO with Oxical-SL. Two external temperatures Sensor Type MicroLite II were used to control every 5 minutes the feed water and aerobic chamber temperatures. Biomass on carriers was measured by placing between 5-10 carriers into a 105ºC oven and drying overnight. After weighing the carriers were cleaned and dried again and the difference in mass was calculated.

4 RESULTS AND DISCUSSION

4.1 Tønsberg Bioreactor start up

4.1.1 Anaerobic process

COD removal efficiency

Different studies carried out on start-up processes of UASB showed differences in time and COD removal efficiencies. Chan et al (2012) achieved 99% COD removal treating POME with organic load up to 10.5 kg COD/m^3day in a 45-day period start-up. The experiment of Najafpour et al. (2006) accomplished a 26-day start-up of treating POME with organic load of OLR of 23.15 kg COD/m^3day. The start-up of UASB reactors is a complicated process with factors including wastewater characteristics, acclimatization of seed sludge, pH, nutrients, presence of toxic compounds, loading rate, up-flow velocity, hydraulic retention time, liquid mixing and reactor design affect the growth of sludge (Rizvi et al. 2013).

The performance of the first 60 days of the HyVAB anaerobic reactor operation is shown in Fig.8. During the first 18 days the reactor was fed an average COD loading of 2.10 Kg COD/m^3day with 2800 mg/L influent COD. During this period, a satisfactory overall COD removal efficiency process of 85% was achieved due to the good granulation conditions of the sludge seed. While the COD removal efficiency remained stable, along with low VFA concentrations of the anaerobic reactor, the COD loading was increased to 14.82 Kg COD/m^3day for two days. As a consequence of this sudden increase of organic loading the COD removal efficiency dropped to 57.7% with COD effluent levels of 8462 mg/L. This drop in the COD removal efficiency shows reactor stress as a consequence of the loading increase. This is because the anaerobic reactor microflora taking time to acclimate to the new environment (Najafpour et al. 2006). However, three days after the loading, the reactor showed a rapid stabilization and was capable of achieving 84.2% COD removal efficiency. This can be attributed to the self-regulation capability inherent to the biological system, making it possible for the microbial consortium to acclimatize itself to the increased loading (Chan et al. 2012). Industrial wastewater usually has changes in quality and quantity, making for a dynamic organic loading rate. As it is observed, the increase of organic loading is the main factor that affects the stability of anaerobic digestion since anaerobic microorganisms are sensitive to organic overloads (Chen et al. 2014).

During the end of the start-up period the influent concentration was increased stepwise until it achieved the designated COD concentration of 10000 mg/L and organic loading of 7.41 Kg COD/m^{3}day During this period the reactor showed an increasing trend of COD removal efficiency. By day 56, the COD removal efficiency was 97.03% at organic load of 7.92 Kg COD/m^{3}day and COD influent concentration of 10690 mg/L.

The results indicate a satisfactory start-up of the reactor in 20 days. A stable COD removal of 85% was achieved, along with low VFA concentrations in the anaerobic stage of treatment with organic loads ranging from 1.74 to 14.82 g/day.

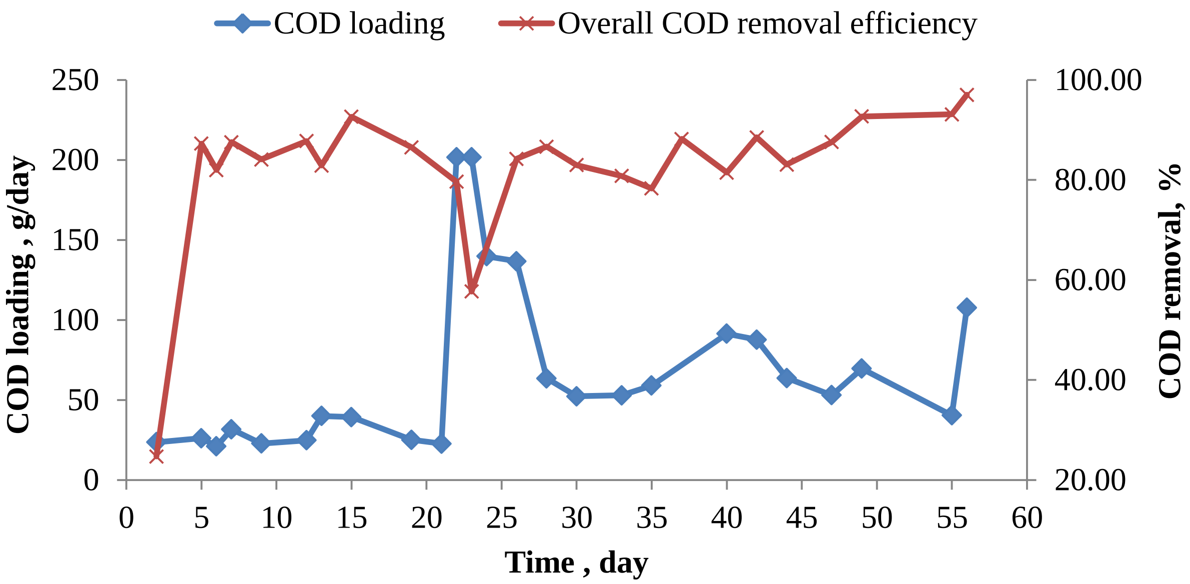


Figure 8 COD removal efficiency during start-up period.

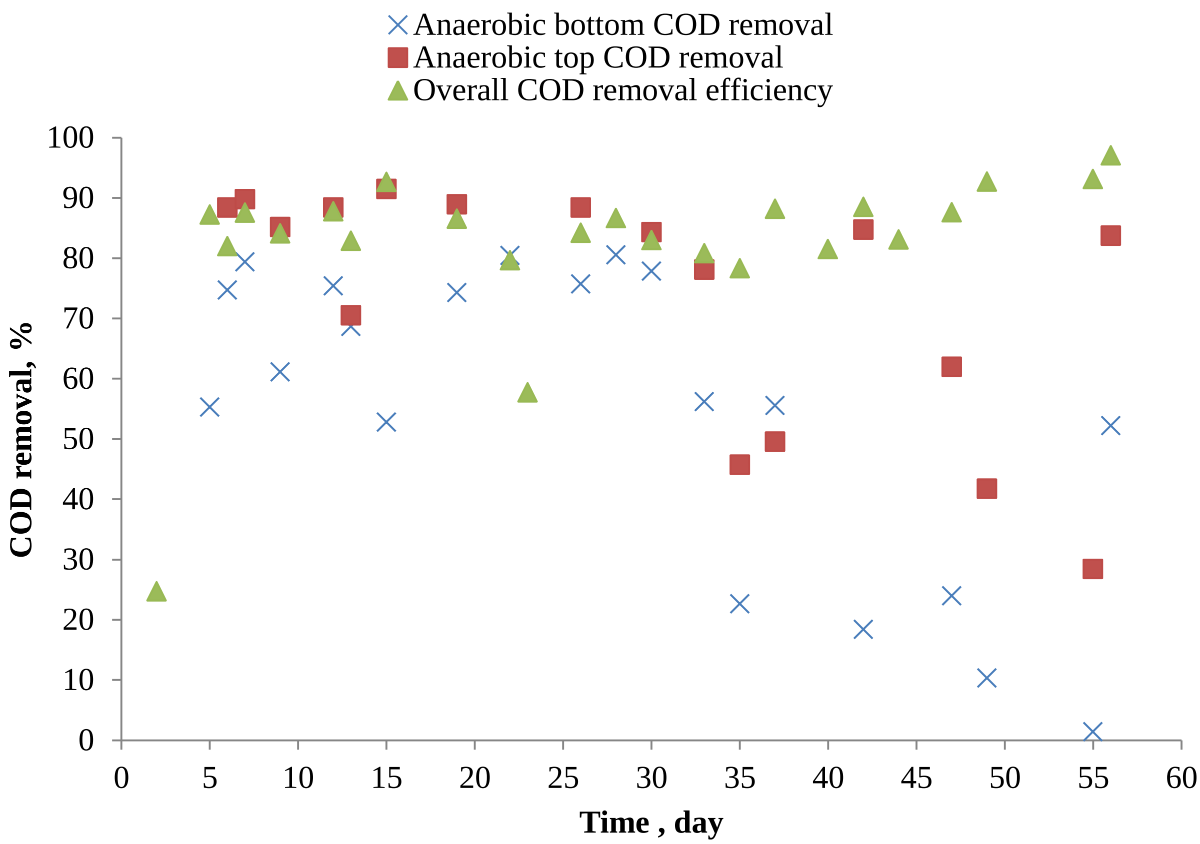


Figure 9 COD removal efficiencies in the reactor

Fig. 9 shows the contribution of each step of the process to the overall removal efficiency of the reactor. At the beginning of the start-up, all the removal treatment was completed in the anaerobic chamber before the sludge blanket was created. In addition, from day 35 the aerobic stage removal efficiency increased and the efficiency removal in the bottom of the aerobic was declined. The biofilm grew and established on the new bio carriers in one month.. Measurements showed that on day 29 the biomass per carrier was 0.77 mg and on day 37 the biomass per carrier was 9.40 mg, confirming the trend of the graph and the establishment of biofilm on the carriers.

Variation of sludge pH and VFA concentration along the height of anaerobic compartment

As mentioned in epigraph 2.2.2 alkalinity was supplied to the feed water to maintain constant pH levels in the anaerobic compartment through the treatment process. This entails a good balance in the process of hydrolysis, acidification of the organic matter and methane formation (Chan et al. 2012).

Sludge pH and VFA in the anaerobic reactor were monitored (Fig 9 and 10 respectively) during the entire period of the study. As illustrated in Fig. 10, the pH shows an increasing trend throughout the anaerobic compartment from the bottom to the top. The opposite trend is represented for VFA concentration.

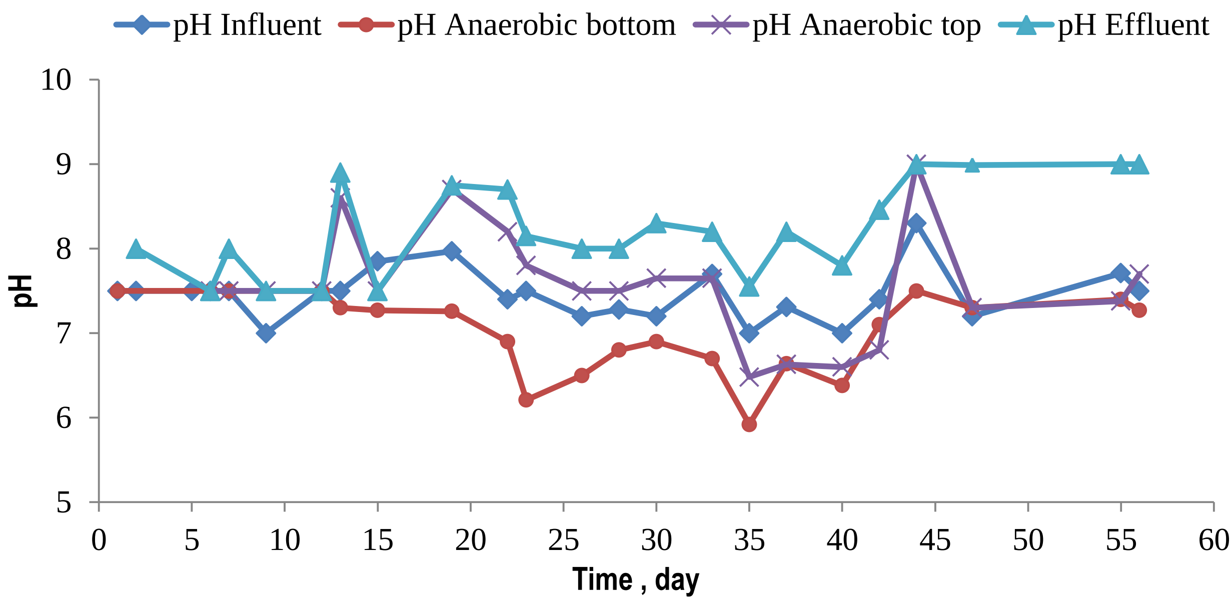


Figure 10 pH concentration along the reactor processes

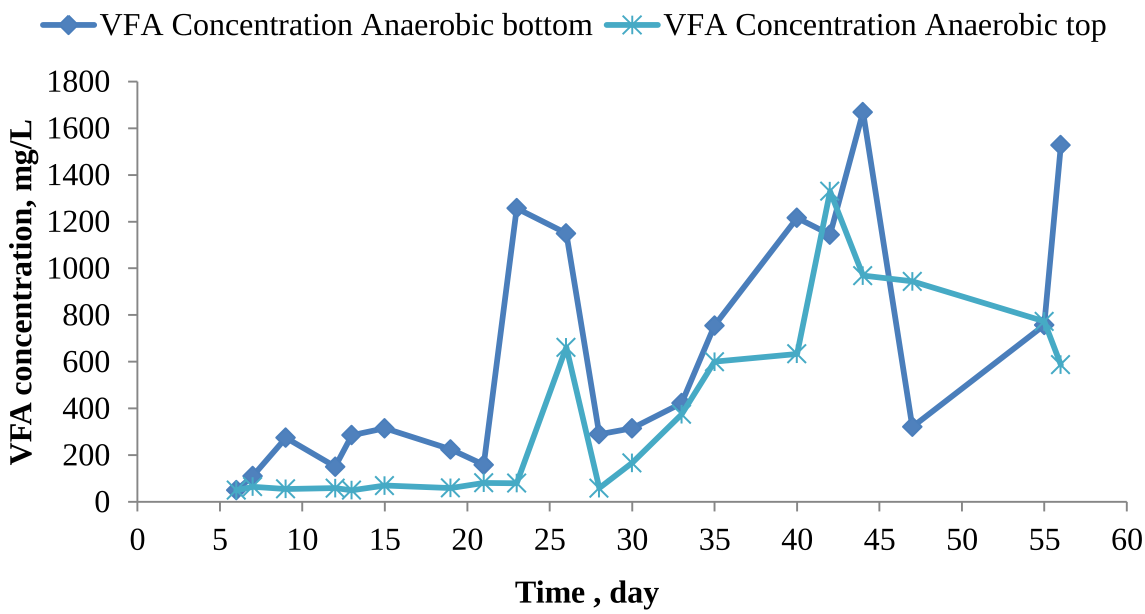


Figure 11 VFA concentration along the height of the anaerobic compartment

The balance in between the pH and VFA concentration through the height of the reactor explains the biochemistry of the digestion of the anaerobic reactor. A good establishment in between the entire microorganism involved is crucial for a success treatment processes. The VFA concentration is normally used to control this equilibrium. If the environmental conditions inside the treatment are good and there are enough methanogenic microorganism, then methanogenic microorganisms use the acids as soon as they are produced. This way, there is no accumulation of acids and the pH remains stable because the alkalinity capacity is not used to neutralize the accumulated acids (Chan et al. 2012). This is what it is observed in Fig. 10 and 11. The pH remains stable and the VFA levels remain under 400 mg/L until day 20 when the organic overload was produced. The overload caused unfavorable conditions and the methanonegic organisms were not capable of using the volatile acids at the same rate as the acidogenic bacteria producing them. As a result, there is an accumulation of acids in the system and the accumulated acids cause pH drops. In order to recover pH levels, extra alkalinity was supplied to the feed after day 20, which is reflected in a recovery of the pH level in the anaerobic bottom. However, as a consequence, an increase of the pH in the outlet was observed as well. During days 40-45, pH of anaerobic top experiments increased due to the recirculation operation.

Variations in sludge pH and VFA concentration in the bottom on the aerobic compartment

A further analysis of the relation between pH and VFA is shown in Fig. 12, where isolated data for a sampling port at the bottom of the anaerobic reactor is presented. As previously mentioned; pH, VFA and alkalinity are closely related. During the first 15 days the pH was stable in values within 7-7.5 and VFA concentration was less than 500 mg/L. After increasing the organic loading in day 20, on day 21 the VFA reached their maximum level of 1257 mg/L and the pH level dropped from 7 to 6.21. This VFA accumulation is produced because acidogenic bacteria produce more VFA than acetogenic and methanogenic bacteria can use. The increase of VFA concentration coincided with a decline in the pH, and this is because the alkalinity was not enough to neutralize the increased concentration of VFA. On day 26, the pH raised to 6.5 and pH VFA concentration was 1550 mg/L, with an organic loading of 136.7 g/day. Within days 35 and 40, while organic load was increased slightly the pH started to recover to initial levels close to 7, and the VFA concentration remained under 500 mg/L. A recirculation in the anaerobic stage was started on day 42, along with an increase of $NaHCO_3$ in the feed water to 5 g/L in order to raise the pH level. This resulted in an increased pH that remained almost constant between 7 and 7.5 until the end of the study. After the recirculation period the VFA concentration dropped. The decrease of the VFA concentration may be a result in an increase of methane production and the COD removal efficiency. These results correspond with results obtained by Buyukkamaci & Filibeli (2004) and Chen et Al (2012), where high COD concentration has influence on high VFA concentration.

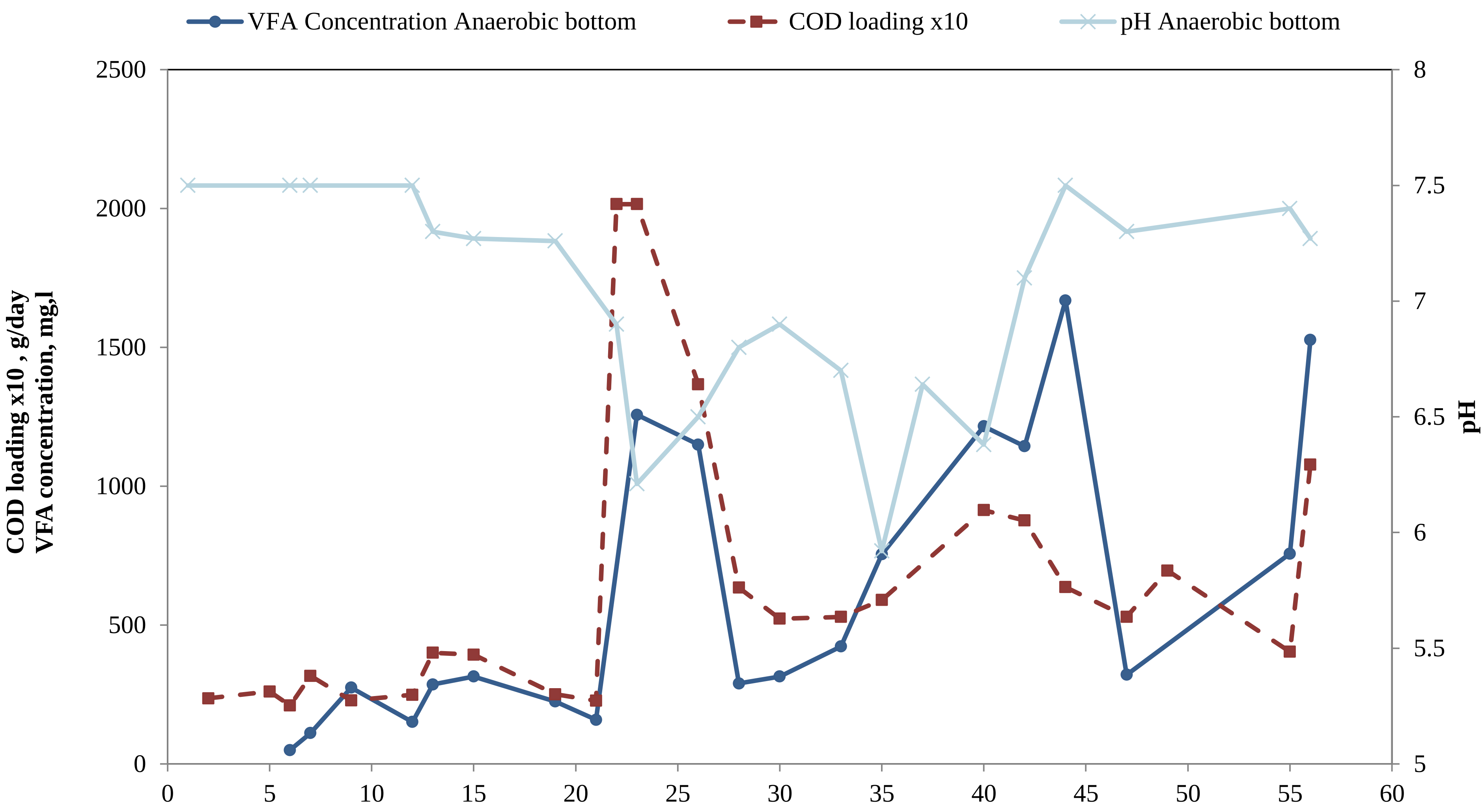


Figure 12 COD loading, pH and VFA concentration on anaerobic bottom during start-up period

4.1.2 *Aerobic process*

The anaerobic and aerobic compartments were started simultaneously. In order to evaluate the start-up performance of the aerobic compartment, COD removal efficiency was closely monitored as well as pH, temperature and DO. Additionally, biofilm carrier mass analyses were performance. The start-up of the aerobic reactor was run with new BTW S-type biofilm carriers with dimensions of 14.5 x 18.5 x 7.3 mm and a protected surface area of 650 m^2/m^3 (Fig13).

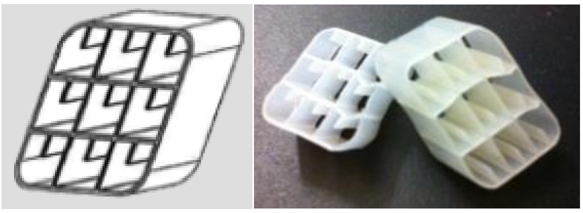


Figure 13 BTW S biofilm carrier

The aerobic reactor was operated at the MBBR mode until day 33 day when it was changed to the CFIC mode. As described in epigraph 4.1.1, from day 35 the removal efficiency of the aerobic stage increased, due to the growth and establishment of biofilm in the carriers. Measurements showed that on day 29 the biomass per carrier was 0.77 mg and on day 37 the biomass per carrier was 9.40 mg. The DO in the aerobic stage (Figure 14) remained stable during the 27 first days of the operation, on day 27 a significant dropped was registered. It can be a result of the COD overload and stress of the reactor. The consequences are reflected in the aerobic treatment more than 24 hours later, which is the total HRT of the reactor. The DO during the entire operation time was over 2 mg/L, which is the optimum for maintaining a good microbial growth and activity.

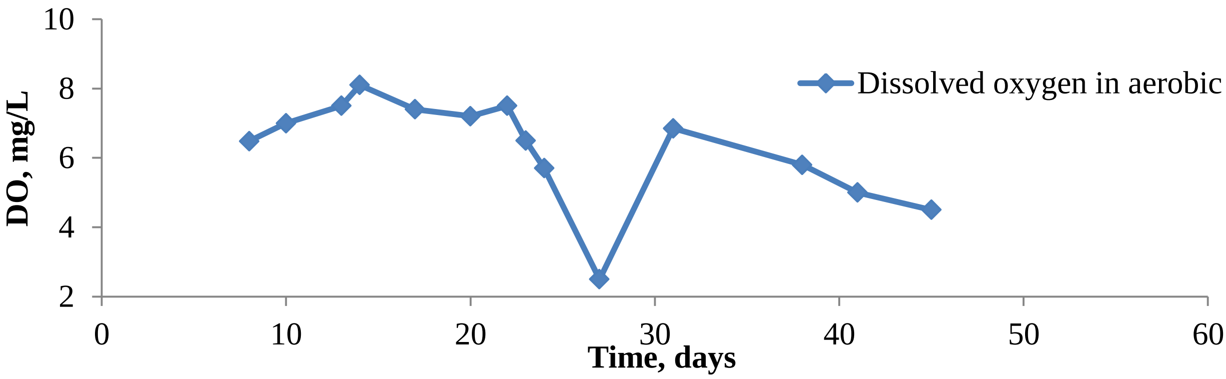


Figure 14 DO in aerobic compartment

4.2 COD removal efficiency in Moss reactor

Figure 15 present results of COD removal efficiency in Moss reactor. During the first 200 days of operation, the influent COD concentration in the wastewater remained stable (11.419 mg COD/day). However, after day 200, the variations in the COD concentration in the effluent were substantial. The reason is that the influent wastewater for the study comes from the NSO oil processing and the NSO process depends on the characteristics of the incoming untreated oil and oily water that can present variations. During this period, the average total efficiency removal of the reactor was 80%. During this period the temperatures registered were above 20°C due to the summer season. Therefore, a stable COD loading and temperatures above 20°C kept the overall performance of the reactor around the design COD removal efficiency of 80%. From day 200, the influent COD loading suffered a significant increase that affected the efficiency of the reactor by decreasing the efficiency to 65%. However, the temperature remains stable during these days. During this period of instability, the COD loading shows a rapid recovery and the average removal efficiency for the last 100 days remained around 75- 80%.

This results shows that the reactor is able to handle changes in organic load with fast recovery of good removal efficiencies. This characteristic is important in the treatment of industrial wastewater where changes in influent characteristics are common.

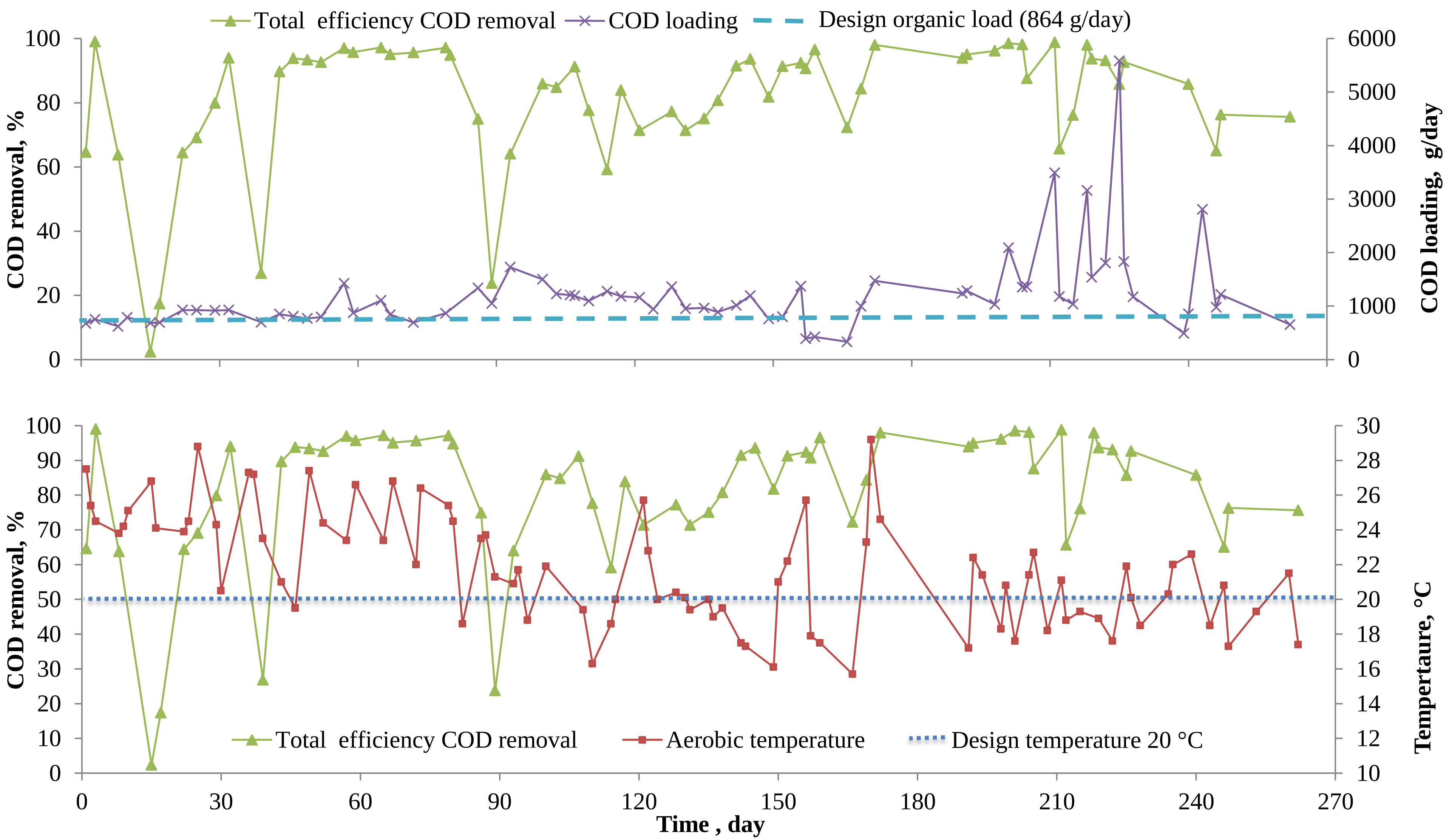


Figure 15 Efficiency removal and COD loading and temperature in Moss reactor.

4.3 Sludge production

In biological processes, the amount of solids produced depends on the wastewater characteristics. The substance that is produced in biological treatment is called biological sludge and it forms from the growth of biomass from microorganisms. This sludge should be removed from the reactor when it accumulates. If the reactor is not capable of handling it and it will flow with the effluent in large quantities. Thus, some sludge wasting is necessary to avoid this situation. Only occasional withdrawal is need in anaerobic reactors compared to other types of biological treatment, like activated sludge reactors. The wasted sludge should be treated and processed adequately for final disposal or reuse (Von Sperling & de Lemos Chernicharo 2005). The HyVAB reactor is designed to minimize sludge production through the digestion of the settled solids produced in the anaerobic chamber during the anaerobic stage.

The solids produced in the aerobic chamber in Tønsberg pilot reactor (Fig 16) shows a clearly increasing trend from day 0 to the end of the study. That is because most of the COD was removed aerobically after day 20, showing higher sludge production than in the first 20 days. This is a result of the establishment and growth of biofilm in the carriers.

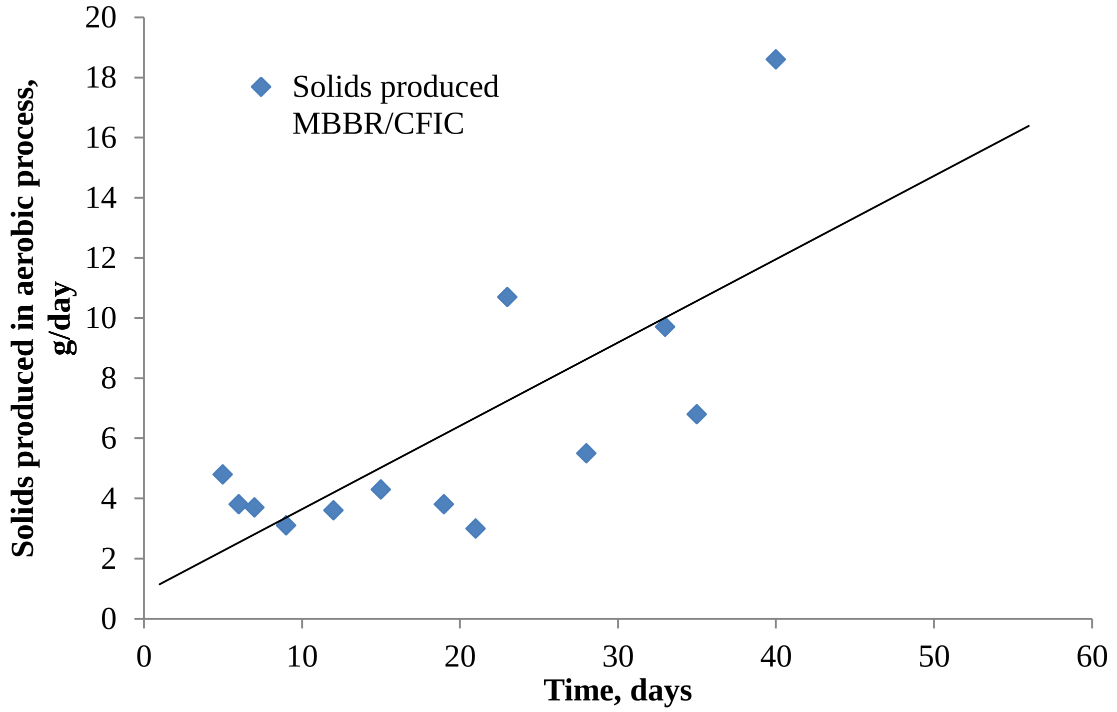


Figure 16 Sludge yield in Tønsberg reactor

Since the production of sludge is directly related with the microbial activity, environmental conditions also affects the production. Differences in sludge yield in summer and winter were observed in the Moss reactor (Fig 17). The trend shows a decrease of sludge production during the winter season. The average observed yield is 0.15 kg TSS/kg COD removed. The amount of solids yielded for the anaerobic treatment of domestic sewage is between 0.10 to 0.20 kg TSS/Kg COD applied. (Lemos Chernicharo 2007).

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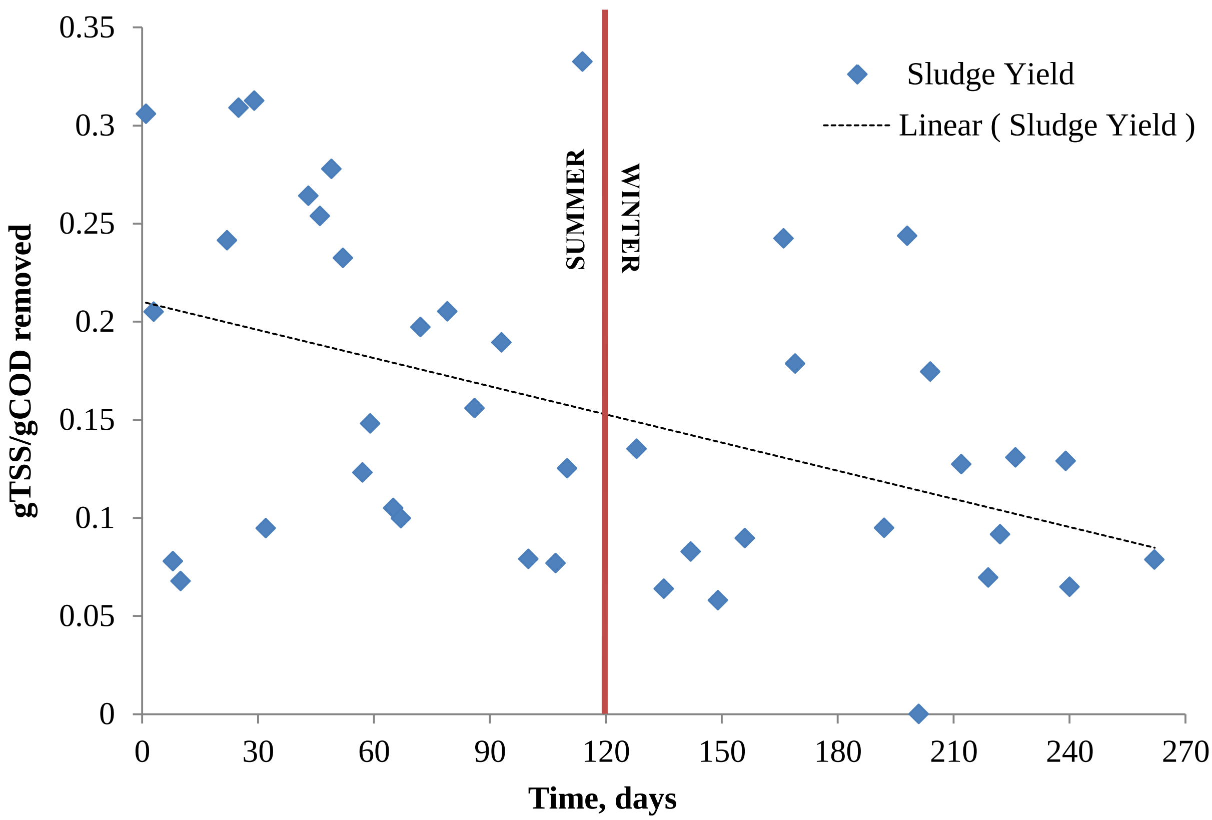

Figure 17 Differences in yield between summer and winter in Moss reactor

4.4 Biogas production

Evaluation of biogas production can be done theoretically based on the degraded COD that Lemos Chernicharo (2007) (pag19) proposes in his book “Biological Wastewater Treatment Series”. The equation is as follows:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_20$$
$$(16g) + (64g) \rightarrow (44g) + (36g)$$

One mole of methane requires two moles of oxygen for its complete oxidation to carbon dioxide and water. Therefore, every 16 grams of CH_4 produced and lost to the atmosphere corresponds to the removal of 64 grams of COD from waste. Under normal temperature and pressure conditions, this corresponds to 350 mL of CH_4 for each gram of degraded COD.

The portion of COD converted into methane gas can be determined as follows:

$$COD_{CH4} = Q \times (S_0 - S) - Y_{obs} \times Q \times S_0$$

where:

COD_{CH4}= COD load converted into methane ($kgCOD_{CH4}/d$)

Q= average influent flow (m^3/d)

S_0= influent COD concentration ($kgCOD/m^3$)

S= effluent COD concentration ($kgCOD/m^3$)

Y_{obs}= coefficient of solids production in the systems, in terms of COD (0.11 to 0.23 $kgCOD_{sludge}/kgCOD_{appl}$)

The methane mass ($KgCOD_{CH4}/d$) can be converted into volumetric production (m^3_{CH4}/d) by using the flowing equations:

$$Q_{CH4} = \frac{COD_{CH4}}{K(t)}$$

where:

Q_{CH4}= volumetric methane production (m^3/d)

K(t)= conversion factor for the operational temperature of the reactor ($kg\ COD/m^3$)

$$K(t) = \frac{P \ x \ K_{COD}}{R \ x \ (273 + T)}$$

where:

P= atmospheric pressure (1 atm)

K_{COD}= COD corresponding to one mole of CH_4 (64 gCOD/mol)

R= gas constant (0.08206 atm.L/mole.K)

T= operational temperature of the reactor (^oC)

Theoretical calculations for methane production for Tønsberg and Moss reactors are presented in Table 8 and 9. The values for the different parameters were extracted from design values (COD), and averages were taken from the observed data collection for COD removal efficiency as well as temperature and sludge yield.

Table 8 Values for theoretical methane production calculations with Lemos Chechinarro (2007) method for Pilot reactor Tønsberg

Parameter	**Value**
COD influent	10 kgCOD/m^3
COD effluent	0,73 kgCOD/m^3
COD removal efficiency	73%
Y_{obs}	0.11
Operational temperature of the reactor	22 ^oC
Flow	0,01 m^3/day
Result	0,0755 $KgCOD_{CH4}$/d 0,028 m^3 COD_{CH4}/d

Table 9 Values for theoretical methane production calculations with Lemos Chechinarro (2007) Pilot reactor Moss

Parameter	Value
COD influent	10 $kgCOD/m^3$
COD effluent	0,77 $kgCOD/m^3$
COD removal efficiency	77%
Y_{obs}	0.15
Operational temperature of the reactor	20 ^oC
Flow	0.089 m^3/day
	0.69 $KgCOD_{CH4}/d$
Result	0.26 m^3 COD_{CH4}/d

In addition, calculations were made to compare with Lemos & Chechinarro's (2007) method using the theoretical production of 350 mL CH_4 per gram of COD removed (Chan et al. 2012). The same assumptions and data were used.

Table 10 Comparison of methane theoretical production

	Theoretical production	
	350mL/gCODremoved	**Lemos Chechinarro 2007**
Pilot reactor	**m^3CH_4/day**	**m^3CH_4/day**
Tønsberg	0.032	0.028
Moss	0.28	0.26

Biogas collection was not possible at the Tønsberg pilot reactor. Some measurements were carried out at the Moss reactor (Table 11) despite the challenges of biogas collection due to clogging in the system. For CH_4 yield calculations, an assumed amount of 70-80% production in the biogas during treatment of domestic sewage was used (Lemos Chernicharo 2007). According to the measurements, the average methane produced was 0.036 m^3/day in the Moss reactor.

Table 11 Measured methane in Pilot reactor Moss

Day	Biogas production m^3/day	CH_4 production m^3/day	Temperature ^oC
72	0.033	0.0267	26.4
79	0.053	0.0423	25.4
80	0.048	0.038	24.5
Average	0.046	0.036	25.4

The comparison between theoretical (Table 10) and measured (Table 11) biogas production for Moss reactor shows a significant difference. It can be attributed to the mentioned clogging problems in the biogas collectors that did not allow all the biogas production being successfully collected.

The theoretical values can be used to calculate the calorific value from the biogas produced (Table 12):

Table 12 Comparison of methane theoretical

	Pilot Tønsberg	Pilot Moss
Biogas production (m^3/day)	0,032	0,28
Energy production*	23 Kwh/m^3treated	19,82 Kwh/m^3treated

The theoretical energy production of biogas for the pilot reactor in Tønsberg will be 23 and in Moss 19.82 Kwh/m^3treated. The differences are attributed to the in different treatment efficiencies in the anaerobic process.

Influence of temperature in methane yield

Calculations and results regarding methane yield should take into account the effect of temperature in gas solubility. At lower temperatures, the solubility of gases increases, and so the temperature of the reactor also has implications on the CH_4 yield. In the study by Singh and Viraraghavan (2003), "Impact of temperature on performance of UASB reactor treating

* Energy content of biogas generated from anaerobic digesters 6.0-6,5 Kwh/m^3 (Tyagi & Lo 2013)

municipal wastewater", they found that the percentage of total biogas increased as temperatures and HRT decreased. They ascribed this to the increased solubility of gases at reduced temperatures and the differences in the components of the biogas. According to their results, up to 50% of the methane produced could be lost as dissolved methane. In another study by Singh and Viraraghavan (1998), the percentage of dissolved methane rose to 60% and was affected by the low temperature and organic concentration in the influent.

Using Henry´s Law (Fig, 18), calculations of the amount of methane dissolved were between 0.26 and 0.21L/day for temperatures ranging from 15 to 25ºC (Q =10L/day, pressure 1,065 bar). These calculations must be taken into account in further studies about methane production and the amount released into the atmosphere from the effluent in full-scale treatments.

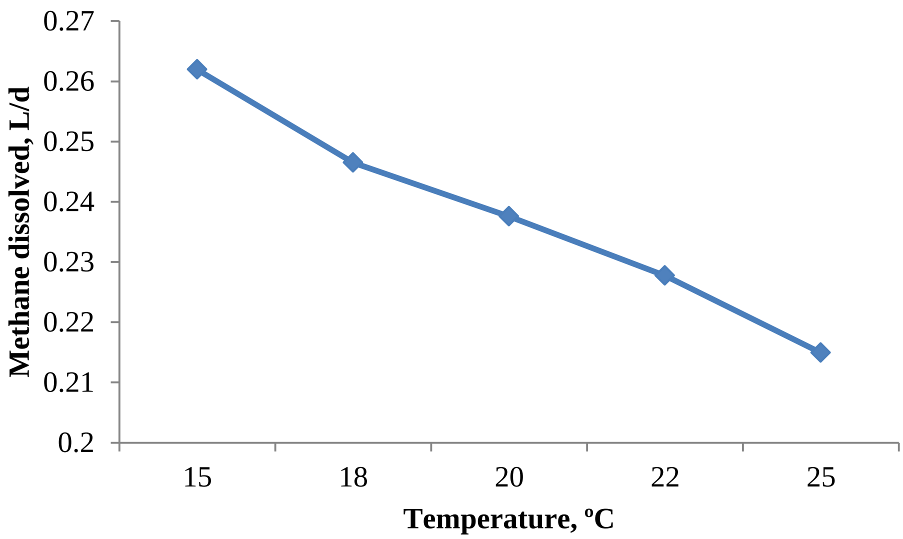

Figure 18 Theoretical methane dissolved in HyVAB at different temperatures

Temperature control in Tønsberg´s reactor

Temperature control during the Tønsberg pilot start-up was chosen to achieve a successful treatment efficiency as well as good biogas yield. The temperature monitoring results are shown in Fig 19 where changes in temperature feed were appreciable and within the acceptable range of 15-35^{o}C. Temperatures in the aerobic chamber were stable at 22^{o}C, which is low for mesophilic reactors (20-40 ºC).

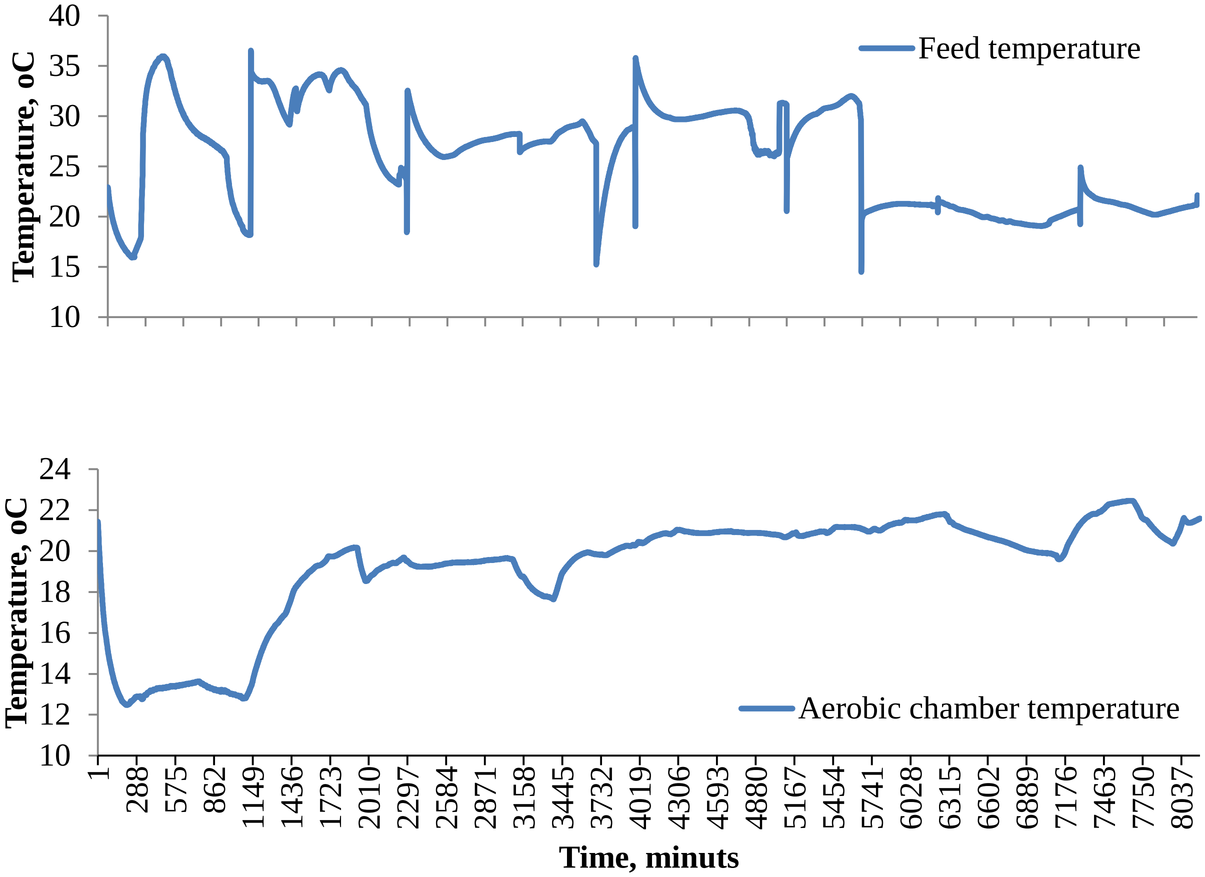

Figure 19 Temperatures monitoring in Tønsberg´s pilot.

4.5 Mass balance

In the HyVAB reactor, an analysis of the mass balance provides an idea of the amount of materials that are in each step of the wastewater process. The law of conservation states that organic matters are neither created nor destroyed. Therefore, by accounting for substances entering and leaving the wastewater process, unknown mass flows can be easily calculated as inputs and outputs. These can easily be translated as costs and benefits. The wastewater treatment competiveness depends on the knowledge and control of these inputs and outputs.

Input= outputs + reactions

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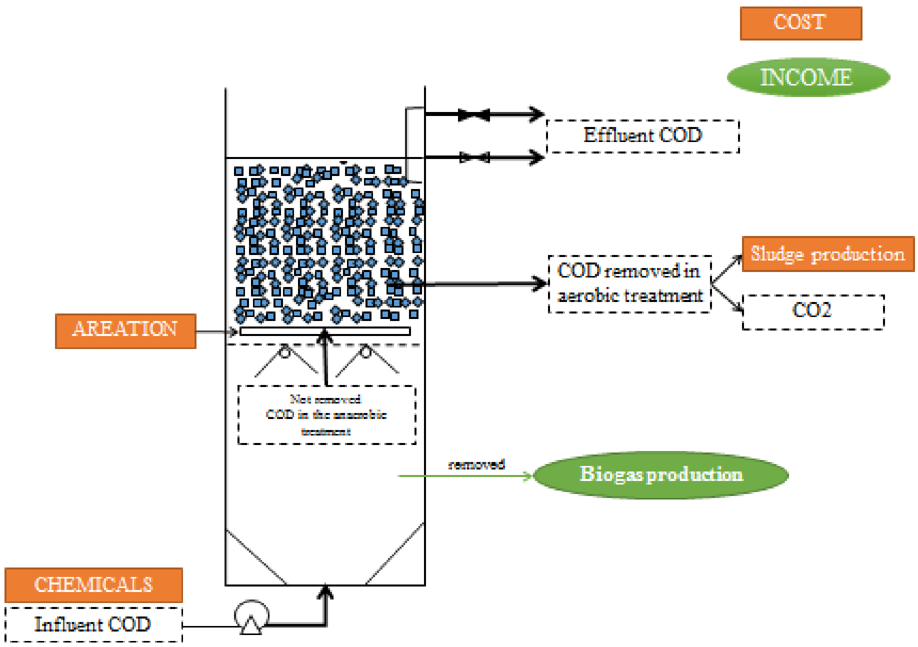

Figure 20 Mass balance for HyVAB

Fig. 20 the mass balance for HyVAB reactor. In HyVAB, the inputs of the global process are the organic load, the chemicals and the energy consumed in the aeration system. During the treatment process biogas, biomass and CO_2 are produced as outputs. Chemicals, energy for the aeration system and sludge management are the main costs of the system. Biogas production can be used as a source of income if it is collected and used for energy. However, a detailed study of biogas production and the costs of the entire wastewater system should be addressed in future studies.

5 CONCLUSION

This study evaluated the performance of a novel high rate integrated anaerobic-aerobic reactor: Hybrid Vertical Anaerobic Biofilm Bioreactor (HyVAB) through a small-scale pilot study treating high strength industrial wastewater. Additional goals were to study the start-up, the effect of COD removal on organic load and temperature, sludge and biogas production.

Successful start-up operation was accomplished in 20 days with an organic loading goal of 7.41 KgCOD m^3/day. During the start-up period, HyVAB exhibited successful treatment efficiencies with an average of 82%. It achieved total efficiency removal of more than 80% by the third day of operation and more than 95% after three months. Biofilm growth was observed after one month of operation. Additionally, the acclimatized microorganisms of the seed sludge helped the anaerobic system to recover fast from COD overloading.

A short start-up of the reactor will lead to an increase of the efficiency and competiveness of HyVAB. For future successful start-ups of the reactor, the following operation procedures must be followed.

- Using seed sludge adapted to the strength and type of wastewater will shorten the start-up period because of the previous acclimatization of the microorganism.
- Increase the organic load in gradual steps during the initial transient period from diluted wastewater to target organic load of the wastewater treatment. VFA and pH must be closely monitored to avoid stress on the reactor and to ensure good methanogenesis.
- Proper control of environmental factors is necessary. The temperature inside the reactor should be close to the optimum bacteria growth and survival rate (30-35 C), pH should be maintained within 6.5-7.5, ensure enough nutrients are available and avoid toxic compounds.

Overall, the COD removal efficiency of the pilot reactor remained stable at 80-95% during normal operation. It was only reduced when COD over loadings provoked shocks on the reactor. A slightly reduction of the efficiency of the reactor was observed during the winter period, and there were also differences in sludge production during this time. Knowing that the reactors are sensitive to their environmental conditions, characteristics of wastewater, mostly COD concentration and pH, must be closely monitored before feeding the reactor in further investigations or in full-scale reactors.

The biogas production and collection has to be improved in further studies to complete the objectives of the reactor. However, theoretical biogas production for Tønsberg´s reactor was 23 Kwh/m^3treated. A simple mass balance for both reactors showed the amounts of inputs and outputs, but they should be translated to economic costs and benefits in future studies.

6 FUTURE RESEARCH NEEDS

To reinforce the good results obtained in this study, the development of HyVAB needs further research for improvements in design and operation. These studies can be an opportunity for collaboration in between interdisciplinary research groups in these areas:

- Differences in production of solids in the effluent between CFIC/MMBR modes.
- Effects of COD removal and methane production on recirculation in the anaerobic chamber.
- Study of differences in biogas composition under different COD loadings and HRT.
- Study of effects of sludge wasting in the anaerobic chamber dealing with COD removal efficiency and methane production.
- Economic feasibility study for the wastewater treatment through Life Cycle Assessment.
- Mass balance over multiple week periods.

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Appendix I: Results from Tønsberg reactor

	Influent				
	COD loading	**Influent COD loading**	**OLR**	**Filt. COD**	**TSS**
Day	**g/day**	**mg/L**	**kg/d/m3**	**mg/L**	**mg/L**
1					
2	23.63	2344	1.74	2109	
3					
4					
5	26.08704	2588	1.92	3013	
6	21.02688	2086	1.55	1918	
7	31.69152	3144	2.33	2380	
8					
9	22.8312	2265	1.68	2011	160
10					
11					
12	24.87744	2468	1.83	2006	330
13	40.02768	3971	2.94	3262	
14					
15	39.35232	3904	2.89	3012	460
17					
18					
19	25.07904	2488	1.84	1688	610
20					
21	22.74048	2256	1.67	1828	230
22	201.6	20000	14.82	20000	
23	201.6	20000	14.82	24140	40
24					
25					
26	136.72512	13564	10.05	13564	
27					
28	63.504	6300	4.67	5750	80
29					150
30	52.3152	5190	3.85	5015	
31					
32					
33	52.96032	5254	3.89	4935	170
34					
35	59.02848	5856	4.34	7292	
36					
37		7840		3621	160
38					
39					
40	91.41552	9069	6.72	8279	220
41					
42	87.67584	8698	6.45	7198	
43					
44	63.67536	6317	4.68		
45					
46					
47	52.99056	5257	3.90	5197	
48					
49	69.63264	6908	5.12	6340	
50					
51					
52					
53					
54					
55	40.40064	4008	2.97	3592	
56	107.7552	10690	7.92	8178	

	Anaerobic bottom	Anaerobic top			Effluent		
	Filt. COD	Total COD	Filt. COD	TSS	Total COD	Filt. COD	TSS
Day	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
1							
2					2114	1765	
3							
4							
5	1157				1175	330	480
6	528		242		789	376	380
7	649	778	322		844	391	370
8							
9	881	656	336	330	771	360	310
10							
11							
12	607	663	286	260	731	302	360
13	1244	1153	1171		1108	680	
14							
15	1843		333	290		288	430
17							
18							
19	640	816	275	540	834	335	380
20							
21				420			300
22	3918	4116				4070	
23		9160		1020		8462	1070
24							
25							
26	3296		1575			2140	
27							
28	1226	838		1000	1424	841	550
29				830			
30	1150	1826	814		1719	884	
31							
32							
33	2304	2000	1150	1040	>2000	1008	970
34							
35	4530	2000	3178	920	2692	1270	680
36							
37	3488	2000	3958	2940	2784	926	
38							
39							
40				1020	3700	1680	1860
41							
42	7099	7571	1330		3144	1000	
43							
44					2332	1069	
45							
46							
47	3998	4464	2000		1075	652	
48							
49	6194	4907	4025		1653	504	
50							
51							
52							
53							
54							
55	3952	3554	2870		1557	276	
56	5108	2761	1743		1492	317	360

	Removal			VFA		
	Anaerobic bottom COD removal	Anaerobic top COD removal	Overall COD removal efficiency	Influent VFA	VFA Concentration Anaerobic bottom	VFA Concentration Anaerobic top
Day	%	%	%	mg/L	mg/L	mg/L
1						
2			24.70			
3						
4						
5	55.29		87.25			
6	74.69	88.40	81.98	180	50	50
7	79.36	89.76	87.56	247	111	65
8						
9	61.10	85.17	84.11		275	55.8
10						
11						
12	75.41	88.41	87.76	403	151	58.9
13	68.67	70.51	82.88	399	286	50
14						
15	52.79	91.47	92.62	244	315	69.6
17						
18						
19	74.28	88.95	86.54	791	225	59.6
20						
21				803	159	81.8
22	80.41		79.65			
23			57.69	828	1257	80
24						
25						
26	75.70	88.39	84.22	631	1150	662
27						
28	80.54		86.65	146	290	58.7
29						
30	77.84	84.32	82.97	142	315	167
31						
32						
33	56.15	78.11	80.81	146	423	375
34						
35	22.64	45.73	78.31	755	755	600
36						
37	55.51	49.52	88.19			
38						
39						
40			81.48	541	1216	634
41						
42	18.38	84.71	88.50	640	1144	1330
43						
44			83.08	50	1669	969
45						
46						
47	23.95	61.96	87.60	114	321	944
48						
49	10.34	41.73	92.70			
50						
51						
52						
53						
54						
55	1.40	28.39	93.11	545	757	773
56	52.22	83.70	97.03	750	1527	587

	pH				Temperature			
Day	pH Influent	pH Anaerobic bottom	pH Anaerobic top	pH Effluent	Influent	Anaerobic bottom	Anaerobic top	Effluent
1	7.5	7.5						
2	7.5			8	28.4			
3								
4								
5	7.5							
6	7.5	7.5	7.5	7.5				
7	7.5	7.5	7.5	8	33.87	21.5	21.5	19.3
8								
9	7		7.5	7.5				19.6
10								
11								
12	7.5	7.5	7.5	7.5				
13	7.5	7.3	8.6	8.9	27.4	20.1	20.5	17.6
14								
15	7.85	7.27	7.5	7.5	28.1	21.8	21.5	21.8
17								
18								
19	7.97	7.26	8.7	8.75	30.4	23.7	22.11	21.3
20								
21								
22	7.4	6.9	8.2	8.7	21.2	22.2	22.5	21.5
23	7.5	6.21	7.8	8.15				
24								
25								
26	7.2	6.5	7.5	8	19.5			19.8
27								
28	7.28	6.8	7.5	8	22.3	22.5	22.8	19.4
29								
30	7.2	6.9	7.65	8.3	22.1	23.1	22.9	21.7
31								
32								
33	7.7	6.7	7.65	8.2	21.9	22.5	22.8	22.2
34								
35	7	5.92	6.48	7.55	22.3	23.2	22.1	23.1
36								
37	7.31	6.64	6.63	8.2	21.8	22.2	23.1	22.7
38								
39								
40	7	6.38	6.6	7.8	23.8	21	23.4	24.5
41								
42	7.4	7.1	6.8	8.46	23.1	23	23.4	22.8
43								
44	8.3	7.5	9	9	22.2	23.2	22.2	21.9
45								
46								
47	7.2	7.3	7.3	8.99	22.1	21.9	22.8	20.6
48								
49								
50								
51								
52								
53								
54								
55	7.71	7.4	7.38	9	22	22	21.8	20.6
56	7.5	7.27	7.7	9	22.2	20.9	20.6	20.2

Day	DO aerobic mg/L	Solids produced MBBR/CFIC g/day	Yield gTSS/gCODremoved
1			
2			
3			
4			
5		4.8	0.16
6		3.8	0.15
7	6.48	3.7	0.10
8			
9	7	3.1	0.11
10			
11			
12	7.5	3.6	0.13
13	8.1		
14			
15	7.4	4.3	0.10
17			
18			
19	7.2	3.8	0.13
20			
21	7.5	3	
22	6.5		
23	5.7	10.7	0.03
24			
25			
26	2.5		
27			
28		5.5	0.08
29			
30	6.85		
31			
32			
33		9.7	0.15
34			
35		6.8	0.09
36			
37	5.8		
38			
39			
40	5	18.6	0.17
41			
42			
43			
44	4.5		
45			
46			
47			
48			
49			
50			
51			
52			
53			
54			
55			
56	6		

Appendix II: Results from Moss reactor

	Influent				
	Influent Total COD	Influent Soluble COD	Influent Temperature	pH	TSS
Day	mg/L	mg/L	oC		mg/L
1	7778	6640	24	6.80	267
2					
3	8695	5960	20.8	7.59	730
4					
5					
6					
7					
8	7190	5750	22.9	7.00	730
9					
10	9125	8500	24	7.80	330
11					
12					
13					
14					
15	7930	7740	24.2	8.57	340
16					
17	8006	6610		8.69	390
18					
19					
20					
21					
22	10722	11070	25.3	8.26	810
23					
24					
25	10699	10860			250
26					
27					
28					
29	10619	1092	23.5	7.9	270
30					
31					
32	10711	9910		7.25	250
33					
34					
35					
36			25	8.58	1350
37			25.5		
38					
39	8074	7530	23.8	7.93	210
40					
41					
42					
43	9827	7420	20.4	8.75	500
44					
45					
46	9368	10590	19.6	7.90	240
47					
48					
49	8890	8860	24.6	8.01	420
50					

	Influent				
	Influent Total COD	Influent Soluble COD	Influent Temperature	pH	TSS
Day	mg/L	mg/L	oC		mg/L
51					
52	9204	8280	22.3	8.16	190
53					
54					
55					
56					
57	16494	6920	22.4	8.42	1820
58					
59	10084	6057	24.1	8.60	2740
60					
61					
62					
63					
64					
65	12810	7670	22	8.00	620
66					
67	9702	7100	29.1	8.45	1640
68					
69					
70					
71					
72	8036	6350	22.8	8.60	720
73					
74					
75					
76					
77					
78					
79	10000	7000	27.2	7.87	2020
80	10000			7.11	
81					
82		6993	17.8	7.95	170
83					
84					
85					
86	15484	11290	23.1	8.00	590
87			24.4	8.25	
88					
89	12166	10106	19.8	7.00	590
90					
91					
92					
93	19990	18450	19.2	8.52	310
94			18.1	8.50	
95					
96	19990				
97					
98					
99					
100	17374	11570	21.6	8.50	340

	Influent				
	Influent Total COD	Influent Soluble COD	Influent Temperature	pH	TSS
Day	mg/L	mg/L	oC		mg/L
101			22.2	8.45	
102					
103	14210	9940			
104					
105					
106	13974			6.20	
107	13746	11060	16.2	6.90	180
108					
109					
110	12692	11626	17.3	7.32	330
111					
112					
113					
114	14752	14380	18.8	8.15	380
115			21.3	8.33	
116					
117	13680	13380			
118					
119					
120					
121	13430	10660	25.7	8.40	
122			22.2	8.96	
123					
124	10886		15	9.50	
125					
126					
127					
128	15760	14380	20.5	8.60	350
129					
130					
131	10998	9969	14.7	8.52	
132					
133					
134					
135	11156	10040	22.2	8.85	236
136			21.7	8.60	
137					
138	10262	9340	17	8.22	
139					
140					
141					
142	11720	8710	18.3	8.54	2070
143					
144					
145	13822	7179	15	8.17	
146					
147					
148					
149	8798	7410	16.5	7.94	475
150					

	Influent				
	Influent Total COD	Influent Soluble COD	Influent Temperature	pH	TSS
Day	mg/L	mg/L	oC		mg/L
151					
152	9273	6537	22.2	7.80	
153					
154					
155					
156	15832	7560	28	8.33	20170
157	4528		15.6	8.60	
158					
159	4900	4200	18.6	8.00	
160					
161					
162					
163					
164					
165					
166	3830	3740	17	7.65	340
167					
168					
169	11512	8100	22.8	8.25	880
170			30.1	8.30	
171					
172	17060	7810	26.6	7.00	
173					
174					
175					
176					
177					
178					
179					
180					
181					
182					
183					
184					
185					
186					
187					
188					
189					
190					
191	13228	9900		8.22	
192	13720	9240	21.7	7.55	810
193					
194		11200	17.6	6.75	
195					
196					
197					
198	11028	9310	21.5	8.30	390
199		4572	20.3	7.00	
200					

	Influent				
	Influent Total COD	Influent Soluble COD	Influent Temperature	pH	TSS
Day	mg/L	mg/L	oC		mg/L
201	22304	8784	17	6.00	
202					
203					
204	14440	10550	22.5	7.89	450
205	14552	9671	22.7	7.89	
206					
207					
208		15616	18.7	7.80	
209					
210					
211	37310	19268	18.2	8.32	
212	12570	11490	18.7	8.17	410
213					
214					
215	11042	10646	19.7	7.30	
216					
217					
218	33740	5454	21.5	7.50	
219	16414	11790	19.8	7.30	420
220					
221					
222	19252	6718	20.5	7.36	530
223					
224					
225	59640	4930	21.8	7.81	2310
226	19586	5429	22.2	8.84	520
227					
228	12518	10524	19.7	7.30	
229					
230					
231					
232					
233					
234			21.3	7.30	
235			24	8.15	
236					
237					
238					
239	5228	4160	22	7.56	900
240	9135	8780			750
241					
242					
243	30000	7898	18.5	7.50	3610
244					
245					
246	10450	7570	20.7	6.50	970
247	12978	7263			1890
248					
249					
250					

	Influent				
	Influent Total COD	Influent Soluble COD	Influent Temperature	pH	TSS
Day	mg/L	mg/L	oC		mg/L
251					
252					
253			22	8.57	
254					
255					
256					
257				7.80	
258					
259					
260			19.6	9.10	
261					
262	6978	1326	19	9.21	610
263					
264					
265					
266					
267					
268					

Day	Anaerobic bottom		
	pH	Anaerobic bottom temperature	Soluble COD Anaerobic bottom
		oC	mg/L
1	6.8	23.8	5660.00
2			
3	7.0	20.5	5160.00
4			
5			
6			
7			
8	7.05	21.70	7120
9			
10	7.16	22.00	3670
11			
12			
13			
14			
15	6.94	24.50	4650
16			
17			5420
18			
19			
20			
21			
22	6.25	28.40	10500
23			
24			
25	6.34	27	11040
26			
27			
28			
29			11210
30			
31			
32	6.66		9920
33			
34			
35			
36	6.9	25.2	
37		25	
38			
39	6.93	22.6	11140
40			
41			
42			
43	7.04	19.04	5770
44			
45			
46	6.8		5300
47			
48			
49	6.7	25.4	4590
50			

	Anaerobic bottom		
	pH	Anaerobic bottom temperature	Soluble COD Anaerobic bottom
Day		oC	mg/L
51			
52	6.7	22.3	4550
53			
54			
55			
56			
57	6.7	23.8	4190
58			
59			
60			
61			
62			
63			
64			
65	6.2	22.8	5890
66			
67	6	27.7	5620
68			
69			
70			
71			
72	6.93	23.4	2500
73			
74			
75			
76			
77			
78			
79	6.39	25.6	5200
80	6.41	24.5	
81			
82	6.46	17.4	4514
83			
84			
85			
86	5.7	22.7	9100
87	5.82	21.5	
88			
89	6.4	19.8	7591
90			
91			
92			
93	7.28	19.4	9790
94	7.25	18	
95			
96	6.56	13.8	20030
97			
98			
99			
100	6.2	21.9	11570

	Anaerobic bottom		
	pH	Anaerobic bottom temperature	Soluble COD Anaerobic bottom
		oC	mg/L
Day			
101	6.26	21.8	
102			
103			11148
104			
105			
106			
107	6.3	15	11180
108			
109			
110	6.5	16.7	9950
111			
112			
113			
114	6.5	17.9	8880
115	6.4	19.5	
116			
117			8616
118			
119			
120			
121	6.37	25.4	8600
122			
123			
124	7.98	15.5	10420
125			
126			
127			
128	8.82	20.5	7500
129			
130			
131	6.69		5253
132			
133			
134			
135	6.63	19.9	3850
136	6.74	17.9	
137			
138	7	18.8	2490
139			
140			
141			
142	6.7	16.2	5760
143	7.15	15.6	
144			
145			1706
146			
147			
148			
149	7.38	16	1710
150	7.43	18.4	

	Anaerobic bottom		
	pH	Anaerobic bottom temperature	Soluble COD Anaerobic bottom
		oC	mg/L
Day			
151			
152	7.22	23	4356
153			
154			
155			
156	7.18	26.3	2600
157	6.88	15.7	
158			
159	7	17.6	3318
160			
161			
162			
163			
164			
165			
166	6.15	17.4	2830
167			
168			
169	6.16	23	5080
170	6.25	29.8	
171			
172	6.6	24.2	4020
173			
174			
175			
176			
177			
178			
179			
180			
181			
182			
183			
184			
185			
186			
187			
188			
189			
190			
191	7.62		2002
192	7.3	21.5	4180
193			
194	7.15	19	1500
195			
196			
197			
198	5.5	19.7	5510
199	5.4	20.1	5200
200			

	Anaerobic bottom		
	pH	Anaerobic bottom temperature	Soluble COD Anaerobic bottom
		oC	mg/L
Day			
201	6.67	16	2720
202			
203			
204	5.55	21	4760
205	5.55	22.5	
206			
207			
208	6.1	17.6	4880
209			
210			
211	7.32	16.3	1502
212	7.34	16.5	1630
213			
214			
215	5.6	17.6	3756
216			
217			
218	6.75	18	1007
219	6.95	17.7	1450
220			
221			
222	7.31	17.5	1471
223			
224			
225	6.9	21.8	2080
226	6.95	19.6	
227			
228	6.1	16.9	4191
229			
230			
231			
232			
233			
234	6.42	19	
235			
236			
237			
238			
239	6.25	19.2	3400
240			
241			
242			
243			
244			
245			
246	6.3	19.5	7090
247	6.6	15.5	
248			
249			
250			

	Anaerobic bottom		
	pH	Anaerobic bottom temperature	Soluble COD Anaerobic bottom
		oC	mg/L
Day			
251			
252			
253	6.22	18	
254			
255			
256			
257			
258			
259			
260	7.25	18.1	
261			
262	6.7	19.3	4650
263			
264			
265			
266			
267	6.6	14.3	
268			

			Anaerobic top		
	pH	Anaerobic top Temperature	Total COD Anaerobic top	Soluble COD Anaerobic top	TSS
		oC	mg/L	mg/L	mg/L
Day					
1	7.2	24.4	5171	1392	2360
2					
3	8	21	10423	786	3280
4					
5					
6					
7					
8	7	22	1946	3940	980
9					
10	7	21		1050	15360
11					
12					
13					
14					
15	7.6	24.7	9732	1000	4560
16					
17	6.88		5647	753	3100
18					
19					
20					
21					
22	6.75	28	9744	6370	4400
23					
24					
25	9340	27.2	9340	3190	250
26					
27					
28					
29	7.66	24.2	7297	2190	270
30					
31					
32	8.6		2751	6740	250
33					
34					
35					
36	7.95	26			3140
37		27			
38					
39	8.29	22.3	8280	7860	2220
40					
41					
42					
43	8.33	20.3	6582	1290	3640
44					
45					
46	8.3	18.7	4266	1030	2160
47					
48					
49	8.35	25.5	3853	1080	2500
50					

	Anaerobic top				
	pH	Anaerobic top Temperature	Total COD Anaerobic top	Soluble COD Anaerobic top	TSS
Day		oC	mg/L	mg/L	mg/L
51					
52	8.3	22.6	4049	1240	2180
53					
54					
55					
56					
57	8.42	23.5	4117	4170	2180
58					
59					
60					
61					
62					
63					
64					
65	8.4	22	2862	487	1590
66					
67	8.2	26.9	2956	1140	1860
68					
69					
70					
71					
72	8.4	23.7	2929	1310	1780
73					
74					
75					
76					
77					
78					
79	8.16	25.3	5336	546	2740
80	8.34	22			
81					
82	8	18.1	7100	1948	2620
83					
84					
85					
86	7.8	23.2	7593	3180	2660
87	7.75	23.3			
88					
89	7.8	20	6133	1936	2560
90					
91					
92					
93	7.06	19.5	11432	7270	1740
94	6.94	21.7			
95					
96	8.07	17.7	7482	2347	2860
97					
98					
99					
100	6.75	21.6	7134	3568	1240

			Anaerobic top		
	pH	Anaerobic top Temperature	Total COD Anaerobic top	Soluble COD Anaerobic top	TSS
Day		oC	mg/L	mg/L	mg/L
101	6.94	22.9			
102					
103			5548	3317	
104					
105					
106					
107	6.3	15	3534	1530	1300
108					
109					
110	7.25	16.2	6020	3464	1230
111					
112					
113					
114	6.98	18.4	74710	4440	2400
115	7.26	19.5			
116					
117			4592	2858	
118					
119					
120					
121	7.37	24.5	7760	8486	
122	7.68	22.3			4220
123					
124			10000	6320	
125					
126					
127					
128	8.12	20.6	7320	31420	1850
129					
130					
131	7.26	17.4	6638	3279	
132					
133					
134					
135	7.6	21	1852		800
136	8.52	18.9			
137					
138	7.55	16.3	12040	2210	
139					
140					
141					
142	8.23	16.5	3160	1250	910
143	8.18	16			
144					
145	8.75	15.5	5184	860	
146					
147					
148					
149	8.24	15.9	6017	2380	1655
150	8	19.8			

	Anaerobic top				
	pH	Anaerobic top Temperature	Total COD Anaerobic top	Soluble COD Anaerobic top	TSS
		oC	mg/L	mg/L	mg/L
Day					
151					
152	8.6	20.3	3371	1872	
153					
154					
155					
156	8	26	2910	3190	1430
157	7.83	16.3			
158					
159	7.88	18	4000	744	
160					
161					
162					
163					
164					
165					
166	7.15	15.7	5483	781	2310
167					
168					
169	7.3	22.2	9140	2580	3970
170	7.4	29.6			
171					
172	7.78		2890	480	
173					
174					
175					
176					
177					
178					
179					
180					
181					
182					
183					
184					
185					
186					
187					
188					
189					
190					
191	9.36		1378	520	
192	9.36	21.6	2555	1310	2580
193					
194	8.34	18.5		896	
195					
196					
197					
198	7.7	19.8	7260	1050	4030
199	8	20.9	6623	558	
200					

	Anaerobic top				
	pH	Anaerobic top Temperature	Total COD Anaerobic top	Soluble COD Anaerobic top	TSS
		oC	mg/L	mg/L	mg/L
Day					
201	8.16	16	11057	590	
202					
203					
204	7.27	19.8	6285	2000	6020
205	7.52	21.4			
206					
207					
208	8.39	17.2	9161	720	
209					
210					
211	9.36	17.3	1844	416	
212	8.17	18	6558	2310	2200
213					
214					
215	7.34	19.3	6219	2356	
216					
217					
218	8	18.8	1057	487	
219	7.88	18.7		1100	1275
220					
221					
222	7.8	17.8	7174	1374	1120
223					
224					
225	7.4	22	9643	2780	
226	6.93	20.2			
227					
228	6.67	17.6	18464	9246	
229					
230					
231					
232					
233					
234	7.62	20.1			
235					
236					
237					
238					
239	7.88	21.1	6402	1070	2320
240					
241					
242					
243					
244					
245					
246	7.51	20.2	10938	3000	
247	8.5	16.2			
248					
249					
250					

	Anaerobic top				
	pH	Anaerobic top Temperature	Total COD Anaerobic top	Soluble COD Anaerobic top	TSS
		oC	mg/L	mg/L	mg/L
Day					
251					
252					
253	7.53	19.6			
254					
255					
256					
257					
258					
259					
260	7.7	19.9			
261					
262	7.7	16.9	7483	2120	2480
263					
264					
265					
266					
267					
268					

	Aerobic					
	DO	pH	Aerobic temperature	Total COD Effluent	Soluble COD Efluent	TSS
Day	mg/L		oC	mg/L	mg/L	mg/L
1	0.1	7.4	27.5	1000	2748	1420
2	5.5	7.8	25.4			570
3	2.8	8.0	24.5	3403	80	1630
4						
5						
6						
7						
8	7.3	8.5	23.8	7660	2600	330
9	8.0	8.3	24.2	717	1320	
10	5.0	8.0	25.1	1282		570
11						
12						
13						
14						
15	5.50	8.06	26.80	7930	7740	2400
16	5.00	7.70	24.10	3566	1000	2080
17	6.00	8.00		8006	6610	1630
18						
19						
20						
21						
22	3.30	6.90	23.90	3781	3810	1540
23	2.05	7.13	24.50	7187	3600	3050
24						
25	3.00	7.50	28.80	6546	3300	2110
26						
27						
28						
29	4.50	7.85	24.30	5770	2130	2450
30		8.80	20.50	3879	1200	10600
31						
32	2.07	8.70		2416.00	636.00	880
33						
34						
35						
36	2.50	8.13	27.30			2150.00
37	7.50	8.23	27.20	13048.00	11410.00	50.00
38						
39			23.50	8086.00	5900.00	1710.00
40						
41						
42						
43	4.87	8.49	21	4222	1010	2150
44						
45						
46	5.2	8.4	19.5	4193	575	2060
47						
48						
49	3.5	8.5	27.4	4212	585	2130
50						

	Aerobic					
	DO	pH	Aerobic temperature	Total COD Effluent	Soluble COD Efluent	TSS
Day	mg/L		oC	mg/L	mg/L	mg/L
51						
52	5.5	8.5	24.4	3887	676	1830
53						
54						
55						
56						
57	4.49	8.48	23.4	3997	485	1820
58						
59	2.03	8.5	26.6	3384	426	1320
60						
61						
62						
63						
64						
65	5	8.5	23.4	2310	356	1207
66						
67	2.4	8.5	26.8	2702	474	850
68						
69						
70						
71						
72	5.11	8.52	22	2388	347	1400
73		8.52	26.4			
74						
75						
76						
77						
78						
79	4	8.36	25.4	3593	282	1840
80	5.5	8.6	24.5	4402	516	2160
81						
82	5.5	8.13	18.6	7938	1723	2900
83						
84						
85						
86	5.9	8.35	23.5	6722	3880	1670
87	7.6	8.22	23.7	6284	2188	2410
88						
89	2.1	8.3	21.3	8345	9269	3900
90						
91						
92						
93	4.5	7.2	20.9	11072	7180	2240
94	8.6	6.95	21.7	10608		2190
95						
96	8.5	8.4	18.8			2480
97						
98						
99						
100	3.3	6.8	21.9	6604	2434	1090

	Aerobic					
	DO	pH	Aerobic temperature	Total COD Effluent	Soluble COD Efluent	TSS
Day	mg/L		oC	mg/L	mg/L	mg/L
101				6520	4789	950
102						
103				5614	2152	
104						
105						
106						
107				2894	1200	890
108		8.3	19.4	3604	1263	980
109						
110	8.2	7.53	16.3	4060	2830	1140
111						
112						
113						
114	9.5	7.23	18.6	9128	6020	2680
115	8.8	7.6	20	4746	1262	1360
116						
117				4496	2196	
118						
119						
120						
121	4	8.4	25.7	8586	3840	
122	8.16	8	22.8	5412	2638	1360
123						
124	6.3	8.5	20	5724	2000	1520
125						
126						
127						
128		8.42	20.4	6520	3580	1520
129						
130	4.47	8.35	20.1	5463	2648	1303
131	6.33	7.67	19.4	6935	3142	
132						
133						
134						
135	4.56	7.77	20	4247	2780	494
136		8.53	19			
137						
138	2.2	8.28	19.5	4212	1970	
139						
140						
141						
142	5.5	8.9	17.5	2642	993	820
143	5.85	8.52	17.3	2226	1144	
144						
145				1920	880	
146						
147						
148						
149	5.5	8.68	16.1	1913	1600	385
150		8.75	21	2336	1167	

	Aerobic					
	DO	pH	Aerobic temperature	Total COD Effluent	Soluble COD Efluent	TSS
Day	mg/L		oC	mg/L	mg/L	mg/L
151						
152		8.80	22.2	1148	801	
153						
154						
155						
156		8.72	25.7	2157	1202	1210
157	10	8.83	17.9	1385	419	
158						
159	8.5	8.64	17.5	1087	166	
160						
161						
162						
163						
164						
165						
166	5	8.13	15.7	1455	1060	620
167						
168						
169	3.5	8	23.3	2882	1802	1600
170	3	8.3	29.2	5540	872	2830
171						
172	3	8.85	24.6	2400	336	
173						
174						
175						
176						
177						
178						
179						
180						
181						
182						
183						
184						
185						
186						
187						
188						
189						
190						
191	6.5	9.41	17.2	1584	800	
192	4.5	8.74	22.4	1304	679	1340
193						
194	2.5	8.8	21.4		706	
195						
196						
197						
198	2.8	8.5	18.3	5259	421	2800
199	5.5	8.62	20.8	6604	294	
200						

	Aerobic					
	DO	pH	Aerobic temperature	Total COD Effluent	Soluble COD Efluent	TSS
Day	mg/L		oC	mg/L	mg/L	mg/L
201	5	9.33	17.6	2038	319	
202						
203						
204	4	8.61	21.4	5627	269	2680
205	2.5	8.44	22.7	6099	1796	
206						
207						
208	4	9.18	18.2	3174	274	
209						
210						
211		9.61	21.1	1640	434	
212	3	9	18.8	6156	4310	1140
213						
214						
215	3.5	7.84	19.3	3997	2632	
216						
217						
218				1206	680	
219	3	8.84	18.9	5809	1030	1160
220						
221						
222		9.52	17.6	9519	1316	1780
223						
224						
225		9.32	21.9	8417	8480	1820
226		8.61	20.1	14566	1432	2570
227						
228		7	18.5	8939		
229						
230						
231						
232						
233						
234		8.73	20.3			
235		8.06	22			
236						
237						
238						
239		8.75	22.6	1843		730
240				2475	1295	550
241						
242						
243		7.5	18.5	4401	2923	
244						
245						
246		8.1	20.8	4884	3650	
247		8.2	17.3	4741	3076	
248						
249						
250						

	Aerobic					
	DO	pH	Aerobic temperature	Total COD Effluent	Soluble COD Efluent	TSS
Day	mg/L		oC	mg/L	mg/L	mg/L
251						
252						
253		8	19.3	2262	1403	780
254						
255						
256						
257						
258						
259						
260		8.5	21.5	2000	775	770
261						
262		8.5	17.4	2368	1700	450
263						
264						
265						
266						
267						
268						

Day	Anaerobic bottom COD removal	Anaerobic top COD removal	Total efficiency COD removal	COD loading	COD volumetric loading	Solids produced MBBR/CFIC	Sludge Yield
	%	%	%	g/d	kg/d/m3	g/day	gTSS/gCODremoved
1	27.23	82.10	64.67	672.02	5.60	132.9	0.3
2						53.4	
3	40.66	90.96	99.08	751.25	6.26	152.6	0.2
4							
5							
6							
7							
8	0.97	45.20	63.84	621.22	5.18	30.9	0.1
9							
10	59.78	88.49		788.40	6.57	53.4	#DIV/0!
11							
12							
13							
14							
15	41.36	87.39	2.40	685.15	5.71	224.6	
16						194.7	
17	32.30	90.59	17.44	691.72	5.76	152.6	
18							
19							
20							
21						0.0	
22	2.07	40.59	64.47	926.38	7.72	144.1	0.2
23						285.5	
24							
25	-3.19	70.18	69.16	924.39	7.70	197.5	0.3
26							
27							
28							
29	-5.57	79.38	79.94	917.48	7.65	229.3	0.3
30						992.2	
31							
32	7.38	37.07	94.06	925.43	7.71	82.4	0.1
33							
34							
35							
36						201.2	
37						4.7	
38							
39	-37.97	2.65	26.93	697.59	5.81	160.1	
40							
41							
42							
43	41.28	86.87	89.72	849.05	7.08	201.2	0.3
44							
45							
46	43.42	89.01	93.86	809.40	6.74	192.8	0.3
47							
48							
49	48.37	87.85	93.42	768.10	6.40	199.4	0.3
50							

Day	Anaerobic bottom COD removal	Anaerobic top COD removal	Total efficiency COD removal	COD loading	COD volumetric loading	Solids produced MBBR/CFIC	Sludge Yield
	%	%	%	g/d	kg/d/m3	g/day	gTSS/gCODremoved
51							
52	50.56	86.53	92.66	795.23	6.63	171.3	0.2
53							
54							
55							
56							
57	74.60	74.72	97.06	1425.08	11.88	170.4	0.1
58							
59	100.00	100.00	95.78	871.26	7.26	123.6	0.1
60							
61							
62							
63							
64							
65	54.02	96.20	97.22	1106.78	9.22	113.0	0.1
66							
67	42.07	88.25	95.11	838.25	6.99	79.6	0.1
68							
69							
70							
71							
72	68.89	83.70	95.68	694.31	5.79	131.0	0.2
73							
74							
75							
76							
77							
78							
79	48.00	94.54	97.18	864.00	7.20	172.2	0.2
80	100.00	100.00	94.84			202.2	
81							
82						271.4	
83							
84							
85							
86	41.23	79.46	74.94	1337.82	11.15	156.3	0.2
87						225.6	
88							
89	37.60	84.09	23.81	1051.14	8.76	365.0	
90							
91							
92							
93	51.03	63.63	64.08	1727.14	14.39	209.7	0.2
94						205.0	
95							
96	-0.20	88.26				232.1	
97							
98							
99							
100	33.41	79.46	85.99	1501.11	12.51	102.0	0.1

Day	Anaerobic bottom COD removal	Anaerobic top COD removal	Total efficiency COD removal	COD loading	COD volumetric loading	Solids produced MBBR/CFIC	Sludge Yield
	%	%	%	g/d	kg/d/m3	g/day	gTSS/gCODremoved
101						88.9	
102							
103	21.55	76.66	84.86	1227.74	10.23		
104							
105							
106				1207.35	10.06		
107	18.67	88.87	91.27	1187.65	9.90	83.3	0.1
108						91.7	
109							
110	21.60	72.71	77.70	1096.59	9.14	106.7	0.1
111							
112							
113							
114	39.80	69.90	59.19	1274.57	10.62	250.8	0.3
115						127.3	
116							
117	37.02	79.11	83.95	1181.95	9.85		
118							
119							
120							
121	35.96	36.81	71.41	1160.35	9.67		
122						127.3	
123							
124	4.28	41.94		940.55	7.84	142.3	
125							
126							
127							
128	52.41	-99.37	77.28	1361.66	11.35	142.3	0.1
129							
130						122.0	
131	52.24	70.19	71.43	950.23	7.92		
132							
133							
134							
135	65.49	100.00	75.08	963.88	8.03	46.2	0.1
136							
137							
138	75.74	78.46	80.80	886.64	7.39		
139							
140							
141							
142	50.85	89.33	91.53	1012.61	8.44	76.8	0.1
143							
144							
145	87.66	93.78	93.63	1194.22	9.95		
146							
147							
148							
149	80.56	72.95	81.81	760.15	6.33	36.0	0.1
150							

Day	Anaerobic bottom COD removal	Anaerobic top COD removal	Total efficiency COD removal	COD loading	COD volumetric loading	Solids produced MBBR/CFIC	Sludge Yield
	%	%	%	g/d	kg/d/m3	g/day	gTSS/gCODremoved
151							
152	53.02	79.81	91.36	801.19	6.68		
153							
154							
155							
156	83.58	79.85	92.41	1367.88	11.40	113.3	0.1
157	100.00	100.00	90.75	391.22	3.26		
158							
159	32.29	84.82	96.61	423.36	3.53		
160							
161							
162							
163							
164							
165							
166	26.11	79.61	72.32	330.91	2.76	58.0	0.2
167							
168							
169	55.87	77.59	84.35	994.64	8.29	149.8	0.2
170						264.9	
171							
172	76.44	97.19	98.03	1473.98	12.28		
173							
174							
175							
176							
177							
178							
179							
180							
181							
182							
183							
184							
185							
186							
187							
188							
189							
190							
191	84.87	96.07	93.95	1238.14	10.32	0.0	
192	69.53	90.45	95.05	1284.19	10.70	115.8	0.1
193							
194							
195							
196							
197							
198	50.04	90.48	96.18	1032.22	8.60	241.9	0.2
199							
200							

Day	Anaerobic bottom COD removal	Anaerobic top COD removal	Total efficiency COD removal	COD loading	COD volumetric loading	Solids produced MBBR/CFIC	Sludge Yield
	%	%	%	g/d	kg/d/m3	g/day	gTSS/gCODremoved
201	87.80	97.35	98.57	2087.65	17.40		
202							
203							
204	67.04	86.15	98.14	1351.58	11.26	231.6	0.2
205			87.66	1362.07	11.35		
206							
207							
208							
209							
210							
211	95.97	98.89	98.84	3492.22	29.10		
212	87.03	81.62	65.71	1176.55	9.80	98.5	0.1
213							
214							
215	65.98	78.66	76.16	1033.53	8.61		
216							
217							
218	97.02	98.56	97.98	3158.06	26.32		
219	91.17	93.30	93.72	1536.35	12.80	100.2	0.1
220							
221							
222	92.36	92.86	93.16	1801.99	15.02	153.8	0.1
223							
224							
225	96.51	95.34	85.78	5582.30	46.52	157.2	
226	100.00	100.00	92.69	1833.25	15.28	222.0	0.1
227							
228	66.52	26.14		1171.68	9.76		
229							
230							
231							
232							
233							
234							
235							
236							
237							
238							
239	34.97	79.53		489.34	4.08	63.1	#DIV/0!
240	100.00	100.00	85.82	855.04	7.13	47.5	0.1
241							
242							
243				2808.00	23.40		
244							
245							
246	32.15	71.29	65.07	978.12	8.15		
247	100.00	100.00	76.30	1214.74	10.12		
248							
249							
250							

Day	Anaerobic bottom COD removal	Anaerobic top COD removal	Total efficiency COD removal	COD loading	COD volumetric loading	Solids produced MBBR/CFIC	Sludge Yield
	%	%	%	g/d	kg/d/m3	g/day	gTSS/gCODremoved
251							
252							
253						67.4	
254							
255							
256							
257							
258							
259							
260						66.5	
261							
262	33.36	69.62	75.64	653.14	5.44	38.9	0.1
263							
264							
265							
266							
267							
268							

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