DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

ANAEROBIC FILTER PERFORMANCE AT DIFFERENT CONDITIONS

by
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İZMİR

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We have read the thesis entitled **"ANAEROBIC FILTER PERFORMANCE AT DIFFERENT CONDITIONS"** completed by **MELİK KARA** under supervision of **ASSIST. PROF. DR. SEVGİ TOKGÖZ GÜNEŞ** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ANAEROBIC FILTER PERFORMANCE AT DIFFERENT CONDITIONS

ABSTRACT

The anaerobic treatment technology has rapidly developed in recent decades. The anaerobic treatment process has also recognized as one of the most effective methods for treating organic waste stream, including industrial and domestic wastewater.

The anaerobic filter reactors are ones of the more common of the anaerobic digestion options for the treatment of industrial wastes. Researches on design and modeling have greatly increased the understanding of the impacts of the fundamental controlling phenomena.

There are various factors affecting design and performance of anaerobic filters. In general these factors can be divided into three categories; physical factors, performance factors and hydraulic factors.

In this study, design and performance parameters such as filter material ratio, organic loading rate, hydraulic retention time, temperature and operation mode were evaluated at four upflow anaerobic filter reactors having different filter material ratio. Anaerobic filters were fed with the synthetic wastewater during the study.

Experimental studies were examined at different organic loading rate for three different hydraulic retention time (HRT), 3, 2 and 1 day at psychrophilic temperature ranged of 16 – 33 ^{o}C. When two reactors named as AFR 100 and AFR 50 were operated in continuous operation mode, other two reactors named as AFR 75 and AFR 25 were operated in semi-continuous operation mode.

During the study, the organic loading rates (OLR) were varied between 0.333 and 8.000 kgCOD/m^{3}d. Firstly, OLR were applied 0.333, 0.666 and 1.333 kgCOD/m^{3}d for HRT of 3 days, respectively. Secondly, OLR values were applied 0.500, 1.000

and 2.000 kgCOD/m³d for HRT of 2 days, respectively. And finally, OLR values were applied 2.000, 4.000 and 8.000 kgCOD/m³d for HRT of 1 day, respectively.

According to the results and the data obtained form experimental and literature studies, filter material ratio affected COD removal efficiencies at the treatment performance of anaerobic filters. Especially, the removal efficiencies of anaerobic filter filled fully are more than the anaerobic filter having different filter material ratio. On the other hands, the operation mode of the anaerobic filters as well is significant from the point of COD removal efficiencies. The removal performance of filters operated as continuous mode is higher than anaerobic filter operated as semi-continuous mode. Moreover, it is incontestable that the temperature is effective on treatment performance. It follows from data obtained that temperature positively increases COD removal efficiencies.

In second part of the study, the reactors were examined in terms of kinetic models. Kinetic constants for filter reactors were determined by the help of applications of the models.

Keywords: Upflow anaerobic filter reactor, filter material ratio, temperature, kinetic models

FARKLI KOŞULLARDA ANAEROBİK FİLTRE PERFORMANSI

ÖZ

Anaerobik arıtma teknolojisi son on yıllar içerisinde hızlı bir şekilde gelişmektedir. Aynı zamanda anaerobik arıtma işlemleri endüstriyel ve evsel atıksularda dahil olmak üzere organik atıkların arıtımı için en etkili metodlardan birisi olarak ta tanımlanmaktadır.

Anaerobik filtre reaktörler endüstriyel atık suların arıtılmasında anaerobik ayrıştırma seçeneklerinin yaygın olanlarından biridir. Modelleme ve tasarımdaki araştırmalar kontrol fenomenlerinin etkilerinin anlaşılmasını büyük ölçüde arttırdı.

Anaerobik filtrelerde performans ve tasarımı etkileyen çeşitli etkenler vardır. Temelde bu faktörler üç kısma ayrılabilir; fiziksel faktörler, performans faktörleri ve hidrolik faktörler.

Bu çalışmada, filtre malzemesi oranı, organik yükleme hızı, hidrolik alıkonma süresi, sıcaklık ve işletme türü gibi tasarım ve performans parametreleri, farklı filtre malzemesi oranına sahip dört yukarı akışlı anaerobik filtre reaktörde değerlendirildi. Bu reaktörlerden iki tanesi sürekli işletilirken diğer ikisi yarı sürekli olarak işletildi. Anaerobik filtreler işletme dönemlerinde sentetik atıksu ile beslendi.

Deneysel çalışmalar psikofilik sıcaklık aralığında üç farklı, 3, 2 ve 1 günlük olmak üzere, alıkonma süresi için farklı organik yüklemelerde incelendi. AFR 100 ve AFR 50 olarak adlandırılan iki reaktör sürekli olarak işletilirken, AFR 75 ve AFR 25 adlı reaktörler yarı sürekli olarak işletildi.

Çalışma boyunca, organik yükleme değeri 0.333 ile 8.000 kgCOD/m^{3}d arasında değiştirildi. İlk olarak 3 günlük alıkonma süresi için 0.333, 0.666 ve 1.333 kgCOD/m^{3}d organik yükleme değerleri uygulandı. İkinci olarak 2 günlük alıkonma süresi için 0.500, 1.000 ve 2.000 kgCOD/m^{3}d organik yükleme değerleri uygulandı.

Ve son olarak ta, 1 günlük alıkonma süresi için 2.000, 4.000 ve 8.000 kgCOD/m^3d organik yükleme değerleri uygulandı.

Elde edilen bu sonuçlara göre, anaerobik filtrelerin arıtma performansında filtre malzemesi oranını arıtma verimini etkilemektedir. Özellikle filtre malzemesi ile tam dolu anaerobik filtrelerin arıtma verimi diğer filtre malzemesi oranına sahip olan anaerobik filtrelerden daha fazladır. Diğer taraftan, anaerobik filtrelerin işletme türü de giderim açısından önemlidir. Sürekli işletilen filtrelerin performansları yarı sürekli işletilenlerden daha fazladır. Bununla birlikte sıcaklığında arıtma verimi üzerindeki etkisi tartışılmazdır. Sıcaklığın artışının KOİ giderim verimini olumlu yönde arttırdığı elde edilen verilerden çıkarılabilir.

Çalışmanın ikinci kısmında reaktörler kinetik modeller açısından incelendi. Filtre reaktörler için kinetik sabitler modellerin uygulanmasıyla belirlendi.

Anahtar sözcükler: Yukarı akışlı anaerobik filtre reaktör, filtre malzemesi oranı, sıcaklık, kinetik modeller

CONTENTS

CHAPTER ONE
INTRODUCTION

1.1 General

Anaerobic wastewater treatment has traditionally been used to treat the sludges, which are made of the treatment plants, and low and high strength wastewater coming from the industrial plants and municipal. The anaerobic treatment process has also recognized as one of the most effective methods for treating organic waste stream, including industrial and domestic wastewater (Çakır, 2004; Cheung, 2003).

Anaerobic treatment systems which are accepted as main subjects of environmental protection, (Lettinga & Hulsoff, 1991) are defined as three phased systems since the liquid, biogas and solid material outputs from the system.

Purposes of anaerobic treatment may be summarized as follow;

- Stabilization of the organic matter
- Elimination of solid materials
- Reduction of pathogenic microorganism concentration
- Odor removal

Anaerobic wastewater treatment is a very complex process involving many microorganisms and metabolic pathways for the degradation of organic matter into a gas mixture, the main components of which are methane and carbon dioxide.

Anaerobic treatment has some advantages and disadvantages. But, its advantages are much more than its disadvantages. These are given as following.

1.1.1 Advantages of Anaerobic Treatment

- In treatment of medium and high strength wastewater (Chemical Oxygen Demand COD $\geq$ 1500 mg/l), use of anaerobic treatment is cheaper than aerobic treatment,
- Dewatering of waste biological sludge is very easy, because the sludge is highly stabilized,
- Biological solid production is very low,
- There is not energy requirement for aeration,
- Nutrient necessity is low,
- A useful last product such as methane is produced,
- It is relatively possible for high loading rates to be applied under appropriate conditions,
- Process is not limited by oxygen transfer,
- As compared with aerobic treatment systems, anaerobic treatment systems require small area,
- Anaerobic treatment has a relatively low cost technology with respect to the equipment' used,
- It is appropriate for seasonal and batch operation,
- It is possible for anaerobic treatment systems to be applied for both big and small scales.

1.1.2 Disadvantages of Anaerobic Treatment

- It needs high temperature (25^{o}C - 40^{0}C),
- Methane bacteria reproduce very slowly and they are easily affected from environmental conditions,
- It has some disadvantages for less concentrated wastewater,
- Anaerobic degradation is a highly sensitive process to the presence of some chemical compounds such as $CHCl_3$, CCl and CN^-,
- Since the growth rate of anaerobic bacteria is slow, start-up period of the process takes a relatively long time,

- Anaerobic process is a pretreatment method in main. Therefore, before giving the treated water to the receiving filter material an appropriate last treatment is required,
- Application of these systems for direct treatment of wastewater needs very little practical experience.

Among the different technical alternatives, anaerobic treatment is suitable not only for low wastewater flow rates but also high wastewater flow rates and also it provides energy thanks to the biogas produced in the system (Boller & Eugster, 1992).

1.2 Development of Anaerobic Treatment

Anaerobic treatment is one of naturally occurring processes involving decomposition and decay, in which complex organic matter is broken down into its simple chemical constituents. The mechanisms of anaerobic degradation of organic materials have occurred for a long period of time in ecological systems such as rivers, lake sediments and fresh water sediments.

The scientists as McCarty, Young and Hobson studied on the matter comprehensively used the large scale anaerobic digester not only for wastewater treatment but also for stabilizing domestic sludge. The conventional digesters were usually operated in continuous mode, since waste was produced continuously (Cheung, 2003).

1.3 Anaerobic Treatment Stages

When the organic matters digested in anaerobic conditions, the reaction of the anaerobic digestion has theoretically carried out in the following way.

$$C_cH_hN_nS_s + yH_2O \rightarrow xCH_4 + (c-x)CO2 + nNH_3 + sH_2S$$

The anaerobic degradation of organic matter is a multi-phase process comprising acidogenesis and subsequent methanogenesis. In the first phase, complex organic materials, carbohydrates, amino acids, long-chain fatty acids and alcohols are degraded to intermediary products such as short-chain fatty acids, which are metabolized in the subsequent phase (Yu, Wilson & Tay, 1998). In the second phase, these products transform acetate and H_2 by acid bacteria. And in the last phase, bacteria producing methane produce biogas by using carbon dioxide and molecular hydrogen or decomposing acetic acids.

A final comment is necessary concerning the approach to be taken in the discussion of process fundamentals that follows. The key efficient of anaerobic treatment is to develop and maintain a large, stable, viable population of methane-forming bacteria. In order to accomplish this aim, it is necessary provide:

- Adequate contact between the bacterial population and appropriate nutrient sources in the substrate
- A suitable, uniform environment
- Sufficient bacterial retention time

Anaerobic biological waste treatment is a complex microbiological process involving many types of bacteria working in an assembly-line style. Treatment performance is dictated by the relative balance in viable populations among the major types of bacteria. And conversion of wastewater organics to methane involves several groups of bacteria carrying out rather specific reactions.

In Figure 1.1, these stages and bacteria types under question are shown;

1. Fermentation bacteria,
2. Acidogenic bacteria producing hydrogen
3. Acidogenic bacteria consuming hydrogen
4. Methogenics reducing CO_2
5. Methogenics using acetic acid

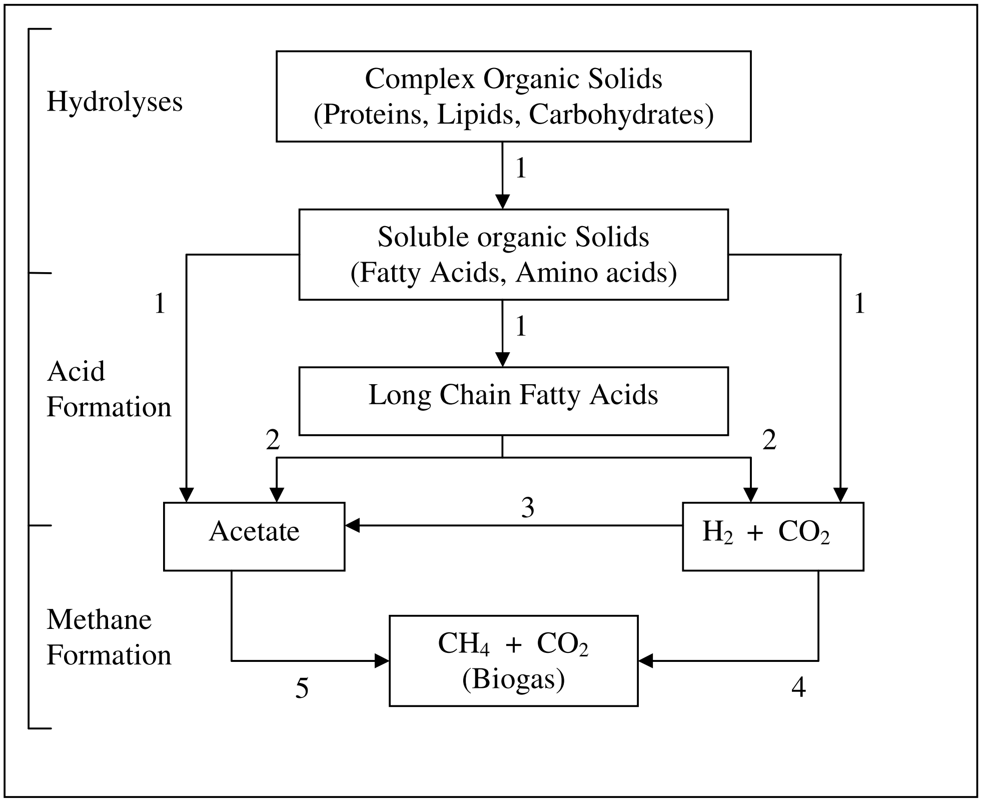


Figure 1.1 Anaerobic treatment stages

The three-stage scheme, involving the aforementioned five groups of bacteria, is shown in Figure 1.1. Conceptually, anaerobic treatment of complex organics can be described as a three-stage process involving. These stages are clarified below;

1.3.1 Hydrolyses Stage

Hydrolyses of complex and/or insoluble organics are necessary to convert these materials to a size and form that can pass through bacterial cell walls for use as energy and nutrient sources. The organic matter is simply converted into o soluble form that can be utilized by the bacteria. Hydrolyses is accomplished by extra cellular, hydrolytic enzymes produced and excreted by the bacterial population for this specific purpose.

Once complex organics are hydrolyzed, they are fermented to long-chain, organic acids, sugar, amino acids, and eventually to smaller organic acids such as propionic acid, butyric acid and valeric acid.

It is carried out this stage that complex organic matters are transformed into the basic dissolved organic compounds. There may be no hydrolyses stage in each anaerobic treatment processes to the characteristics of the treated wastewater. But, for such kind of wastewaters (such as biological sludge comprising of municipal wastewater treatment plant, paper industry wastewater, food and medicine industry wastewater), hydrolyses stage is the most important part of the anaerobic treatment. In other words, hydrolyses are able to determine the rate of all anaerobic treatment process in the some conditions.

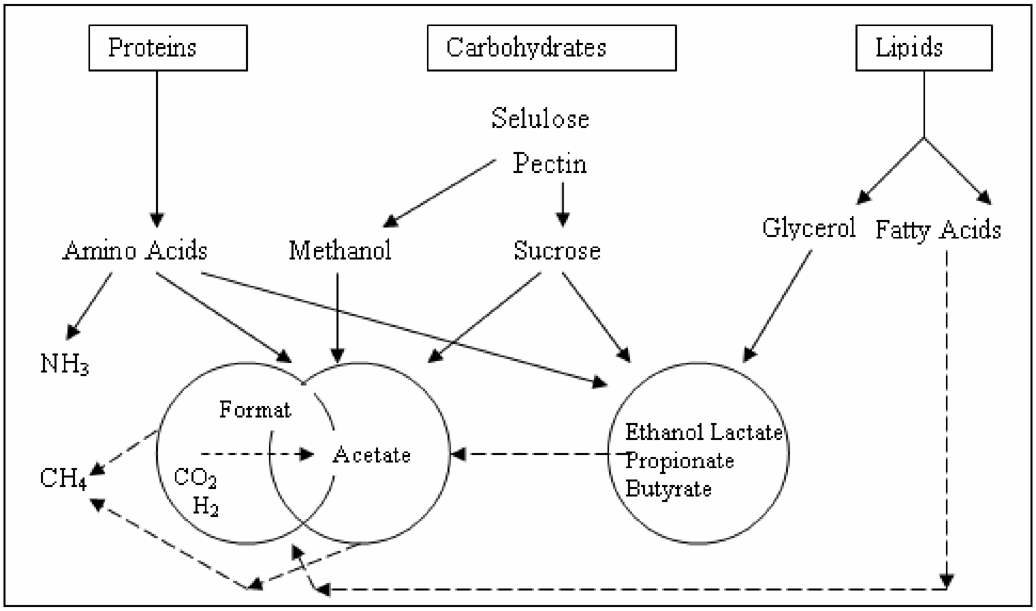


Figure 1.2 The conversion of complex organic matters into the basic dissolved organic compounds.

1.3.2 Acid Production Stage

It is believe that hydrogen is produced by the fermentative bacteria and by hydrogen-consuming acidogenic bacteria (groups 1 and 2, Figure 1.1). Acetate is also produced by these groups in addition to hydrogen-consuming acidogenic bacteria (group 3, Figure 1.1). Hydrogen has recently been shown to play a key role in regulating organic acid production and consumption.

Acidogenesis is the stage that the dissolved organic compounds are turned to the volatile fatty acids and it is carried out by the microorganism group so-called acidogenic bacteria. After, the great part of the volatile fatty acids produced from basic organic compounds is transformed to acetic acid, formic acid, H_2 and CO_2. Acidogenesis stage can occur in ranged of a wide temperature and pH.

1.3.3 Methane Production Stage

Waste stabilizations occur during the methanogenic phase by conversion of the acetic acid into methane. Carbon dioxide is also produced and either escapes as gas or is converted to bicarbonate alkalinity.

It is stage that the products occurring second phase are converted to methane and carbon dioxide. For many organic wastes, methane and carbon dioxide originate from digesting of acetic acid as anaerobic. But, methane can occur in the conclusion of the reduction of carbon dioxide with hydrogen produced in the course of the fact that carbon dioxide digests to propionic acid and other volatile acid. Methogenics bacteria are much more sensitive against environmental conditions such as pH, temperature and toxicity in comparison with acidogenic bacteria. In addition, the growth rate of methogenics bacteria is much lower than the growth rate of acidogenic bacteria.

One of the most important characteristics of the methanogenic phase is that very few substrates can act as energy sources for the methane bacteria. Recently, it is believed that only formic acid, acetic acid, methanol and hydrogen can be used as energy sources by the various methanogens (Parkin & Owen, 1986)

Approximately 72% of the methane formed in the anaerobic digestion of wastewater sludges comes from acetate cleavage.

$$CH_3COOH \rightarrow CH_4 + CO_2$$

The remaining 28% results from reduction of carbon dioxide using hydrogen as the energy source by CO_2-reducing methanogens;

$$CO_2 + H_2 \rightarrow CH_4 + H_2O$$

In addition, formic acid and methanol are also intermediate products of the process which are used by methanogenic bacteria as energy source. The pathways for methane production in anaerobic treatment are shown in Figure 1.3.

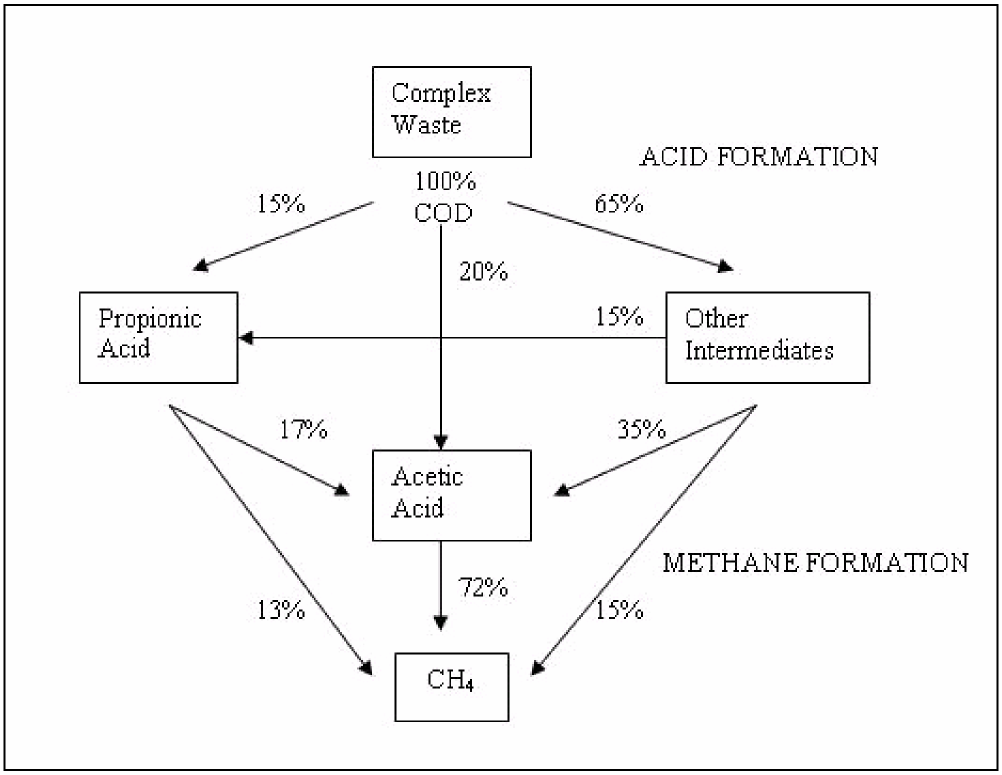


Figure 1.3 The pathways for methane fermentation of complex organic wastes (Parkin & Owen, 1986)

1.4 Environmental Factors Affecting Anaerobic Treatment Efficiency

As known to scientists involved this matter, microorganisms in anaerobic digestion are very sensitive in terms of surround conditions. That’s why, these conditions should be provided to utility of the microorganisms in an optimum way.

Nutrients, pH, temperature and toxicity are significant in the anaerobic treatment. In Table 1.1, Optimum Conditions for Anaerobic microorganisms are shown;

Table 1.1 Optimum conditions for anaerobic microorganisms (Tokgöz, 1998)

Parameter	**Optimum Environmental Conditions**
Wastewater Composition	It should contain C,N,P and trace elements and not contain inhibitory and oxidizing elements
Temperature (^oC)	Psychrophilic interval 10 – 25 ^oC Mesophilic interval 25 – 38 ^oC Thermophilic interval 50 – 60 ^oC
C:N:P Ratio	100 / 2-10 / 0.5-1
pH	6.5 – 8.0
Alkalinity	1000 – 4000 mg $CaCO_3$/L
Total Volatile Acid (TVA)	<1000 – 1500 mg acetic acid/L
TVA / Alkalinity	<0.1
Oxygen	None
Toxic materials	None

1.4.1 Nutrients

There are needed to nutrients for the cell development of anaerobic microorganisms. For the efficient treatment, the wastewater should contain some nutrients such as nitrogen and phosphorus, which are the most important. Because nitrogen is used by the organisms for synthesis of nucleic acids, which is necessary for the synthesis of RNA and DNA. $C_5H_7O_2N$ as empirical expression for bacteria is taken into consideration. Here, %12 of bacterial cell can be seen to be nitrogen (Tokgöz, 1998).

Nutrient demand is depend on content of the organic matters to be treated and the sludge retention time of the system. Anaerobic microorganisms generally require trace organic and inorganic nutrients as well such as sulfur, iron, calcium, magnesium, sodium, potassium, cobalt and nickel, apart from nitrogen and phosphorus.

Although such kind of the nutrients especially is present in domestic wastewater, they may not exist in some industrial wastewater. Therefore, there is no need for nutrient addition to the systems in the anaerobic treatment of domestic or municipal wastewater. But for treatment of wastewater containing a high percentage of industrial waste; additional nitrogen or phosphorus should be added into the system.

1.4.2 pH

Inasmuch as methane producing bacteria are very sensible to pH, for an efficient treatment, the range of optimum pH value should be between 6.5 and 8.0 in anaerobic degradation. But methogenics bacteria are not lost their biological activities if pH value does not fall lower than 6.

In the anaerobic treatment, buffering capacity is commonly measured as alkalinity and as a dominant buffering system, bicarbonate alkalinity is used. Protection of a sufficient alkalinity in the system is significant in protecting the operation against low pH value (Tokgöz, 1998).

If bicarbonate alkalinity value fall inferior of 500 mg/l and approximately 38% of the gas produced is made of carbon dioxide, pH of system falls under 6 and, in consequence of this, all the systems stay under the toxic effect.

When pH has fallen in the system, two approaches are applied to the system. In the first approach, feeding of organic matter should be cut. Thus, fatty acid concentration can be decreased by being increased the concentration of methanogens bacteria in the environment. After pH came to acceptable level (for instance 6.8), the feedings is continued again. In the second approach, chemical substances can be added to the system to augment buffering capacity and to raise pH (Öztürk, 2005).

1.4.3 Temperature

Anaerobic treatment processes are strongly affected by temperature, which affects the microbial activity of system. Production of methane forming in an anaerobic process is also closely related to the temperature of the reactor. It has been observed that methane production is most favorable at temperatures ranging from 0 to 60 °C (Cheung, 2003).

Such as in the other treatment methods, anaerobic bacteria have worked in the range of two different temperatures. They can be operated as mesophilic (25 – 40 °C) or thermophilic (50 – 70 °C). In addition, these systems are able to be operated in psikophilic interval, which temperature is in range of 18 – 25 °C. But reactions and growth rate of microorganisms are really slower in psikophilic intervals. Because of this, anaerobic systems are operated under higher temperatures than ambient air temperatures. High temperatures have some advantages;

- Organic material degradation rate and degree increase,
- Sludge volume decreases,
- Pathogenic microorganisms removal rate increases,
- Dewatering characteristics of sludge increases.

The substrate removal rate and the decay rate of anaerobic microorganisms together with the temperature increase and so the substrate removal rate and specific growth rate of thermophilic microorganisms are much greater than the substrate removal rate and specific growth rate of mesophilic microorganisms. But, it is much more slow that the thermophilic systems should be taken the operating because of the fact that the net microorganism synthesis rate be lower. Moreover, thermophilic systems are much more sensible against the changing in the organic load and the contents of substrate and the alteration in the environmental parameters.

1.4.4 Toxicity

Toxic materials cause inhibition in anaerobic treatment, now that the methogenics bacteria among the all microorganisms are the most sensible group against toxicity. However, it is known that methogenics can tolerate many toxic subjects until the definite levels and will be able to acclimate against these subjects. However, it is decreased also their toxic effects for many toxic subject under the definite concentrations to be treatable.

Many materials show toxic characteristic for system. For example, at 200 – 1000 mg/L total ammonia nitrogen positively affects the system performance. But if the concentration reaches 3000 mg/L, it shows inhibitory effect. A lot of cations as well (sodium, potassium, calcium, magnesium and ammonium), which have affirmative effects to anaerobic systems in low concentration have toxic effect in high concentrations. The cationic toxicity can be prevented by adding to the system the other cations which will provide antagonist effect. For example, toxicity due to sodium can be prevented by adding potassium or calcium to the environment.

Also, dissolved heavy metals affect the anaerobic treatment as toxic materials. The heavy metals at low concentrations such as 0.1 – 10 mg/L and some organic matters should be considered as inhibitory subjects.

On the other hand, under the anaerobic conditions, the sulfate ion (SO_4^{-2}) comes down to the sulfite ion (S^{-2}). Sulfite ion as well comprises such kind hydrogen sulfite compounds (H_2S, HS^- and S^{-2}) by merging with hydrogen. Hydrogen sulfite is quite toxic subject and is of great importance in terms of toxicity for methanogenic bacteria. Sulfite toxicity depends on pH of the wastewater. Inhibitory concentrations of some materials for anaerobic treatment process are shown in Table 1.2.

Table 1.2 Concentration of toxic materials preventing anaerobic biodegradation process (Tokgöz, 1998; Filibeli, Büyükkamacı, Ayol, 2000; Öztürk, 2005)

Material	**Harmful Concentration (mg/L)**
NH_4^+ , NH_3	1500-2000*
Dissolved H_2S, HS^-, S^{-2}	100-150
Sodium (Na^{+1})	3.500-5.500
Potassium (K^{+1})	2.500-4.500
Calcium (Ca^{+2})	2.500-4.500
CN^-	0,5-1
Magnesium (Mg^{+2})	1.000-1.500
SO_3^{-2}	200^+
Copper (Cu^{+2})	100
Chrome (Cr^{+3})	200^+
(Cr^{+6})	3^+
Nickel (Ni^{+2})	200-500
Zn^{+2}	1^+
Sulfate (SO_4^{-2})	5.000
Sodium chloride and general salts (NaCl)	40.000
Nitrate (determined as N)	0.05
Manganese (Mn^{+2})	>1.500

(* harmful especially at pH>7.5; + dissolved)

In the anaerobic treatment, acetic, propionic and butyric acids are produced as intermediate products. These volatile acids produced are not still known to show inhibitory effect for methanogenic bacteria. Inhibitory organic volatile acid concentration depends on the pH of the system. Since, if system pH is controlled at a certain interval, volatile acid concentration can be tolerated at a certain value. (Tokgöz, 1998).

1.4.5 C/N Ratio

Nutrient demands of the anaerobic microorganisms are rather different to aerobic microorganisms because cell formation of the anaerobic microorganisms is completely different. Nitrogen and phosphorus demand of the anaerobic microorganisms is 20% of the demand of aerobic microorganisms. Typically, COD/N/P rate for aerobic systems is 100/5-20/1-5, whereas this value for anaerobic systems is 100/2-10/0.5-1

Carbon in organic matter is necessary for the energy required of the microorganisms to be provided. The most important nutrient materials are nitrogen and phosphorus. Nitrogen is required for growing and reproducing of bacteria.

Optimum C/N ratio can be obtained by the help of the fact that the different organic matters are mixed. Stable mixture is needed to guarantee continuous gas product.

CHAPTER TWO
ANAEROBIC FILTERS AND FACTORS AFFECTING DESIGN AND PERFORMANCE

2.1 General

In the last few years, newly-advanced anaerobic reactor systems, such as upflow anaerobic sludge blanket (UASB), anaerobic filter (AF), anaerobic fluidized bed (FB), anaerobic sequencing batch reactors (AnSBR) and other modifications of anaerobic reactors have also been used for the treatment of low and high strength wastewater. All these systems are designed to achieve high retention of biomass for efficient and stable operation. The biomass retention is accomplished by immobilizing microorganism either as biofilm attached on the support material surfaces such as that in anaerobic filters and expanded fluidized beds or by a process of spontaneous aggregation of the bacteria to granular sludge with high activity and good settling properties such as that in UASB. In the following sections, anaerobic filter will particularly be discussed and its characters will be given in detail.

The anaerobic filter is one of the more common of the anaerobic digestion options for the treatment of industrial wastes and extensive research on design and modeling has greatly increased the understanding of the impacts of the fundamental controlling phenomena (Ahn & Forster, 2002).

The anaerobic filter (AF) is mainly a column or tower filled with support filter material for the growth of biomass. It is operated in vertical flow mode either upflow or downflow. A variety of natural materials such as smooth quartzite pebbles, shells, granite stones, cinder, brick ballast and synthetic materials like polyvinylchloride sheets, needle-punched polyester, glass, raschig ring and other materials have been used for attachment and growth of anaerobic biomass. Generally the average material diameter varies between 0.2 and 60 mm. However, anaerobic filters may suffer blockages if an excessively small medium is employed and to minimize this, filter material tend to have relatively large diameters (>20 mm). These materials have voids for the passage of wastewater and also for the accumulation of suspended biomass. The sloughed biomass in upflow anaerobic filter gets accumulated in the bottom portion of the filter and leads to clogging. So, recycling effluent to the influent can be used as required. The upflow anaerobic filter is used/recommended for dilute soluble wastes, soluble wastes which can be made dilute by recirculating effluent, or wastes with easily degradable suspended materials (Jawed & Tare, 2000).

In anaerobic filter, 60% of the biomass is the sludge accumulated in the pores of filter material and the most of the organic matter removal is accomplished by the microorganisms in this portion of the biomass. The biomass in the reactor is attached in the form of a thin film layer on the filter material. The soluble organic compounds in the inflow wastewater pass by contacting with the biomass in the reactor and they convert into intermediate and last productions (especially carbon dioxide and methane) by diffusing to the surface of the solids in granule form.

2.2 Development of Anaerobic Filter

The anaerobic filter process was firstly developed by Coulter (1957), but was forgotten until 1969 when Young and McCarty renewed interest by demonstrating the process's ability to treat a medium to high strength carbohydrate/protein wastewater. Anaerobic filters have grown to represent an advanced technology that has been used effectively for treating a variety of industrial wastes. Young and McCarty demonstrated the importance and potential of the anaerobic filter process by successfully treating a medium strength synthetic waste at 25 °C, at organic loading rates ranging from 1.06 kg to 3.53 kg COD/ m^3 of filter volume.

The theory and kinetics of the anaerobic filter process were examined by several investigators. Mueller presented a mathematical model incorporating a two stage reaction sequence in 1975. Two types of reaction kinetics were analyzed with his model. Employing Monod kinetics and the other first-order kinetics, both were shown to adequately approximate the filter performance. A model formulated by DeWalle and Chian in 1976 showed that at high substrate concentrations, the substrate removal rate is proportional to the square root of the substrate concentration used and the specific area of the filter medium. Jennings developed a mathematical model for percent removal of a nonabsorbable biogradable substrate in a submerged biological filter in 1976. He used nonlinear Monod expression for the substrate utilization rate and theoretically investigated the effects of diffusion in a plug flow reactor under steady-state conditions.

The performance of the anaerobic filter has also been tested on variety types of wastewater. This includes landfill leachates, high strength acid wastewater by Chian in 1977, heavy metals by Dek'alle in 1979, wheat starch-gluten plant waste by Taylor in 1972, pharmaceutical wastes by Jennett and Dennis in 1975, shellfish processing wastes by Hudson in 1978, brewery wastes by Lovan and Fores in 1971, food processing wastes by Plummer in 1968 and the removal of organic particulates by Morris in 1981. Almost all of these investigations were directed at the treatment of medium to high strength wastes (1000 mg/L or greater COD).

There have been other investigations of the anaerobic filter to further ascertain its usefulness. The pH tolerance of anaerobic digestion was presented by Clark and Speece in 1970 while Shafie and Blood-good investigated the progressive breakdown of a synthetic waste to volatile fatty acids by analyzing samples from a multiple upflow filter system in 1973.

2.3 Advantages and Disadvantages of Immobilized Growth in Anaerobic Filters

Anaerobic filters have advantages and disadvantages depending on their process characteristics which are different than the ones given in Section 1.1. They are more suitable for handling high pollutional load wastewaters as it presents high substrate removal efficiencies at short hydraulic retention times and high organic loading rates. Immobilized cell applications in anaerobic filter treatment processes have the following advantages (Wen-Chien & Tzu-Yueh, 2004; Kuo & Shu, 2004);

- The biomass is easily retained and no recirculation is required,

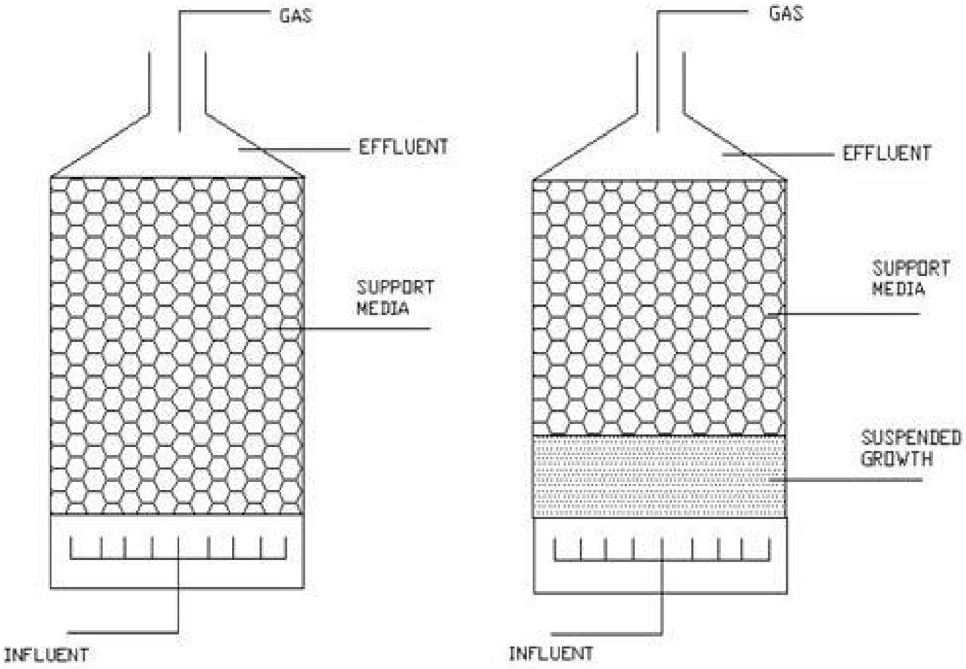
- Dissolved solids can be efficiently treated,
- With a higher biomass concentration in the reactor, the system can tolerate higher hydraulic or organic loads,
- This system is easy to operate and maintain. Solids separation is easy and no final clarifier is needed,
- Since a high solid matter concentration is preserved in the filter, operation, termination and adaptation to new operation conditions are easier than other anaerobic processes,
- Sludge production may be low,
- It tolerates high hydraulic and organic overloadings,
- Biomass loss as a result of various inhibitory agents is limited,
- If the construction area is limited for the reactor, tower type structures may be applied.

Disadvantages of immobilized cell applications in anaerobic filter treatment processes may be summarized as follows (Tokgöz, 1998);

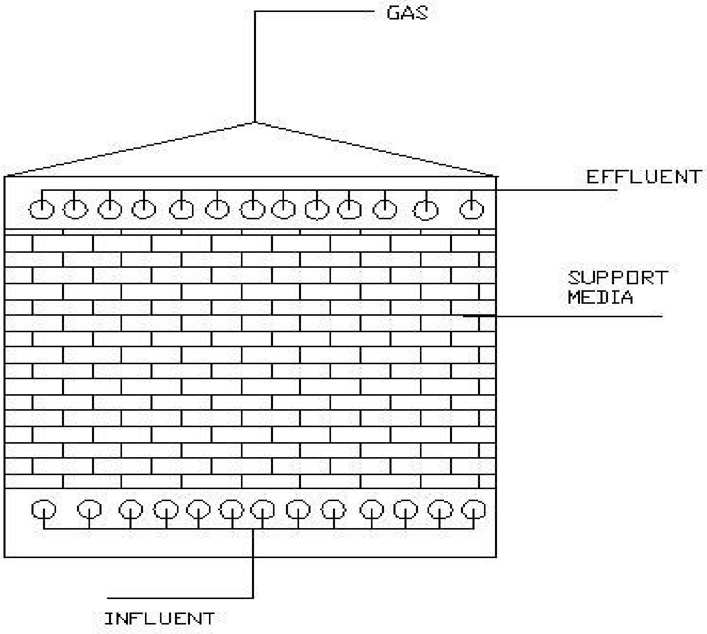
- Because of their clogging problem, anaerobic filters should be used only for dilute soluble wastes or wastes with easily degradable suspended materials,
- Biofilm development takes generally time,
- Back washing is not available
- When biological solid matter concentration in the reactor reaches a certain value, channels get in the filter material,
- Synthetic filter material increases initial investment cost.

2.4 Types of Upflow Anaerobic Filter

Upflow anaerobic filters have three different types depending on their design and operation conditions. These types are fully packed reactor, which is completely filled material, hybrid reactor, which operates with a sludge blanket at the bottom zone and filter material forming a filter on the top zone, and modular reactor, which is filled with the special filter materials. These types are shown in Figure 2.1.



a- Fully Packed Reactor b- Hybrid Reactor



c- Modular Reactor

Figure 2.1 Schematically presentations of upflow anaerobic filters (Filibeli et al., 2000)

2.4.1 Hybrid Reactor

The anaerobic hybrid reactors are high rate anaerobic treatment systems which gather the advantages of anaerobic systems while minimizing the disadvantages. The anaerobic hybrid reactor, which consists of an upflow sludge blanket in the lower part and an anaerobic filter, which acts as a gas-solid separator and enhances solid's retention without causing channeling or short circuiting, in the upper part, combines advantages of upflow anaerobic sludge blanket and anaerobic filter reactors.

The anaerobic hybrid reactor was firstly developed by Maxham and Wakamiya in 1981. Since then, much work has been carried out on both laboratory and full-scale reactors in order to optimize the design and operation parameters.

The performance of anaerobic hybrid reactors depends on contact of the wastewater with both the suspended growth in the sludge layer and the attached biofilm in the material matrix. So, hybrid reactor configurations generally have better operating characteristics than fully packed reactors (Young, 1991).

The filter material ratio is considered to be an important design parameter in an anaerobic hybrid reactor. However, different filter material ratios have been recommended by different researchers (Wu, Wilson & Tay, 2000).

The different filter material ratio was discussed by Wu et al in 2000. In this study of Wu, the anaerobic hybrid reactors (AHR) were randomly packed with raschig rings at different material ratios. Four reactors were exerted with different filter bed height/total reactor height, of 20% (AHR20), 40% (AHR40), 60% (AHR60) and 75% (AHR75).

According to this study, the filter material ratio had a significant impact on the performance of anaerobic hybrid reactors at high organic loading rates (>16 gCOD/Ld). On the other hand, the filter material ratio showed an influence on the performance at medium organic loading rates (4 ± 12 gCOD/Ld) and showed little effect on the performance of anaerobic hybrid reactor at low organic loading rates

(<2 gCOD/Ld). In addition, the reactor (AHR20) with least filter material ratio showed the best performance during this study.

When the anaerobic filter reactor is compared to anaerobic hybrid, it appears that anaerobic filters provide a better removal for COD and moreover the performance of the filter is more stable.

Anaerobic filter and anaerobic hybrid operated by Elmitwalli, Sklyar, Zeeman & Lettinga (2002) without any problems with clogging or other factors showed that the performance of the filter reactor was not only significantly better than the simultaneously tested hybrid reactor but also superior to formerly published results, on the other hand, as an advantages of hybrid reactor, the excess sludge from the hybrid reactor was more stabilized and has a higher settling capacity and dewaterability, although the filter reactor showed a better performance for COD removal efficiency.

2.5 Factors Affecting Design and Performance of Anaerobic Filters

In the section, factors affecting design and performance of anaerobic filters and the studies made by the other researchers on this matter have been examined.

In general the factors affecting design and performance of anaerobic filters are divided into three categories (Young, 1991);

- Physical Factors: including reactor design, wastewater feeding type, filter material type and placement,
- Performance Factors: including waste characteristics, temperature, pH, specific surface area, organic loading rate and biological biomass,
- Hydraulic Factors: including hydraulic retention time, hydraulic mixing regime, effluent recycle

Tests with laboratory and full-scale plants operated under a variety of conditions have identified hydraulic retention time, temperature and organic loading rate as the most important design and performance parameters. But at the same time, none of all these factors can be separated; for example, organic loading rate includes the combined effect of influent waste strength and hydraulic retention time, effluent recycle.

2.5.1 Physical Factors

2.5.1.1 Reactor Design

Anaerobic filters in full-scale are cylindrical or rectangular with a 6 – 26 m diameter or width, respectively and 3 – 13 m height. Reactor volumes change between 100 or 10000 m³.

In the anaerobic filters design, another point which must be considered is reactor height. The microbial activity along the filter represents the various differences. The studies indicated that COD removal generally carried out at the bottom of the anaerobic filter. As shown in Figure 2.2, Berardino, Costa & Converti (2000) realized that organic matter was nearly totally degraded before reaching the first sampling port in the filter.

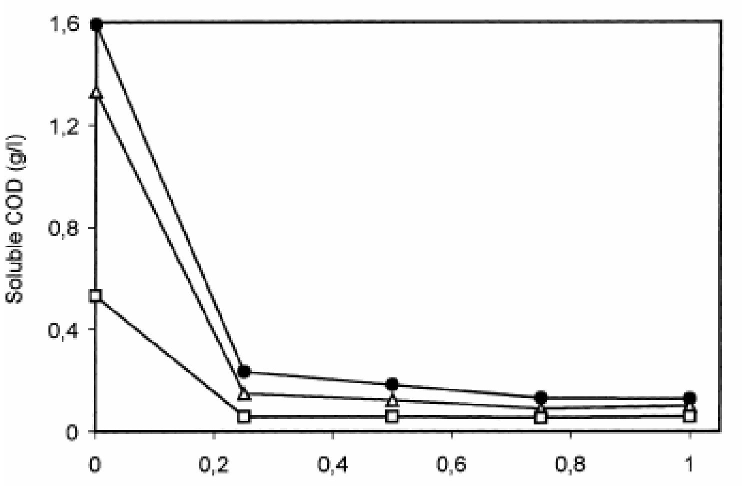


Figure 2.2 Distribution of soluble COD concentration along the filter height (Berardino, Costa & Converti, 2000).

On the other hand, another important respect is also the development of the biofilm model, because anaerobic filters as well are biofilm model. The design is generally based on fixed-film fundamental and much attention has been focused on the growth of biofilm attached on the filter material surfaces. For optimum design and scale-up of filters, mathematical models are required. There are various parameters which should be considered while anaerobic filters design in terms of biofilm. The parameters are the effect of hydrodynamics/flow pattern on reactor performance, the mass transfer within biofilms, the kinetic effects and the structure of biofilm (Saravanan & Sreekrishnan, 2006).

2.5.1.2 Feeding Types

There are two feeding types used widely in anaerobic filters. These types are the multi-fed and the single-fed. The feeding flow is carried out from an only influent in the single-fed, whereas in the multi-fed, the feeding flow is made from two or more influents.

The feeding type is of great importance in terms of performance criteria. A comparative study made by Punal and co-workers of multi-fed and single-fed anaerobic filter reactors demonstrated that multi-fed reactor had superior performance to the single-fed reactor in terms of COD removal efficiency, hydraulic behavior and sludge distribution along the support material. However, it is not clear whether such a multi-fed anaerobic filter reactor was also better than a single-fed anaerobic filter reactor for the treatment of high strength wastewaters and that it could be effectively operated under ambient conditions or not. Therefore, a bench-scale study was conducted to examine the effectiveness of a multi-fed upflow anaerobic filter process and to provide a further evaluation on this new operating mode for anaerobic reactors.

The operation of a multi-fed anaerobic filter allows a better biomass distribution to be obtained in comparison with what happens in a single-fed reactor. Because of that, the different trophic groups responsible for the overall anaerobic degradation are present throughout the multi-fed reactor, implying a higher effectiveness (Punal, Mendez-Pampin & Lema, 1999).

In the study in 1999, Punal showed efficiency different of two feeding types, which are the multi-fed and the single-fed, in terms of percent COD removal working at different OLR. Figure 2.3 gives the results of the study under discussion.

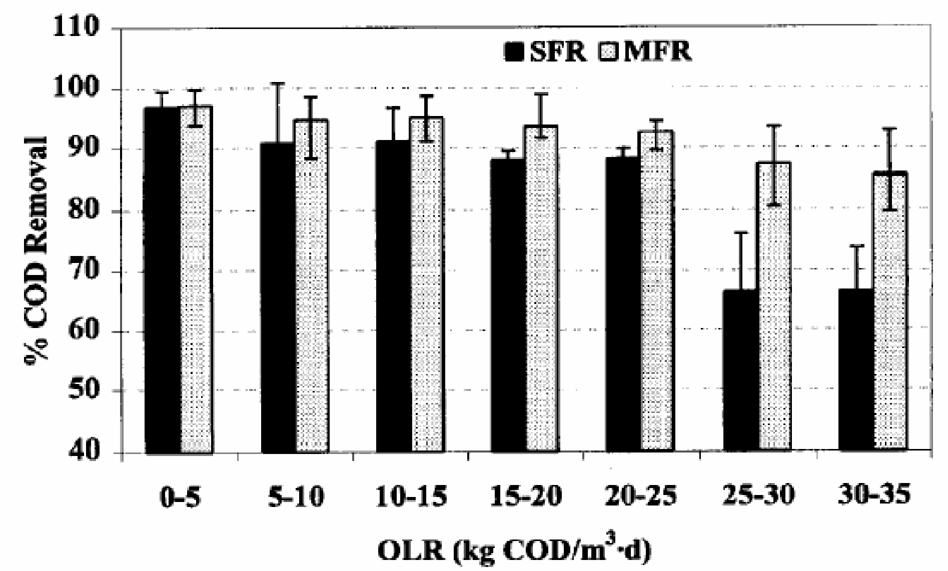


Figure 2.3 COD removal efficiency in the single-fed reactor (SFR) (■) and in the multi-fed reactor (MFR) (□) at several OLR. Bars indicate standard deviation (Punal, Mendez-Pampin & Lema, 1999).

As can be seen at the Figure 2.3, when working at 35 kgCOD/m³d, the COD removal efficiency is 65 and 85% in the single-fed reactor and the multi-fed reactor, respectively (Punal et al, 1999).

In another study made by Yu, Zhao & Tang, (2006), the results similar to the results obtained by Punal are found. In same way, the COD removal efficiency are observed by using two different anaerobic filter reactors which the feeding flow enters the lowest port and is distributed along the reactor via the lower three ports. Result obtained from the study showed that the multi-fed anaerobic filter had a better potential than the single-fed one for treating industrial wastewater at ambient temperatures.

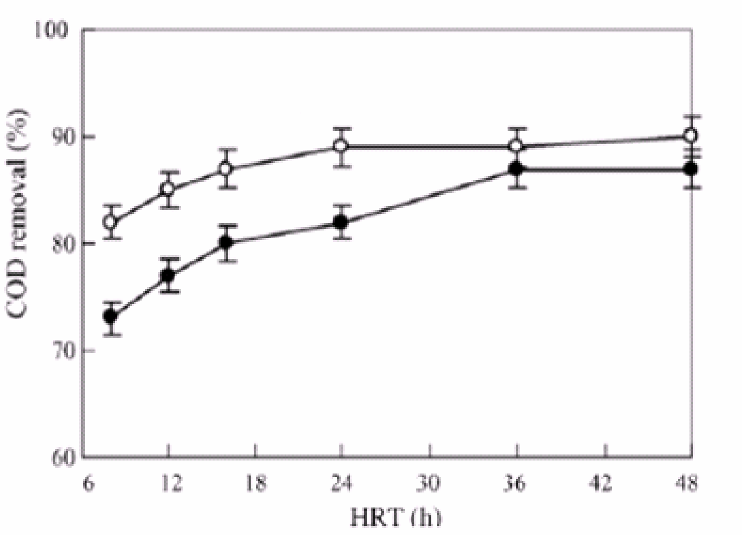


Figure 2.4 COD removal efficiency in the single-fed reactor (SFR) (—●—) and in the multi-fed reactor (MFR) (—○—) at various hydraulic retention times. Bars indicate standard deviation (Yu et al, 2006).

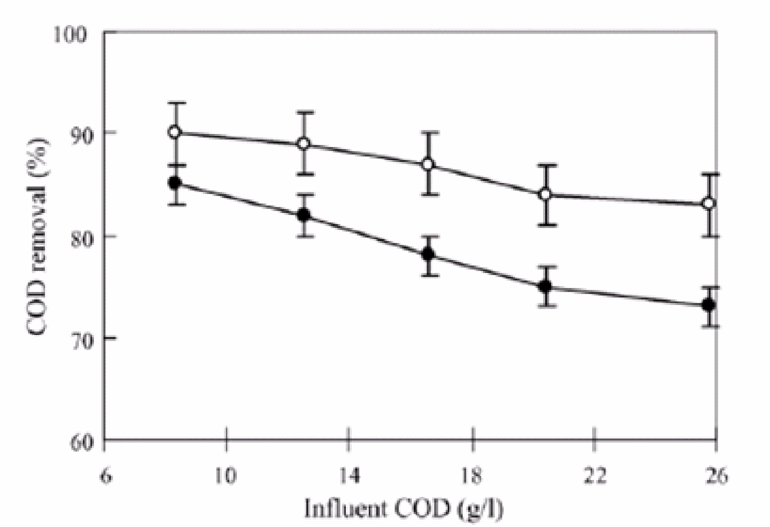


Figure 2.5 COD removal efficiency in the single-fed reactor (SFR) (—●—) and in the multi-fed reactor (MFR) (—○—) at various influent COD concentrations. Bars indicate standard deviation (Yu et al, 2006).

Figures 2.4 and 2.5 as well indicate that the COD removal efficiency of the multi-fed filter is higher than that of the single-fed reactor at any given HRT or wastewater concentration (Yu et al, 2006).

2.5.1.3 Filter Material Type and Placement

In any fixed film process including anaerobic filters and hybrid reactors, surface area, void volume, material replacement and other characterizations of filter material influence process efficiency to a large extent. Moreover, the ability of the filter material to redistribute flow is probably the most important design factor in terms of the design of the system. At the same time, filter material is a significant capital cost of the system (Song & Young, 1986).

The principal role of the material in an anaerobic filter is to hold biological solids either as a biofilm attached to the surface of the filter material or as loose solids suspended within interstitial void spaces.

Many different materials have been tested as support material for biomass retention in anaerobic filter systems. The performance of these materials appears to be directly related to the ease with which bacteria can become entrapped or attached. The surface state is important. Support material with a high surface roughness activates the bacterial biofilm development better than smooth support material (Gourari & Achkari-Begdouri, 1997). Laboratory results in the various studies suggest that filter material surface texture and porosity play a significant role in the performance of upflow anaerobic filters. To optimize the retention of biofilm attached on the material surfaces and the suspended biomass trapped within the interstitial void spaces, support material of open-pored surfaces and high porosity should be used.

Research studies on biomass growth in anaerobic filters have been focused on the biofilm attached on the support materials. Study of the development of methanogenic fixed films on pieces of polyvinyl chloride (PVC) plastic etched glass and baked clay showed that support material markedly affected the rate of attachment and growth of bacteria converting acetic acid to methane (Show & Tay, 1999).

It can be summarized from most of the studies that the ability of the filter material in anaerobic filters to retain high concentrations of biomass is a significant factor for satisfactory performance, especially COD removal efficiency.

Commercial filter materials for use in anaerobic filters are available either in the form of loose fill or modular-block fabricated from corrugated plastic sheets. As shown in Figure 2.6, these modular material (or media) types are cross flow media, tube settlers (or tubular media), vertical flow media and pall rings. The predominant pathways in modular-block material (or media) may be tubular so that lateral flow is not permitted, or counter-stacked so that a cross flow effect occurs at the contact points within the filter material matrix. It has been shown that cross flow modular media produced significantly higher performance than those loosely filled pall rings and perforated spheres (Show & Tay, 1999).

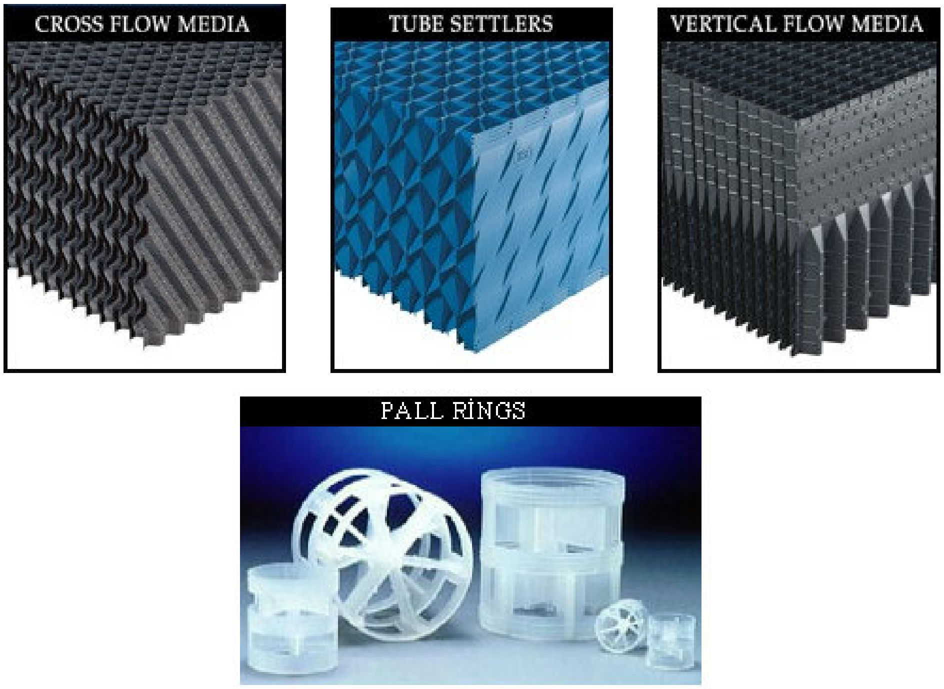


Figure 2.6 Schematic diagram of modular materials (or media) used in the anaerobic filters

The study results on the filter material types indicated that the cross-flow media provided much better performance than did tubular media having the same specific surface area when reactors that contained modular media were operated at the different organic loading rates. Filter materials having a shallower channel slope provided better performance indicating that the solids capturing capacity of the material becomes greater as the channel slope becomes shallower. However, the cross flow media is less sensitive to organic loading rate changes.

The filter material replacement as well is of importance from the point of performance of the system. The slope of interstitial channels within a cross-flow media significantly affected COD removal performance. Considering the term resistance to plugging structural strength, the optimum channel slope seems to be between 45^0 and 60^0 (Song & Young, 1986).

2.5.2 Performance Factors

2.5.2.1 Temperature

As temperature is of importance in the whole anaerobic systems, it has also been effective in the anaerobic filter. The studies having made in this field showed that temperature affected COD removal efficiency and the biomass growth in the system.

Changes in temperature, both increases and decreases, may negatively affect the anaerobic filter performance. A sudden temperature change causes a simultaneous increase in the concentration of all the volatile fatty acids, especially in acetic and propionic acids. The amount of the impact depends on factors such as the magnitude of the temperature change applied, the exposure time and the bacterial composition of the sludge. At temperatures exceeding the maximum value for growth, decay exceeds the growth rate of bacteria, which will then result in a decrease of the sludge activity and consequently in the reactor removal capacity (Ahn & Forster, 2002).

In anaerobic filters, the effects of temperature have been examined by many researchers. The study which presented by Cordoba, Riera and Sineriz showed the effect of the temperature. In this study, the reactor has been operated at 40, 30, 26, 20 and 16 °C. Cordoba et al found that the test at the higher temperature showed the best removal efficiency, which observed 95 – 84% and the work at lower temperature showed the worse removal efficiency, which was 69.1% (Cordoba et al, 1988).

Some different works indicated that the effect of the temperature varies with organic loading rate. When the organic loading rate is low, the temperature is not less effective on the COD removal efficiency. On the other hand, the COD removal efficiency is affected by temperature at the high organic loading rate. In the study carried out in 2000, Ahn and Forster found out that when they used the two anaerobic filter reactors which have the same specification, at the lower organic loading rates, there was little difference between the two types of filter and that, at the higher organic loading rates, however, the removal efficiency of the mesophilic filter was significantly lower and that a thermophilic filter operating at an OLR of 13.75 kgCOD/m^{3}d achieved a better performance than a mesophilic filter at the same organic loading rate (Ahn & Forster, 2000). In Figure 2.7, the results of the above mentioned work is given.

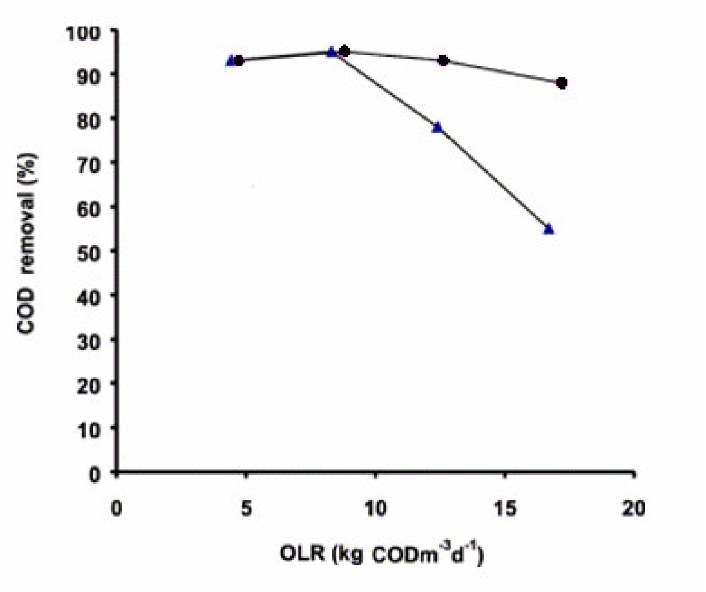


Figure 2.7 COD removal efficiency in the mesophilic (▲) and thermophilic (●) reactors at different organic loading rates (Ahn & Forster, 2000)

2.5.2.2 pH

The pH values of influent in anaerobic filter systems are generally ranged of 7.4 - 7.7. It is unwanted condition that pH value is in excess of 8.0. The methane producing bacteria are active in range of 6.7 - 8.0 because of their physiological structures.

The studies of Vijayaraghavan and Ahmad showed the importance of the effect of pH. They used an anaerobic system for biodegradation of palm oil mill effluent. The system was carried out for varying initial pH of 4, 5, 6, and 7, respectively, for an influent COD concentration of 10000 and 59300 mg/L. They found out that COD removal efficiency was lowest at pH 4 when compared to other operating pH and a maximum CO D removal rate occurred when the anaerobic systems was operated at pH 5 (Vijayaraghavan & Ahmad, 2006). The results of the work are given in Figure 2.8.

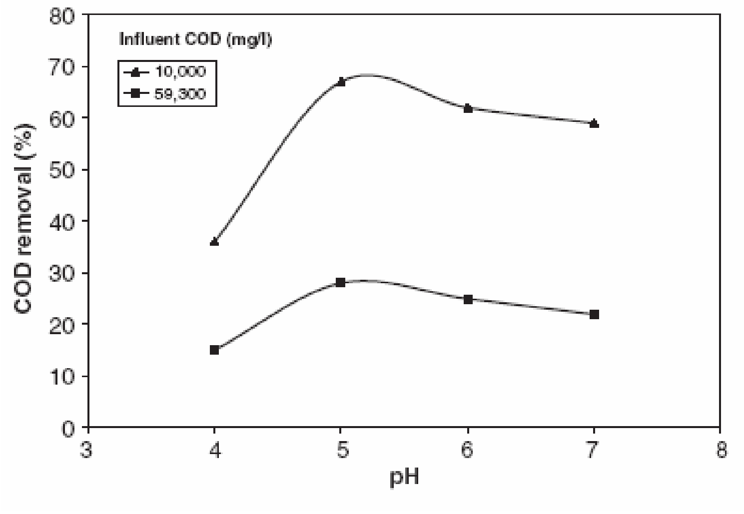


Figure 2.8 COD removal efficiency at various pH values (Vijayaraghavan & Ahmad, 2006).

2.5.2.3 Specific Surface Area

Most reactors have been designed with channels with nominal diameters on the order of 1 – 2.5 cm and specific surfaces in the range of 100 – 150 m²/m³. The void volume in the reactors is 60 – 90% of the total reactor volume (Gourari & Achkari-Begdouri, 1997).

Increased surface area will promote higher biomass concentrations in the reactor. Larger filter material surface area should also decrease film thicknesses with benefits in mass transfer.

High filter material surface area seems to be desirable in anaerobic filter applications for higher growth of biofilm. However, it has been reported that material specific surface area seems to have only a minor effect on wastewater treatment performance of upflow anaerobic filters, with less than 5% improvement in COD removal efficiency gained by more than doubling the specific surface area (Gourari & Achkari-Begdouri, 1997).

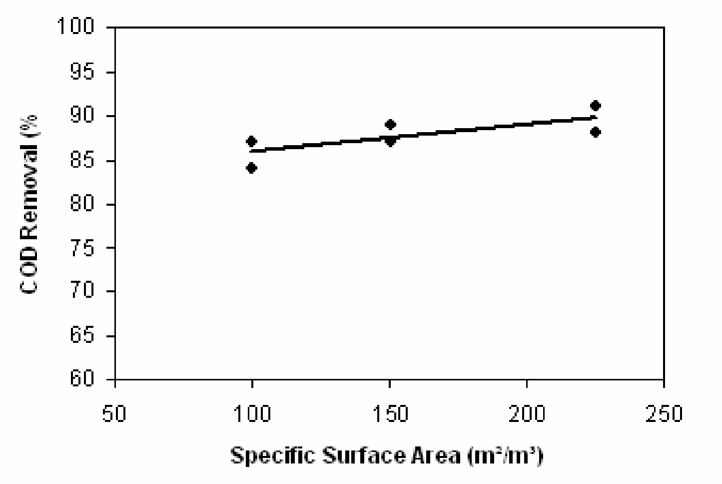


Figure 2.9 COD removal efficiency in laboratory scale upflow anaerobic filters using material having different specific surface area (Young, 1991)

The amount of material to use in hybrids reactor is quite subjective. Since the growth on the filter material surface provides some COD removal and since the material aids in settling of biological solids, there is a limit to how little material can be used. The material/height ratio seems to be the critical factor, and reactors having 50% or less filter material volume generally have experienced increased solids less and reduced efficiency (Young, 1991).

2.5.2.4 Organic Loading Rate

In anaerobic filters, the bacteria used in the systems are sensitive against organic loading rate. Optimum organic loading rate should be preserved in the course of the anaerobic treatment if this is possible.

When the organic loading rate is high, the acid accumulation occurs and pH value decreases in the reactor. This situation as well affects the activity of the bacteria in a negative way.

The studies thereon for a long time indicated that the organic loading rate was an important parameter in terms of the design of systems. As known, the anaerobic systems can tolerate the high strength wastewater influent. But, if the organic loading rate is very high, it can not tolerate the excessive loadings. In this situation, the COD removal efficiency will decrease.

Organic loading rate applies as the high rates such 16 kg COD/m^{3}d for design of the anaerobic filter systems. But, to obtain a good COD removal efficiency, organic loading rate should not exceed 12 kg COD/m^{3}d (Filibeli, Büyükkamacı & Ayol, 2000).

2.5.2.5 Biological Biomass

The biomass in the anaerobic filters is grouped into three parts: biofilm at the bottom, which is the largest amount; biofilm at the top, which has the highest specific methanogenic activity; and nonattached biomass. Soluble organic compounds in the influent wastewater pass in close proximity to the biomass and diffuse into the surfaces of the attached or granulated solids.

Anaerobic filters use the porous medium packed in the reactor to support the biomass in the form of microbial films. Filter material facilitates retention of biomass in the reactor for longer duration achieving longer mean cell residence time (Bodkhe, 2006). This is important feature of anaerobic filter for achieving better treatment efficiency.

2.5.3 Hydraulic Factors

2.5.3.1 Hydraulic Retention Time

Hydraulic retention time (HRT) is the time that the wastewater is in the anaerobic filter or anaerobic systems. Hydraulic retention time is one of the most performance parameters for upflow anaerobic filters.

The various hydraulic retention times can be used for anaerobic systems. While the retention time is decided on, the COD removal efficiency should be taken into consideration.

Hydraulic retention time values affected the efficiency and extent of COD removal and methane production. There is a relationship between the COD removal performance of anaerobic filter and hydraulic retention time. This correlation can be shown as follows;

$$E = 100\left(1 - \frac{\varepsilon}{HRT}\right)$$

In equation, ε is a proportionality coefficient and E is COD removal efficiency as %.

In Figure 2.9, the data which show relationship between the COD removal efficiency and hydraulic retention time are given;

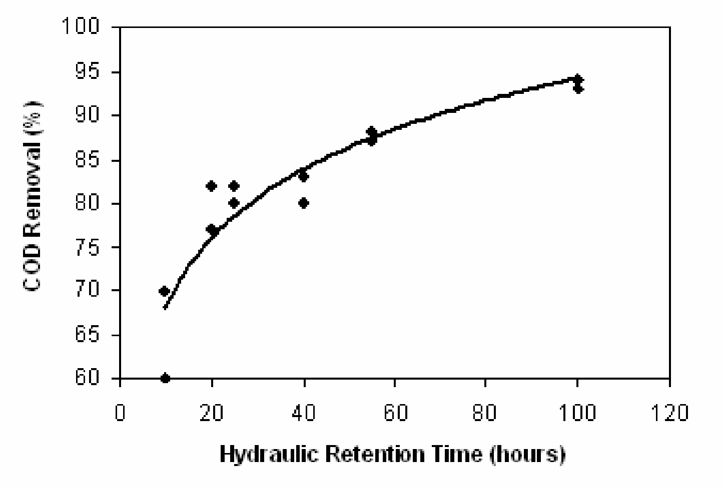


Figure 2.10 COD removal efficiency in upflow anaerobic filters versus hydraulic retention time (Young, 1991)

2.5.3.2 Hydraulic Mixing Regime

The hydraulic mixing regime in a reactor exerts a fundamental influence on the treatment efficiency of any chemical or biological process whenever substrate dependent kinetics apply. However, the analysis of mixing effects on overall treatment efficiency in an anaerobic process is not straightforward as a result of the different growth characteristics of the species involved and other factors.

The hydraulic mixing regime in an anaerobic filter is of great importance in terms of problems of clogging and channeling. The anaerobic filter often encounters the problems of clogging and channeling, in particular when the anaerobic filter is packed with filter material having high specific surface and is used for the treatment of wastewaters with high levels of suspended solids. These problems are associated with the accumulation of biomass within the filter, and the presence of support materials is an obstacle to mixing, resulting in large amounts of SS to be trapped in the lower part of the filter, where mixing due to gas evolution is poor (Yu, Zhao & Tang, 2006).

So, the problems of clogging and channeling should be prevented for treatment efficiency. The distribution of the wastewater in the anaerobic filter is provided in a good way.

2.5.4 Other Factors

2.5.4.1 Start-up Period

The start-up period is importance parameter for operation of the anaerobic filter. The purpose of the start-up is to grow, build up and retain a sufficiently high concentration of active and well balanced biomass. This period actually takes a long time and usually is very delicate in fixed film high-rate systems such as anaerobic filters because the attached biomass develops and accumulates quite slowly. Start-up usually is carried out, after inoculating biomass taken from other reactor, by progressively increasing the organic loading rate applied to the reactor (Punal, Trevisan, Rozzı & Lema 2000).

Four factors affect the start-up period of anaerobic filters;

- Quality of the inoculum in terms of the concentration of slow growing methonagenic bacteria acclimatized to a particular waste,
- Rate of adaptation of these microorganisms to the waste,
- Rate of growth of anaerobic microorganisms,
- Rate of loss of anaerobic microorganisms.

2.5.4.2 Shock Loadings

The shock loadings have an effect on the performance of the anaerobic filters. The shock loadings can be divided into two categories, which are hydraulic and organic loading rates. At the same time, the other factors affecting efficiency of the system may also create the shock effects on the system, for instance temperature or pH.

During organic and hydraulic shocks, the treatment performance generally deteriorates, often resulting in process souring and failure. COD removal efficiency, methane concentration in the biogas and pH decrease, whereas volatile fatty acids (VFA) accumulate in the effluent (Cavaleiro, Alves & Mota, 2001). But, operational performance, during the organic shock, is more affected than in the hydraulic one.

Anaerobic filters can well tolerate these shocks. Cayless, Motta Marques & Lester (1989) presented that quantitative increases in organic loading rates under varying are well-tolerated, in a same way, temperature variations as well are the best tolerated of the shocks.

CHAPTER THREE
MATERIALS AND METHODS

3.1 General

In this study, the upflow anaerobic filter performance was examined at different conditions. For that purpose, design and performance parameters such as filter material ratio, organic loading rate, hydraulic retention time and temperature changes were evaluated at four upflow anaerobic filter reactors having different filter material ratio. Anaerobic filters were fed with the synthetic wastewater and they were operated at psychrophilic temperatures during experimental studies.

3.2 The Characteristics of Model Reactors

The experimental anaerobic filter reactors were made of a plexiglas column with an inside diameter of 10.7 cm and a height of 31.0 cm. The column was filled with plastic material, which cut insulating tubes of diameter 1.50 cm and of length 1.0 – 1.5 cm. The four upflow anaerobic filter reactors filled different filter material ratio were operated in the course of experimental period. Four reactors are identical except their filter material ratio.

Four anaerobic filter reactors (AFR) were exerted with different filter bed height/total reactor height; of 25% (AFR 25), 50% (AFR 50), 75% (AFR 75) and 100% (AFR 100). Filter materials were not fixed in the reactors except the full-filled reactor. Filter materials were randomly placed into reactors in an unfixed way.

The anaerobic filter reactors have an empty volume of 2.95 L and a void volume (with an installed support filter materials) of 1.94 L, 2.20 L for AFR 100 and AFR 50 and 2.14 L, 2.25 L, for AFR 75 and AFR 25, respectively. The influents were pumped from same fed tank to the bottom of the columns by the help of peristaltic pumps. And the effluent was collected in separate bottles for every reactor.

The all reactors were operated at psychrophilic temperature interval that was ranged 16 – 33 ^{o}C. So, four identical filters were placed into external water jackets to maintain a stable temperature. Temperature of external water jacket was saved by the help of the three water heater. The temperature value of the heater was configured for them to work at 35 ^{o}C. But, temperature value of water jacket changed because of ambient temperature, especially, in winter months.

The characteristics of the anaerobic filters and flow scheme of the anaerobic filter reactors are given in Table 3.1 and Figure 3.1, respectively. But Figure 3.1 only shows the reactor called as AFR 100 having fully packed. The other reactors, AFR 75, AFR 50 and AFR 25 are not fully with filter materials. This is only different between AFR 100 and the other reactors in terms of their structure.

Table 3.1 The specifications of the upflow anaerobic filter reactors

Characteristics	**Unit**	**Values**			
		AFR 100	**AFR 50**	**AFR 75**	**AFR 25**
Operation mode	-	Continuous	Continuous	Semi-Continuous	Semi-Continuous
Flow mode	-	Upflow	Upflow	Upflow	Upflow
Feeding type	-	Single-Fed	Single-Fed	Single-Fed	Single-Fed
Total height	cm	31.0	31.0	31.0	31.0
Diameter	cm	10.7	10.7	10.7	10.7
Total volume	m^3	0.00295	0.00295	0.00295	0.00295
Total void volume	m^3	0.00194	0.00220	0.00214	0.00225
Total effective area	m^2	1.012	0.508	0.760	0.252

In Table 3.1, total void volume indicates reactor's volume except the total volume of filter materials in the reactor. As for total effective area, it expresses the surface areas which total filter material in reactor has in terms of the filter number.

Feeding to the reactors was made from the bottom as a single-fed by the help of the peristaltic water pump. When AFR 100 and AFR 50 were operated in continuous operation mode, AFR 75 and AFR 25 were operated in semi-continuous operation mode. The synthetic wastewater were continuously fed during hydraulic retention time in continuous operation mode, however in semi-continuous operation mode, the synthetic wastewater were fed four or eight hours and were waited for hydraulic retention time.

Sludge was taken by the way of an influent valve. Operation of the reactors was stopped a very short time during the sludge withdrawal. The gas effluent structure was designed at the top of the reactors by an upside down conical with 45° slope in order to provide gas and liquid separation.

In order to get samples from reactor inlet, sampling valve was placed medium of the reactor height. The valve was used for being taken of the inlet samples. Effluent samples were taken from the effluent valve at the upper of the reactors.

The fixed bed filter material in the anaerobic filter reactors are hard plastic hose with groove inside and outside surfaces. And they had high specific surface area. Detailed information in relation to these filters materials and their shapes are given in Table 3.2 and Figure 3.2, respectively.

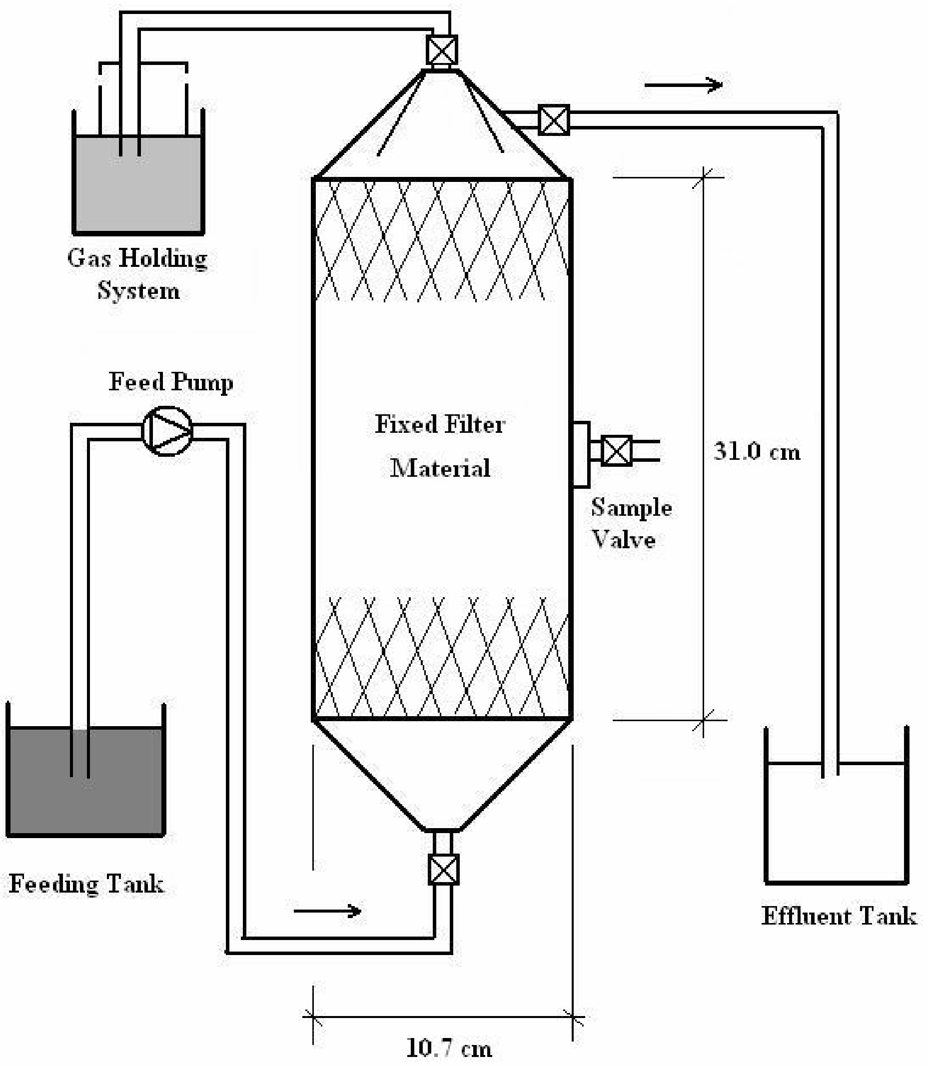


Figure 3.1 Schematically view of the anaerobic filter reactor named as AFR 100 used for studies

Table 3.2 Filter material specifications

Characteristics	**Unit**	**Values**			
		AFR 100	**AFR 75**	**AFR 50**	**AFR 25**
Length	cm	1.0 – 1.5	1.0 – 1.5	1.0 – 1.5	1.0 – 1.5
Diameter	cm	1.5	1.5	1.5	1.5
Specific surface area	m²/m³	313	313	313	313
Porosity	%	89	89	89	89
Filter material number	number	506	380	254	126

In Table 3.2, porosity shows a measure of the void spaces in filter material in the reactor. And specific surface area defines the total available surface area of filtration material per unit of solid volume that bacteria can live on. The specific surface area can be simply calculated from a particle size distribution, making some assumption about the particle shape.

Figure 3.2 Filter material used in reactors

3.3 Wastewater Characterization

A synthetic waste prepared in the laboratory was used to provide a consistent organic substrate for all organic loading rates. These components were mixed together in a tank after the necessary nutrients and buffer chemicals such as NaOH were added.

Using synthetic wastewater has several advantages such as; preparation being easy, having degradation possibility, the most important of all having fixed pollutant parameter. These advantages consequently minimize probable problems during start-up and operation periods.

By chancing the concentration of the chemicals in the synthetic wastewater, it is possible to provide different organic loads and influent COD concentration and to make efficiency studies for the reactor at different organic loads. So, in the course of the experimental studies, different organic loads and influent COD concentrations obtained by chancing the concentration of the chemicals were exerted to the filter reactors.

To prepare the synthetic wastewater, the molasses obtained yeast industry, from Izmir Pakmaya Yeast Industry, used as carbon source. The molasses contains 50% sugar and is an appropriate carbon source. And molasses contains approximately $1*10^6$ mg/L of COD.

Firstly, a COD/N/P ratio of synthetic wastewater was determined as 100/2/1. Molasses was used as carbon source, urea $CO(NH_2)_2$ as nitrogen source and KH_2PO_4 as phosphorus source were used during experimental studies. Trace elements; $MnSO_4$, Fe SO_4 and Mg SO_4 were added in the amount of 0.05 mg/L concentration. For pH balance, NaOH was used as a buffer. Additionally, to provide anaerobic conditions, $Na_2S_2O_5$ was used in 2.5 – 3.0 mg/L concentration. And finally, synthetic substrate was fully mixed by a stirrer in the storage tank then pumped into the reactor inlet distributor by a variable speed peristaltic pump.

3.4 Analytical Methods

COD (chemical oxygen demand), pH, temperature, alkalinity, total solid and volatile solid measurements were made on the influent and effluent samples during the experiments. All experimental studies were carried out according to Standard Methods (APHA-AWWA, 1992)

3.4.1 Chemical Oxygen Demand (COD) Analysis

COD measurements were carried out according to Standard methods (APHA, 1992). Closed reflux colorimetric methods were used.

In closed reflux colorimetric method, borosilicate culture tubes with 10 ml capacity were used. A visible spectrophotometer was used to measure absorbance at 600 nm. Digestion solution was prepared by adding 10.216 g $K_2Cr_2O_7$, 167 ml concentrated H_2SO_4 and 33.3 g $HgSO_4$ into distilled water to be 1000 ml and the solution was cooled to room temperature. Sulfuric acid reagent and potassium hydrogen phthalate (KHP) standard were used. KHP was used for preparation of the calibration curve. KHP was lightly crushed and then dried to constant weight at 120 ^{0}C. Then different initial KHP concentrations were dissolved in distilled water for different concentrations. KHP solution had a theoretical COD of 900 mg/L for 0.765 g KHP/L. 16 standards of KHP were prepared to obtain COD concentration of 10 – 900 mgCOD/L. The calibration curve was used for determination of COD contents of samples. The absorbencies of samples are placed to the equation for calculating the COD concentration.

3.4.2 pH and Temperature Analysis

pH and temperature measurement was done by using WTW 330i pH METER.

3.4.3 Total Solid and Volatile Solid Measurement

Total solid; the residue remaining after a wastewater sample which has a definite volume is evaporated in a weighed dish and dried to constant weight in an oven at 103 to 105 °C. The increase in weight over that of the empty dish represents the total solids. The result may not represent the weight of actual dissolved and suspended solids in wastewater samples (APHA-AWWA, 1992).

Calculations were made by using the following equation 3.1;

$$M_{TS} = \frac{(A-B)*1000}{V} \tag{3.1}$$

A= weight of water + dish, mg
B= weight of dish, mg
V= volume of the sample

Volatile solid; the residue from total solid is ignited to constant weight at 500 ± 50 °C. The remaining solids represent the fixed total, dissolved or suspended solids while the weight lost on is the volatile solids. The determination is useful in control of wastewater treatment plant operation because it offers a rough approximation of the amount of organic matter present in solid fraction of wastewater, activated sludge and industrial wastes (Standard Methods, 1992).

Calculations were made by using the following equation 3.2;

$$M_{VS} = \frac{(A-B)*1000}{V} \tag{3.2}$$

A= weight of water + dish before ignition, mg
B= weight of residue + dish after ignition, mg
V= volume of the sample

3.4.4 Total Alkalinity

Total alkalinity measurements were carried out according to standard methods by using titration method.

Alkalinity is usually measured using sulfuric acid. Firstly 0.02 N H_2SO_4 solution was prepared, 3 or 4 drops phenol phitalein were added into the sample of 100 ml. If the color of sample turns to pink, the sample is titrated 0.02 N H_2SO_4 solution until color disappears. Unless it turns to pink, any process is not made. In the wake of this process, 3 or 4 drops methyl orange indicator were added into the sample in the baker. The sample is titrated with 0.02 N H_2SO_4 solution until color turns to the dark red from orange yellow.

Calculations were made by using the following equation 3.3;

$$Alkalinity(mgCaCO_3 / L) = \frac{A * N * 50 * 1000}{V} \tag{3.3}$$

A= consumption of H_2SO_4 solution, ml
N= Normality of H_2SO_4 solution
V= volume of the sample

3.5 Experimental Study Plan

The anaerobic filter reactors were fed with an influent COD concentration of 5000 mg/l at a hydraulic retention time (HRT) of 10 day, corresponding to a low organic loading rate of 0.5 kgCOD/m^{3}d. This was to allow acclimatization of biomass to the new environment with minimum organic and hydraulic stresses during the sensitive startup period. After startup, the reactors were operated simultaneously at the same hydraulic and organic loading rates.

During start-up period, the synthetic wastewater was fed to the reactors by being mixed rate of 50% by volume with the inoculum from Pakmaya Yeast Industry Anaerobic wastewater treatment plant. The reactors were operated until a steady-state performance was reached as indicated by constant effluent COD concentration. The steady-state conditions were maintained to enable collection of data for analysis and performance evaluation.

Upon completion of data collection, the organic loading rate to all reactors was then increased simultaneously and the reactors were operated until the next steady-state conditions were reached. These anaerobic filters were developed and operated at psychrophilic temperature interval which was controlled by the help of the heater, on synthetic wastewater prepared from molasses. Table 3.3 summarizes the operational conditions applied to the all reactors throughout the study.

Table 3.3 Operating schedules and applied organic loading rates

Test Phase	**Organic Loading Rate (kgCOD/m^{3}d)**	**Influent COD Concentration (mg/L)**	**Hydraulic Retention Time (day)**
1	0.333	1000	3
2	0.666	2000	3
3	1.333	4000	3
4	0.500	1000	2
5	1.000	2000	2
6	2.000	4000	2
7	2.000	2000	1
8	4.000	4000	1
9	8.000	8000	1

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Experiments Carried Out With Model Reactors

The four anaerobic filters having filter material ratio were operated with synthetic wastewater containing molasses as COD source in experimental studies. Experimental studies were examined at different organic loading rate for three different hydraulic retention time (HRT), 3, 2 and 1 day at psychrophilic temperature ranged of 16 – 33 ^{o}C.

At the experimental studies, when AFR 100 and AFR 50 were operated in continuous operation mode, AFR 75 and AFR 25 were operated in semi-continuous operation mode.

Oxidation-Reduction Potential also known as Redox Potential (ORP) was measured to appreciate that the treatment mechanism worked as anaerobic. Redox Potential measurements were done on withdrawal sludge taken from the reactors with definite time intervals. ORP values were found to be ranged of -310 and -380 mV during the experimental studies. These values were recorded as an indicator of the fact that the systems worked as anaerobic.

4.1.1 Organic Loading Rates and COD Removal Efficiencies for Model Reactors

During the study, the organic loading rates (OLR) were varied between 0.333 and 8.000 kgCOD/m^{3}d. Firstly, OLR were applied 0.333, 0.666 and 1.333 kgCOD/m^{3}d for HRT of 3 days, respectively. Secondly, OLR values were applied 0.500, 1.000 and 2.000 kgCOD/m^{3}d for HRT of 2 days, respectively. And finally, OLR values were applied 2.000, 4.000 and 8.000 kgCOD/m^{3}d for HRT of 1 day, respectively.

The experimental analyses were intermitted because of the adaptation of the reactor systems to the organic loading rate changes, when every organic loading rate was changed. The measurements were not done throughout 1 or 2 weeks in the wake of the changes.

In due course of the reactors were operated, some very low or unconcerned COD removal efficiency values obtained from the experimental analyses. These values were not evaluated because they were very low or unconcerned.

When organic loading rate was increased, COD removal efficiencies were observed to decrease due to organic loading rate values.

To all operation periods, laboratory results and the chancing of COD removal efficiencies with OLR values are given in from Table 4.1 to Table 4.9 and from Figure 4.1 to Figure 4.12.

Table 4.1 Laboratory results for the model reactors at HRT = 3 days and OLR = 0.333 kgCOD/m³d (average values)

Parameters	**AFR 100**	**AFR 50**	**AFR 75**	**AFR 25**
$COD_{Influent}$ (mg/L)	1134	1134	1134	1134
$COD_{Effluent}$ (mg/L)	422	565	712	723
$pH_{Influent}$	8.01	8.01	8.01	8.01
$pH_{Effluent}$	6.69	6.55	6.67	6.67
$Temperature_{Inf.}$ (°C)	13.9	13.9	13.9	13.9
$Temperature_{Eff.}$ (°C)	20.7	20.9	21.2	20.6
Alkalinity (mg/L)	1450	1520	1420	1460
Total $Solid_{reactor}$ (mg/L)	1930	2120	2050	1820
Total Volatile $Solid_{react.}$(mg/L)	1180	1450	1580	970
Organic Loading Rate (kgCOD/m³d)	0.378	0.378	0.378	0.378
COD Removal Efficiency (%)	63	50	37	36

The experimental results were evaluated in terms of the COD removal efficiency which was depended on the change of organic loading rate, 8 measurements were carried out for the all reactors at HRT= 3 days and OLR = 0.333 kgCOD/m³d. The influent COD concentration was same in the all reactors, minimum and maximum influent COD concentrations were 971 mg/L and 1245 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 100 and AFR 50 which were operated in continuous operation mode were taken 324 mg/L - 526 mg/L and 512 mg/L - 658 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 75 and AFR 25 which were operated in semi-continuous operation mode were obtained 621 mg/L - 768 mg/L and 668 mg/L - 812 mg/L, respectively. In consequence of the experiments made, the COD removal efficiencies of AFR 100 varied between 53 and 71%, the COD removal efficiencies of AFR 50 varied between 45 and 57%, the COD removal efficiencies of AFR 75 varied between 32 and 41% and the COD removal efficiencies of AFR 25 varied between 30 and 41%. The standard deviations of these COD removal efficiencies were found to be 6.2, 4.4, 2.8 and 3.4% for AFR 100, AFR 50, AFR 75 and AFR 25, respectively.

Table 4.2 Laboratory results for the model reactors at HRT = 3 days and OLR = 0.666 kgCOD/m³d (average values)

Parameters	**AFR 100**	**AFR 50**	**AFR 75**	**AFR 25**
$COD_{Influent}$ (mg/L)	2230	2230	2230	2230
$COD_{Effluent}$ (mg/L)	707	1058	1342	1394
$pH_{Influent}$	8.27	8.27	8.27	8.27
$pH_{Effluent}$	6.49	6.54	6.55	6.67
$Temperature_{Inf.}$ (°C)	16.0	16.0	16.0	16.0
$Temperature_{Eff.}$ (°C)	20.9	20.8	21.2	20.5
Alkalinity (mg/L)	1980	2100	1990	1860
Total $Solid_{reactor}$ (mg/L)	3376	4584	3272	4524
Total Volatile $Solid_{react.}$(mg/L)	1732	3020	2160	3384
Organic Loading Rate (kgCOD/m³d)	0.743	0.743	0.743	0.743
COD Removal Efficiency (%)	68	53	40	38

For the all reactors at HRT= 3 days and OLR = 0.666 kgCOD/m³d, 9 measurements were carried out. In the all reactors, minimum and maximum influent COD concentrations were 1956 mg/L and 2714 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 100 and AFR 50 which were operated in continuous operation mode were taken 548 mg/L - 915 mg/L and 863 mg/L - 1385 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 75 and AFR 25 which were operated in semi-continuous operation mode were obtained 1025 mg/L - 1723 mg/L and 1038 mg/L - 1750 mg/L, respectively. In consequence of the experiments made, the COD removal efficiencies of AFR 100 varied between 60 and 73%, the COD removal efficiencies of AFR 50 varied between 49 and 57%, the COD removal efficiencies of AFR 75 varied between 36 and 48% and the COD removal efficiencies of AFR 25 varied between 32 and 47%. The standard deviations of these COD removal efficiencies were found to be 4.1, 3.4, 4.1 and 4.6% for AFR 100, AFR 50, AFR 75 and AFR 25, respectively.

Table 4.3 Laboratory results for the model reactors at HRT = 3 days and OLR = 1.333 kgCOD/m³d (average values)

Parameters	**AFR 100**	**AFR 50**	**AFR 75**	**AFR 25**
$COD_{Influent}$ (mg/L)	3952	3952	3952	3952
$COD_{Effluent}$ (mg/L)	1259	1900	2344	2429
$pH_{Influent}$	8.18	8.18	8.18	8.18
$pH_{Effluent}$	6.67	6.82	6.61	6.73
$Temperature_{Inf.}$ (°C)	14.0	14.0	14.0	14.0
$Temperature_{Eff.}$ (°C)	20.4	19.4	20.8	19.7
Alkalinity (mg/L)	2100	2450	2150	2340
Total $Solid_{reactor}$ (mg/L)	1880	3340	2040	2130
Total Volatile $Solid_{react.}$(mg/L)	1270	1820	1500	1370
Organic Loading Rate (kgCOD/m³d)	1.317	1.317	1.317	1.317
COD Removal Efficiency (%)	68	52	41	38

For the all reactors at HRT= 3 days and OLR = 1.333 kgCOD/m³d, 7 measurements were carried out. In the all reactors, minimum and maximum influent COD concentrations were 3682 mg/L and 4125 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 100 and AFR 50 which were operated in continuous operation mode were taken 1129 mg/L - 1524 mg/L and 1780 mg/L - 2190 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 75 and AFR 25 which were operated in semi-continuous operation mode were obtained 2234 mg/L - 2461 mg/L and 2340 mg/L - 2660 mg/L, respectively. In consequence of the experiments made, the COD removal efficiencies of AFR 100 varied between 59 and 72%, the COD removal efficiencies of AFR 50 varied between 47 and 55%, the COD removal efficiencies of AFR 75 varied between 37 and 45% and the COD removal efficiencies of AFR 25 varied between 33 and 42%. The standard deviations of these COD removal efficiencies were found to be 4.5, 3.1, 3.3 and 3.1% for AFR 100, AFR 50, AFR 75 and AFR 25, respectively.

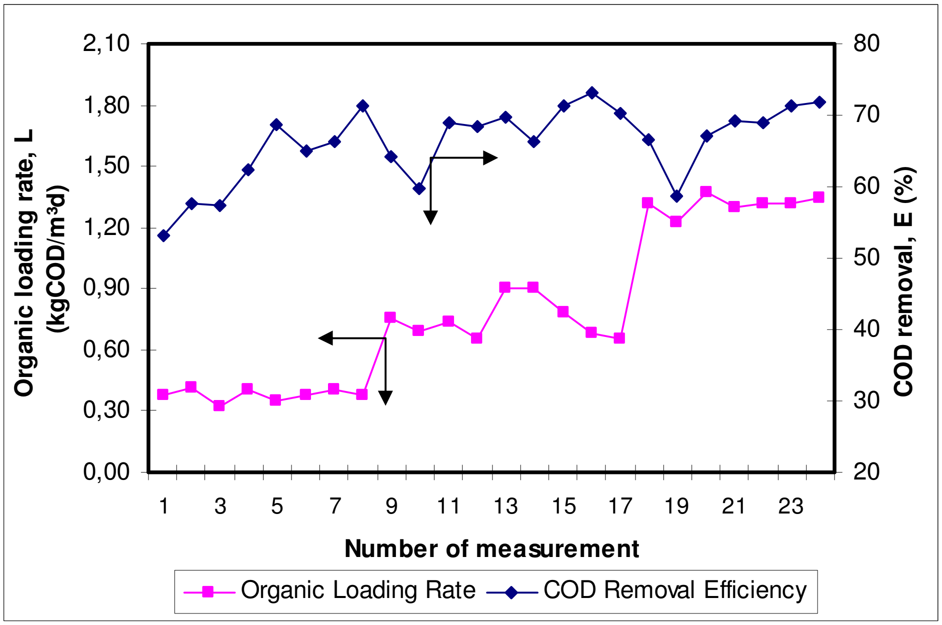


Figure 4.1 Organic loading rates and COD removal efficiencies for AFR 100 at HRT = 3 days

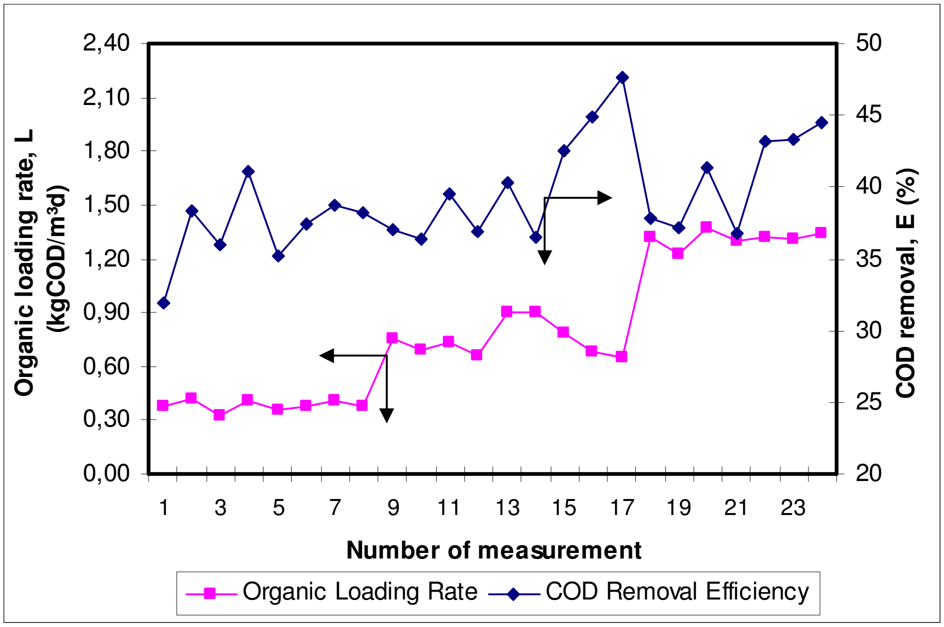


Figure 4.2 Organic loading rates and COD removal efficiencies for AFR 75 at HRT = 3 days

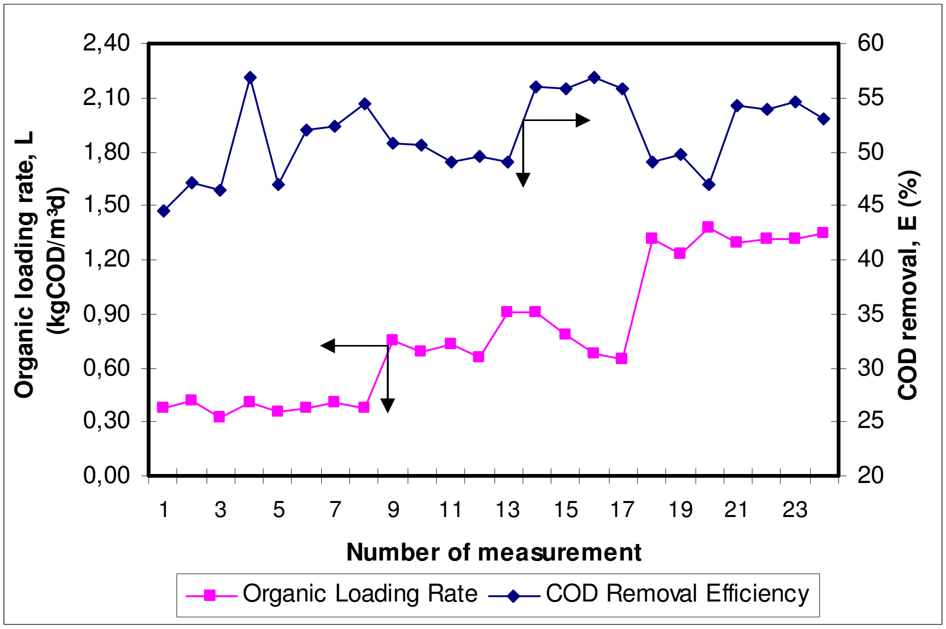


Figure 4.3 Organic loading rates and COD removal efficiencies for AFR 50 at HRT = 3 days

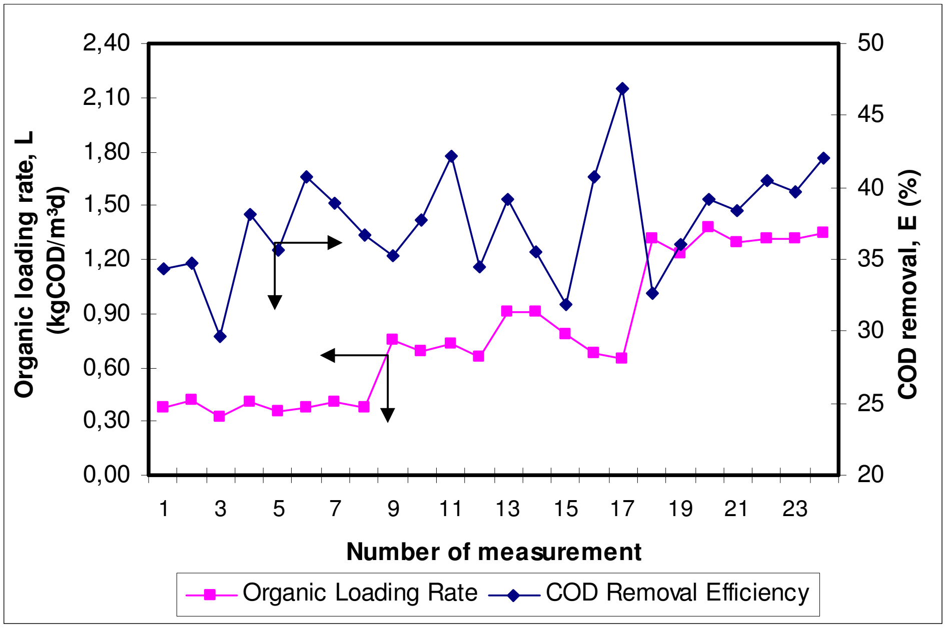


Figure 4.4 Organic loading rates and COD removal efficiencies for AFR 25 at HRT = 3 days

Table 4.4 Laboratory results for the model reactors at HRT = 2 days and OLR = 0.500 kgCOD/m³d (average values)

Parameters	**AFR 100**	**AFR 50**	**AFR 75**	**AFR 25**
$COD_{Influent}$ (mg/L)	1142	1142	1142	1142
$COD_{Effluent}$ (mg/L)	417	578	715	676
$pH_{Influent}$	7.51	7.51	7.51	7.51
$pH_{Effluent}$	6.79	6.50	6.68	6.60
$Temperature_{Inf.}$ (°C)	14.5	14.5	14.5	14.5
$Temperature_{Eff.}$ (°C)	21.2	21.4	21.0	21.0
Alkalinity (mg/L)	1160	1210	1280	1350
Total $Solid_{reactor}$ (mg/L)	2000	2150	1580	1700
Total Volatile $Solid_{react.}$(mg/L)	770	1060	1100	890
Organic Loading Rate (kgCOD/m³d)	0.571	0.571	0.571	0.571
COD Removal Efficiency (%)	64	50	38	41

For the all reactors at HRT= 2 days and OLR = 0.500 kgCOD/m³d, 8 measurements were done. In the all reactors, minimum and maximum influent COD concentrations were 952 mg/L and 1402 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 100 and AFR 50 were measured 243 mg/L - 562 mg/L and 427 mg/L - 768 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 75 and AFR 25 were obtained 578 mg/L – 884 mg/L and 556 mg/L - 910 mg/L, respectively. In the result of the experiments, the COD removal efficiencies of AFR 100 varied between 57 and 78%, the COD removal efficiencies of AFR 50 varied between 45 and 60%, the COD removal efficiencies of AFR 75 varied between 33 and 41% and the COD removal efficiencies of AFR 25 varied between 35 and 46%. The standard deviations of these COD removal efficiencies were found to be 8.4, 2.6, 3.6 and 3.1% for AFR 100, AFR 50, AFR 75 and AFR 25, respectively.

Table 4.5 Laboratory results for the model reactors at HRT = 2 days and OLR = 1.000 kgCOD/m³d (average values)

Parameters	**AFR 100**	**AFR 50**	**AFR 75**	**AFR 25**
$COD_{Influent}$ (mg/L)	2333	2333	2333	2333
$COD_{Effluent}$ (mg/L)	663	1109	1362	1462
$pH_{Influent}$	7.74	7.74	7.74	7.74
$pH_{Effluent}$	6.60	6.51	6.39	6.40
$Temperature_{Inf.}$ (°C)	16.0	16.0	16.0	16.0
$Temperature_{Eff.}$ (°C)	25.3	25.3	24.4	25.4
Alkalinity (mg/L)	1360	1600	1760	1920
Total $Solid_{reactor}$ (mg/L)	1500	2517	2160	2650
Total Volatile $Solid_{react.}$(mg/L)	680	1366	1340	1616
Organic Loading Rate (kgCOD/m³d)	1.167	1.167	1.167	1.167
COD Removal Efficiency (%)	72	53	42	38

At HRT= 2 days and OLR = 1.000 kgCOD/m³d, 5 measurements were done. In the all reactors, minimum and maximum influent COD concentrations were 2130 mg/L and 2523 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 100 and AFR 50 were measured 625 mg/L - 765 mg/L and 890 mg/L - 1230 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 75 and AFR 25 were obtained 1254 mg/L - 1542 mg/L and 1250 mg/L - 1648 mg/L, respectively. In the result of the experiments, the COD removal efficiencies of AFR 100 varied between 69 and 74%, the COD removal efficiencies of AFR 50 varied between 47 and 58%, the COD removal efficiencies of AFR 75 varied between 39 and 43% and the COD removal efficiencies of AFR 25 varied between 34 and 43%. The standard deviations of these COD removal efficiencies were found to be 2.3, 4.1, 1.8 and 4.4% for AFR 100, AFR 50, AFR 75 and AFR 25, respectively.

Table 4.6 Laboratory results for the model reactors at HRT = 2 days and OLR = 2.000 kgCOD/m³d (average values)

Parameters	**AFR 100**	**AFR 50**	**AFR 75**	**AFR 25**
$COD_{Influent}$ (mg/L)	3867	3867	3867	3867
$COD_{Effluent}$ (mg/L)	1256	1882	2369	2428
$pH_{Influent}$	8.01	8.01	8.01	8.01
$pH_{Effluent}$	6.55	6.21	6.10	6.08
$Temperature_{Inf.}$ (°C)	19.0	19.0	19.0	19.0
$Temperature_{Eff.}$ (°C)	27.3	25.7	27.4	26.6
Alkalinity (mg/L)	1420	1250	1530	1640
Total $Solid_{reactor}$ (mg/L)	2060	2690	2580	2442
Total Volatile $Solid_{react.}$(mg/L)	980	1745	1740	1571
Organic Loading Rate (kgCOD/m³d)	1.934	1.934	1.934	1.934
COD Removal Efficiency (%)	68	50	37	36

For the all reactors at HRT= 2 days and OLR = 2.000 kgCOD/m³d, 4 measurements were carried out. In the all reactors, minimum and maximum influent

COD concentrations were 3813 mg/L and 3944 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 100 and AFR 50 which were operated in continuous operation mode were taken 1086 mg/L - 1462 mg/L and 1685 mg/L - 2150 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 75 and AFR 25 which were operated in semi-continuous operation mode were obtained 2214 mg/L - 2562 mg/L and 2150 mg/L - 2695 mg/L, respectively. In consequence of the experiments made, the COD removal efficiencies of AFR 100 varied between 63 and 72%, the COD removal efficiencies of AFR 50 varied between 45 and 53%, the COD removal efficiencies of AFR 75 varied between 34 and 41% and the COD removal efficiencies of AFR 25 varied between 32 and 39%. The standard deviations of these COD removal efficiencies were found to be 4.4, 3.3, 3.3 and 3.3% for AFR 100, AFR 50, AFR 75 and AFR 25, respectively.

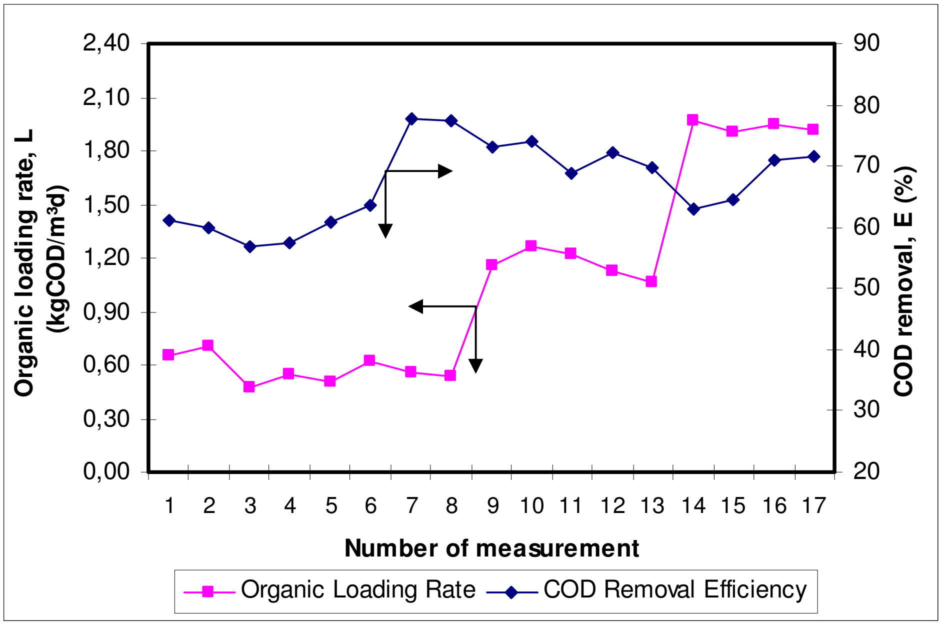


Figure 4.5 Organic loading rates and COD removal efficiencies for AFR 100 at HRT = 2 days

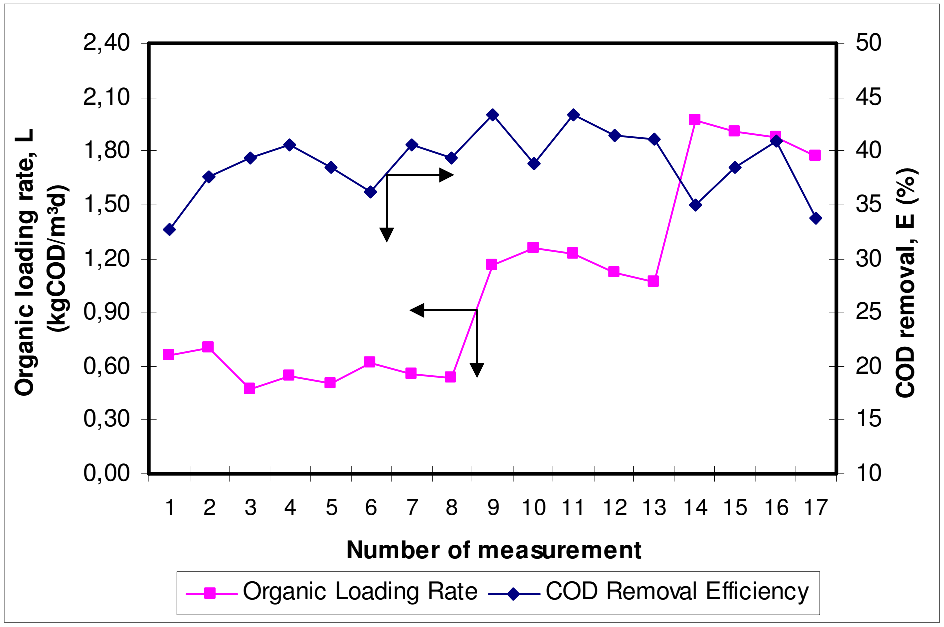


Figure 4.6 Organic loading rates and COD removal efficiencies for AFR 75 at HRT = 2 days

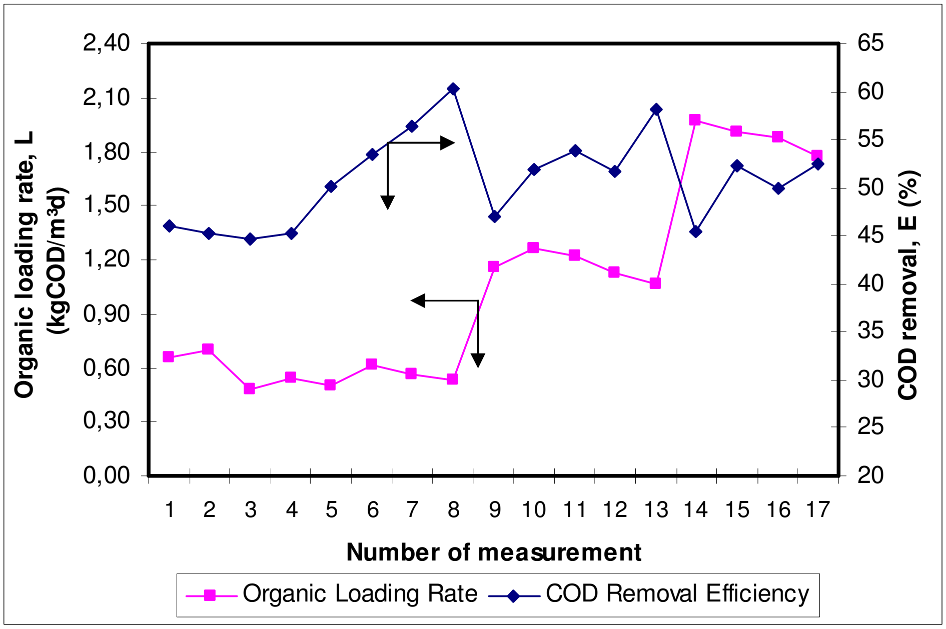


Figure 4.7 Organic loading rates and COD removal efficiencies for AFR 50 at HRT = 2 days

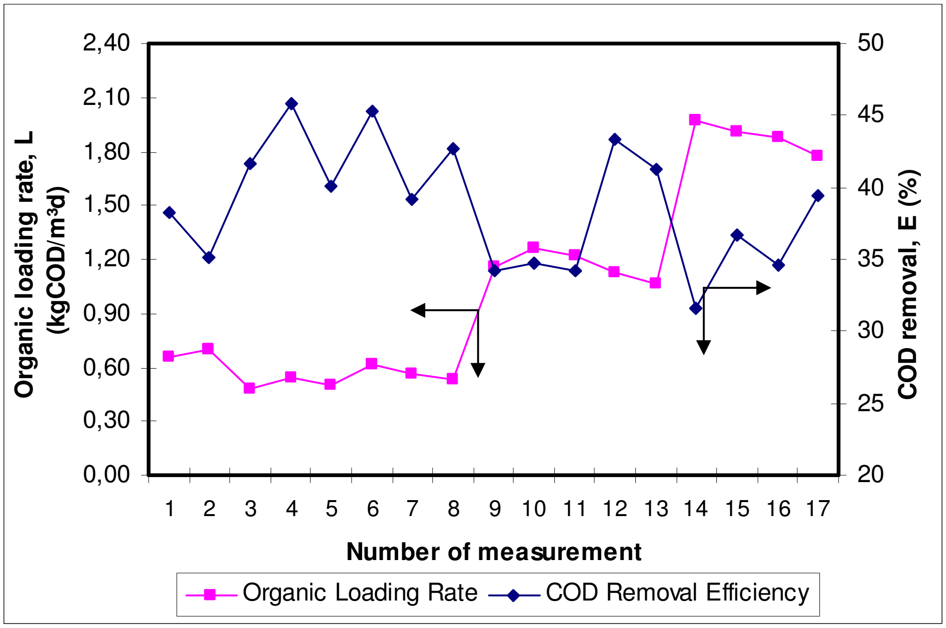


Figure 4.8 Organic loading rates and COD removal efficiencies for AFR 25 at HRT = 2 days

Table 4.7 Laboratory results for the model reactors at HRT = 1 day and OLR = 2.000 kgCOD/m³d (average values)

Parameters	**AFR 100**	**AFR 75**	**AFR 50**	**AFR 25**
$COD_{Influent}$ (mg/L)	2127	2127	2127	2127
$COD_{Effluent}$ (mg/L)	662	1242	1047	1339
$pH_{Influent}$	8.06	8.06	8.06	8.06
$pH_{Effluent}$	6.79	6.49	6.61	6.48
$Temperature_{Inf.}$ (°C)	21.4	21.4	21.4	21.4
$Temperature_{Eff.}$ (°C)	26.9	26.7	26.5	26.7
Alkalinity (mg/L)	1820	2060	1970	1980
Total $Solid_{reactor}$ (mg/L)	3750	5260	4437	4500
Total Volatile $Solid_{react.}$(mg/L)	2650	4100	3050	3257
Organic Loading Rate (kgCOD/m³d)	2.128	2.128	2.128	2.128
COD Removal Efficiency (%)	69	42	51	37

For the all reactors at HRT= 1 days and OLR = 2.000 kgCOD/m³d, 5 measurements were done. In the all reactors, minimum and maximum influent COD concentrations were 1949 mg/L and 2500 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 100 and AFR 50 were measured 521 mg/L - 826 mg/L and 820 mg/L - 1198 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 75 and AFR 25 were obtained 1085 mg/L - 1462 mg/L and 1120 mg/L - 1489 mg/L, respectively. In the result of the experiments, the COD removal efficiencies of AFR 100 varied between 62 and 75%, the COD removal efficiencies of AFR 50 varied between 46 and 58%, the COD removal efficiencies of AFR 75 varied between 34 and 47% and the COD removal efficiencies of AFR 25 varied between 32 and 43%. The standard deviations of these COD removal efficiencies were found to be 5.3, 5.2, 5.3 and 4.4% for AFR 100, AFR 50, AFR 75 and AFR 25, respectively.

Table 4.8 Laboratory results for the model reactors at HRT = 1 day and OLR = 4.000 kgCOD/m³d (average values)

Parameters	**AFR 100**	**AFR 75**	**AFR 50**	**AFR 25**
$COD_{Influent}$ (mg/L)	4398	4398	4398	4398
$COD_{Effluent}$ (mg/L)	1613	2695	2392	2795
$pH_{Influent}$	7.84	7.84	7.84	7.84
$pH_{Effluent}$	6.67	6.50	6.30	6.65
$Temperature_{Inf.}$ (°C)	22.1	22.1	22.1	22.1
$Temperature_{Eff.}$ (°C)	28.3	28.5	28.3	28.8
Alkalinity (mg/L)	2450	2640	2560	2240
Total $Solid_{reactor}$ (mg/L)	2425	3246	2827	3107
Total Volatile $Solid_{react.}$(mg/L)	1325	1846	1773	1988
Organic Loading Rate (kgCOD/m³d)	4.398	4.398	4.398	4.398
COD Removal Efficiency (%)	63	39	46	37

For the all reactors at HRT=1 days and OLR = 4.000 kgCOD/m³d, 4 measurements were carried out. In the all reactors, minimum and maximum influent

COD concentrations were 4120 mg/L and 4780 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 100 and AFR 50 which were operated in continuous operation mode were taken 1456 mg/L - 1760 mg/L and 1994 mg/L - 2984 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 75 and AFR 25 which were operated in semi-continuous operation mode were obtained 2403 mg/L - 3155 mg/L and 2420 mg/L - 3250 mg/L, respectively. In consequence of the experiments made, the COD removal efficiencies of AFR 100 varied between 60 and 67%, the COD removal efficiencies of AFR 50 varied between 38 and 54%, the COD removal efficiencies of AFR 75 varied between 34 and 44% and the COD removal efficiencies of AFR 25 varied between 32 and 41%. The standard deviations of these COD removal efficiencies were found to be 2.6, 6.7, 4.3 and 4.1% for AFR 100, AFR 50, AFR 75 and AFR 25, respectively.

Table 4.9 Laboratory results for the model reactors at HRT = 1 day and OLR = 8.000 kgCOD/m³d (average values)

Parameters	**AFR 100**	**AFR 75**	**AFR 50**	**AFR 25**
$COD_{Influent}$ (mg/L)	8475	8475	8475	8475
$COD_{Effluent}$ (mg/L)	3540	5050	4643	5246
$pH_{Influent}$	8.01	8.01	8.01	8.01
$pH_{Effluent}$	6.78	6.47	6.88	6.58
$Temperature_{Inf.}$ (°C)	25.4	25.4	25.4	25.4
$Temperature_{Eff.}$ (°C)	31.4	31.4	31.4	31.8
Alkalinity (mg/L)	3000	3120	3280	3160
Total $Solid_{reactor}$ (mg/L)	3690	3767	3478	3255
Total Volatile $Solid_{react.}$(mg/L)	2240	2233	1922	1867
Organic Loading Rate (kgCOD/m³d)	8.475	8.475	8.475	8.475
COD Removal Efficiency (%)	58	40	45	38

For the all reactors at HRT= 1 days and OLR = 8.000 kgCOD/m³d, 5 measurements were done. In the all reactors, minimum and maximum influent COD concentrations were 7920 mg/L and 9200 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 100 and AFR 50 were measured 2850 mg/L - 4520 mg/L and 4120 mg/L - 5245 mg/L, respectively. Minimum and maximum effluent COD concentrations at AFR 75 and AFR 25 were obtained 4625 mg/L - 5520 mg/L and 4505 mg/L - 6015 mg/L, respectively. In the result of the experiments, the COD removal efficiencies of AFR 100 varied between 45 and 66%, the COD removal efficiencies of AFR 50 varied between 39 and 52%, the COD removal efficiencies of AFR 75 varied between 37 and 44% and the COD removal efficiencies of AFR 25 varied between 31 and 43%. The standard deviations of these COD removal efficiencies were found to be 8.9, 5.6, 3.2 and 5.1% for AFR 100, AFR 50, AFR 75 and AFR 25, respectively.

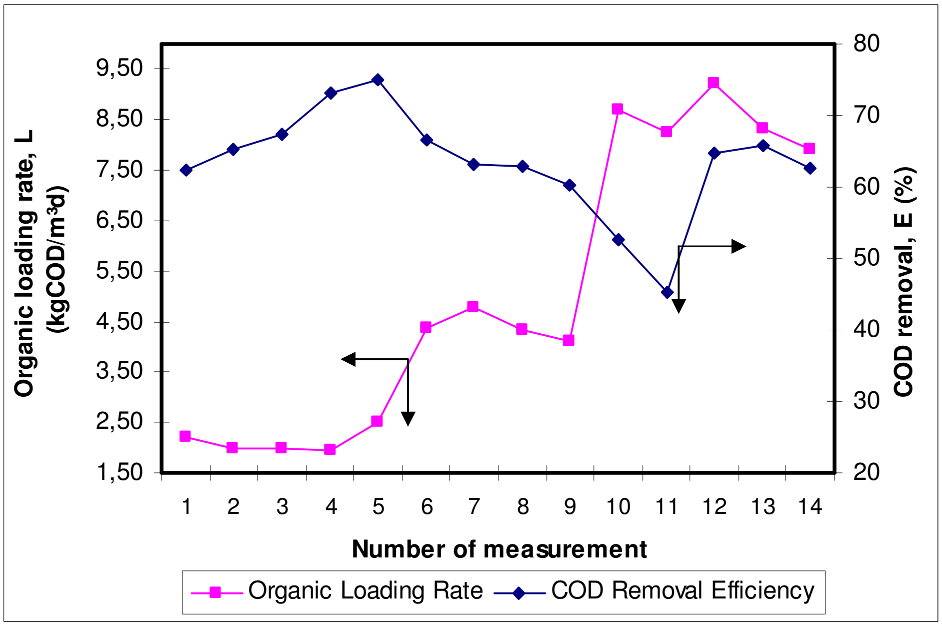


Figure 4.9 Organic loading rates and COD removal efficiencies for AFR 100 at HRT = 1 days

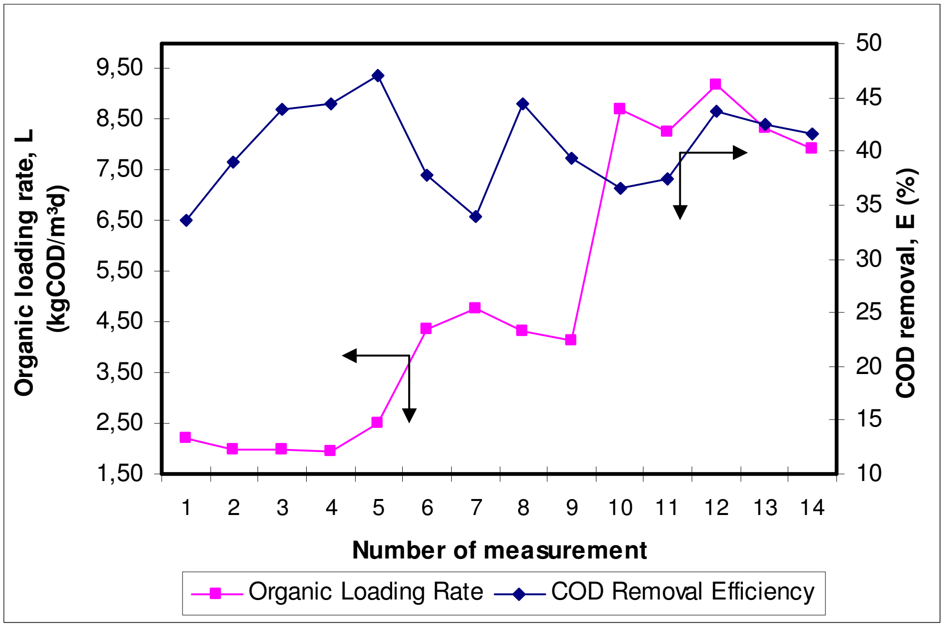


Figure 4.10 Organic loading rates and COD removal efficiencies for AFR 75 at HRT = 1 days

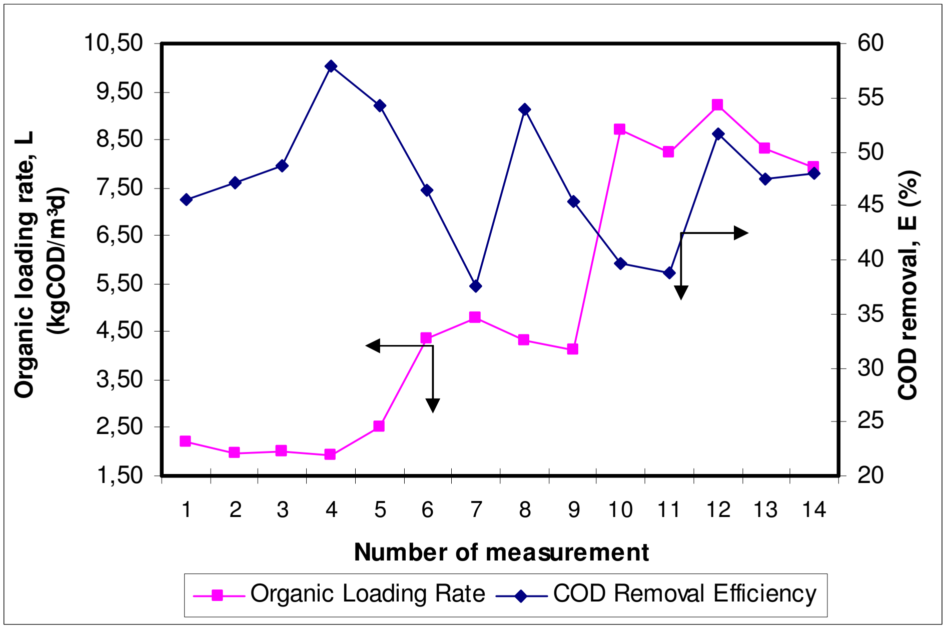


Figure 4.11 Organic loading rates and COD removal efficiencies for AFR 50 at HRT = 1 days

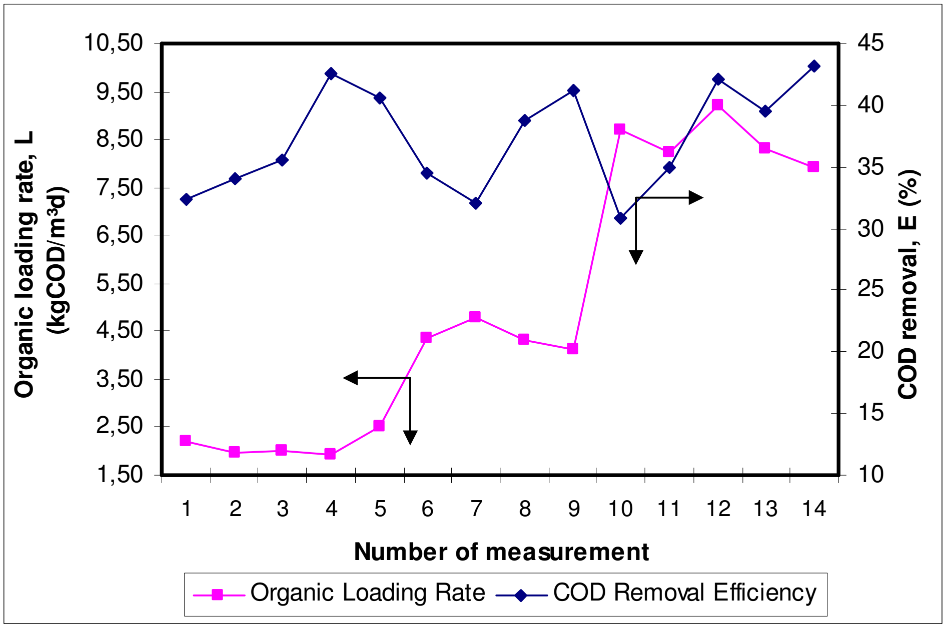


Figure 4.12 Organic loading rates and COD removal efficiencies for AFR 25 at HRT = 1 days

4.1.2 Filter Material Ratio and COD Removal Efficiencies for Model Reactors

In experimental studies, the filter material ratio was indicated to be effective on the COD removal efficiency. AFR 100 and AFR 50 were operated same operation mode, which is continuous mode, had different COD removal efficiencies. Removal efficiencies of the AFR 100 were higher than ones of the AFR 50. In a similar way, AFR 75 and AFR 25, which is semi-continuous operation mode, had also different COD removal efficiencies. Removal efficiencies of the AFR 100 were the highest. But, the difference between AFR 75 and AFR 25 is lower than difference between AFR 100 and AFR 50. For instance, at HRT=3 days, when COD removal efficiencies of AFR 75 and AFR 25 were found in range of 32 – 48% and 30 – 47%, COD removal efficiencies of AFR 100 and AFR 50 were measured 53 – 73% and 45 – 57%, respectively.

In the removal efficiency, operation mode may be thought to be important. In AFR 100 and AFR 50 operated in continuous mode, higher efficiency was obtained. AFR 75 and AFR 50 had lower COD removal.

Figures 4.13 to 4.18 have shown how COD removal efficiencies in the all reactors altered at different HRT values.

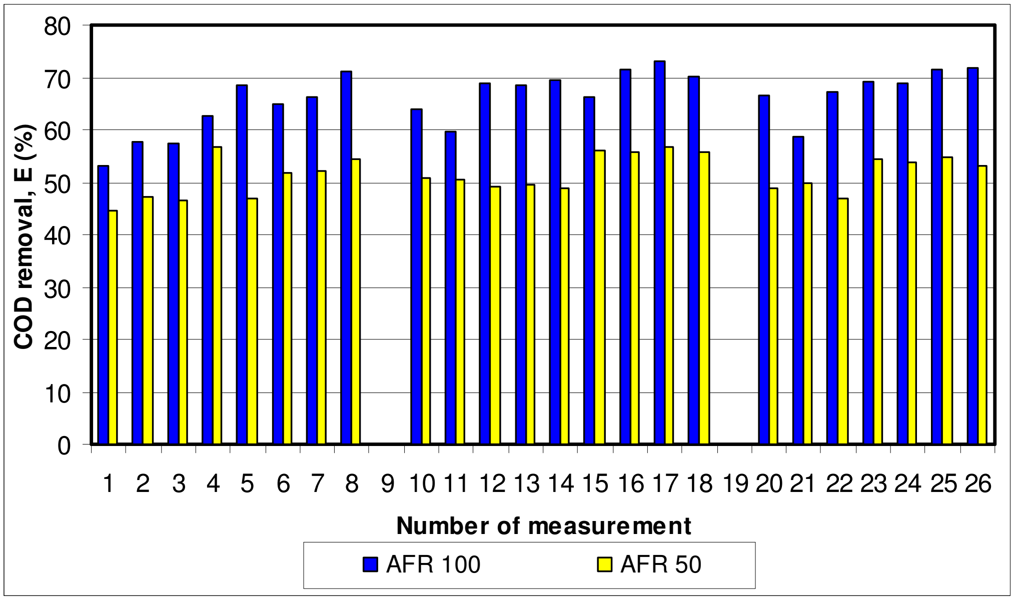


Figure 4.13 COD removal efficiencies for all organic loading rates at HRT=3 days for AFR 100 and AFR 50

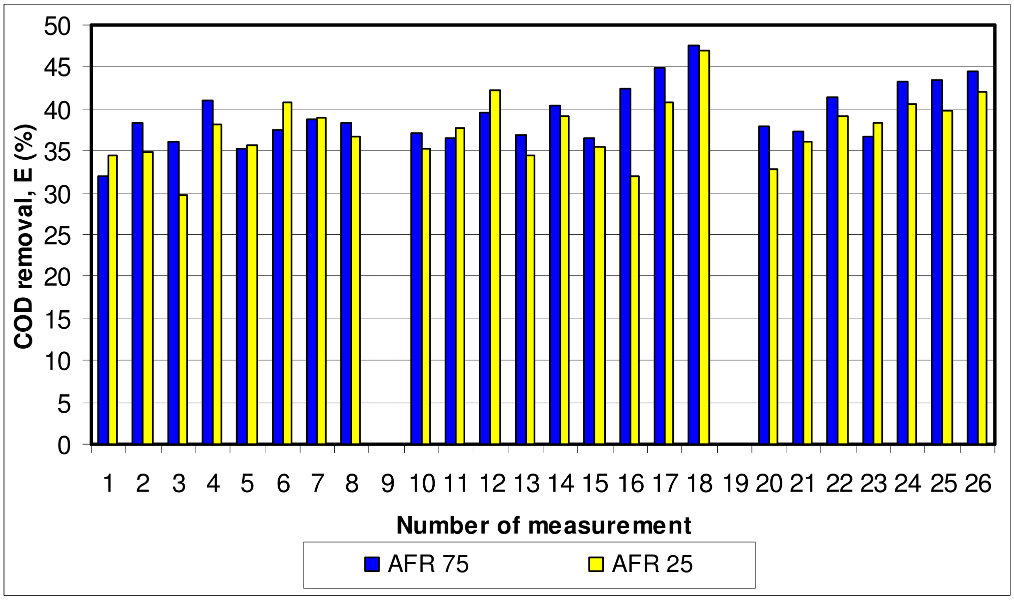


Figure 4.14 COD removal efficiencies for all organic loading rates at HRT=3 days for AFR 75 and AFR 25

At hydraulic retention time of 3 days, COD removal efficiencies of AFR 100 are higher than ones of AFR 50. At 2 days and 1 days, the situation is similar to above-mentioned those. But, the COD removal efficiencies differences between AFR 100 and AFR 50 at hydraulic retention time of 1 and 2 days are lower than those at hydraulic retention time of 3 days. This situation indicated that when hydraulic retention time was decreased, COD removal efficiency was affected less than the changes of the filter material ratio.

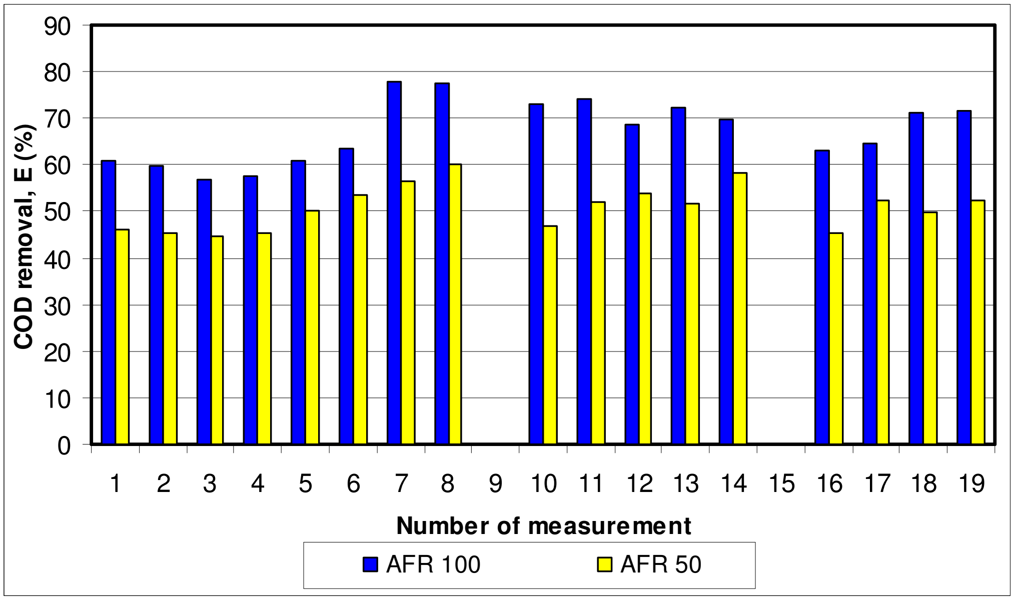


Figure 4.15 COD removal efficiencies for all organic loading rates at HRT=2 days for AFR 100 and AFR 50

The situation on AFR 75 and AFR 25 operated as semi-continuous operation mode is more different from the removal efficiencies of AFR 100 and AFR 50. At all values of hydraulic retention times, the difference between AFR 75 and AFR 25 are not too much in terms of COD removal efficiencies. The reason of that can be thought depending on operation mode. Moreover, the COD removal efficiencies are lower in reactors which are operated in semi-continuous mode.

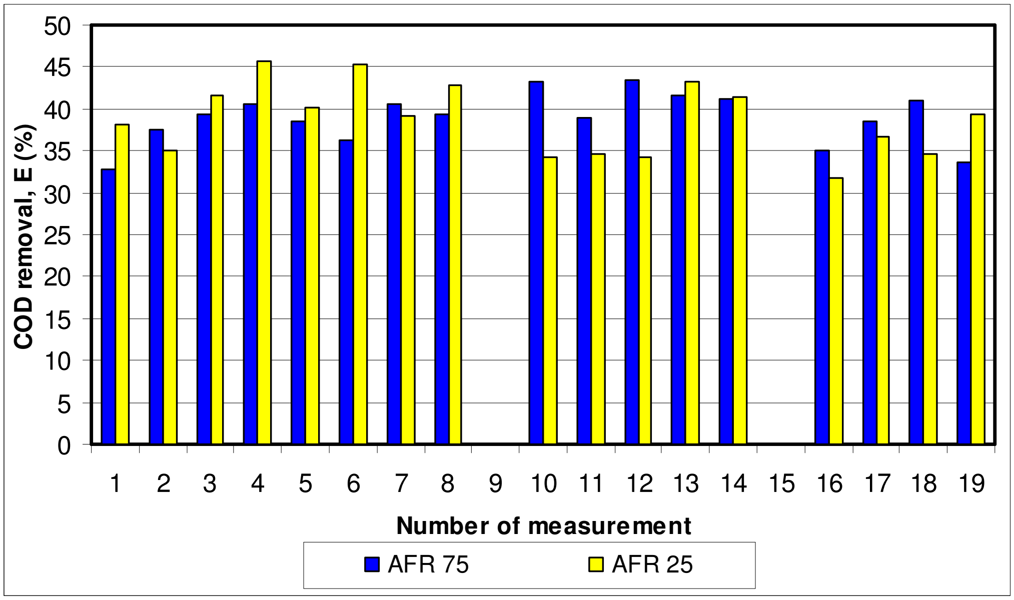


Figure 4.16 COD removal efficiencies for all organic loading rates at HRT=2 days for AFR 75 and AFR 25

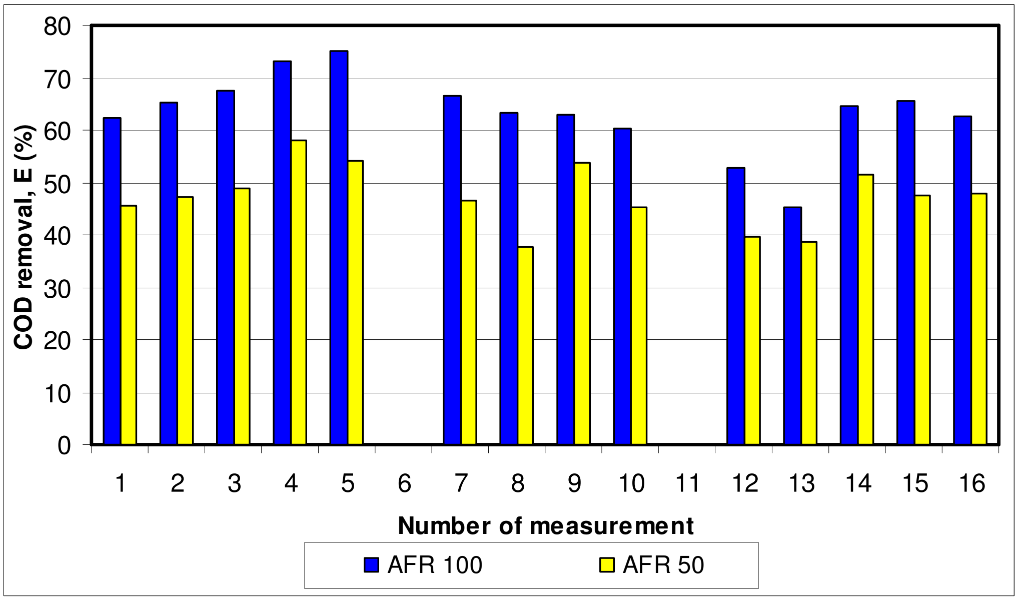


Figure 4.17 COD removal efficiencies for all organic loading rates at HRT=1 days for AFR 100 and AFR 50

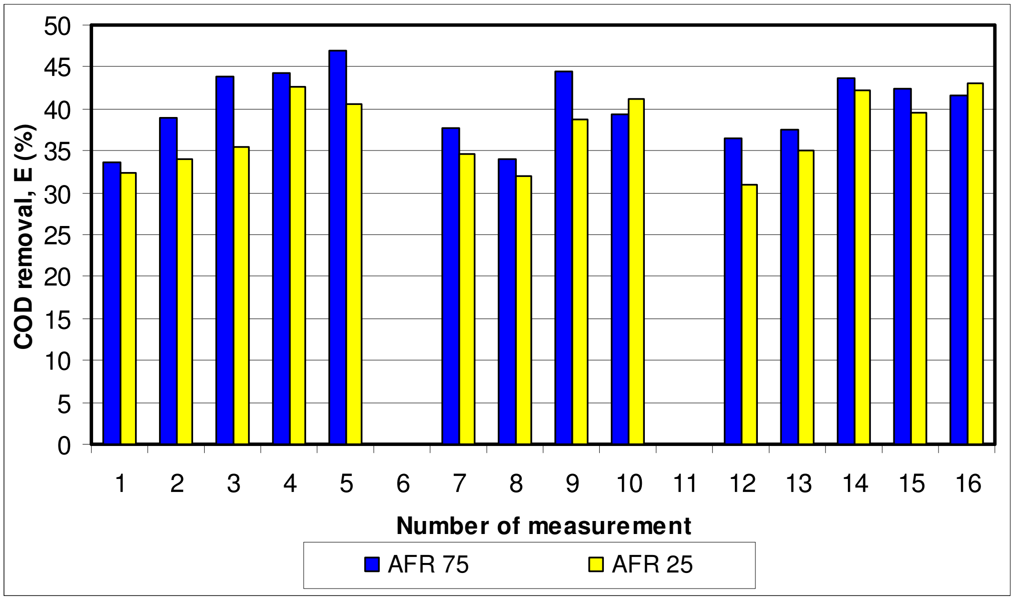


Figure 4.18 COD removal efficiencies for all organic loading rates at HRT=1 days for AFR 75 and AFR 25

4.1.3 Temperature and COD Removal Efficiencies for Model Reactors

Laboratory studies indicated that temperature was an effective parameter on COD removal efficiency, on the other hand, that anaerobic filters were able to be operated at low temperatures.

The all anaerobic filter reactors were operated at psychrophilic temperature interval. As known, the COD removal efficiency is low below 30 °C. So, the values obtained are lower in comparison with other studies.

At the end of the experimental studies, although the organic loading rate value was increased, COD removal efficiencies did not decrease too much. We can explain this situation as depending on temperature. Temperature reached to about 33 °C at the last, although, at the beginning, it was at 20 °C.

Figures 4.19 to 4.22 have shown how COD removal efficiencies in the all reactors altered at temperature values.

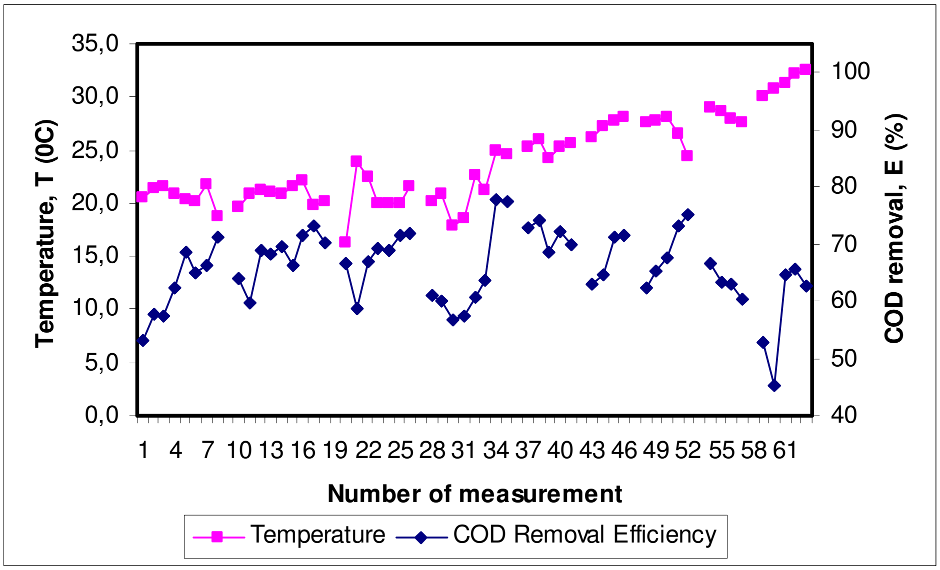


Figure 4.19 Temperature and COD removal efficiency values for the AFR 100 during experimental studies

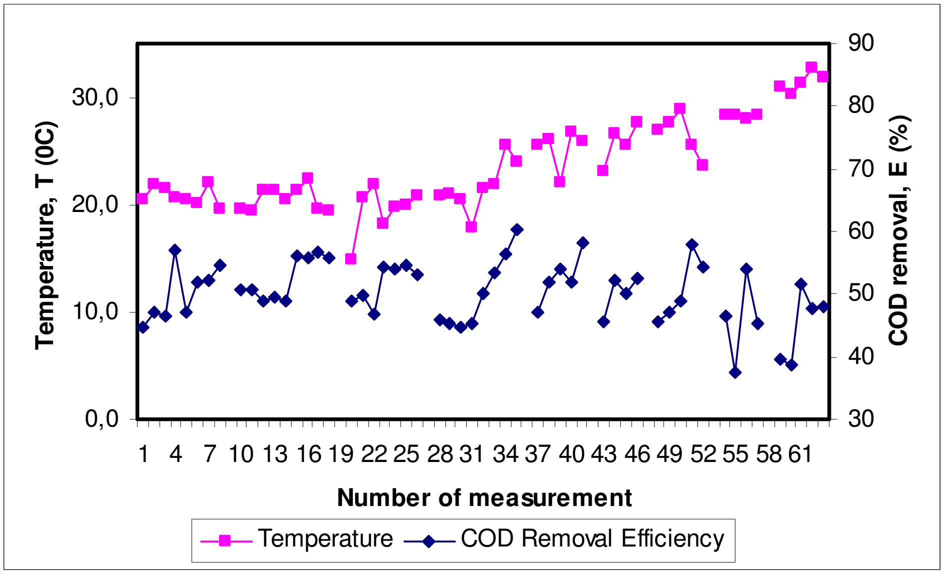


Figure 4.20 Temperature and COD removal efficiency values for the AFR 50 during experimental studies

The temperature risings occurred during studies caused COD removal efficiencies to increase in the course of time. When considered every period which the different organic loading rates were applied, risings of temperature increased removal efficiencies at the same organic loading rates. However, the peaks depended on temperature did not consist since temperature increasing was not too high.

If the evaluations are made in terms of operation mode, AFR 100 and AFR 50 which was operated in continuous mode adjusted to the changes of temperature in a good way.

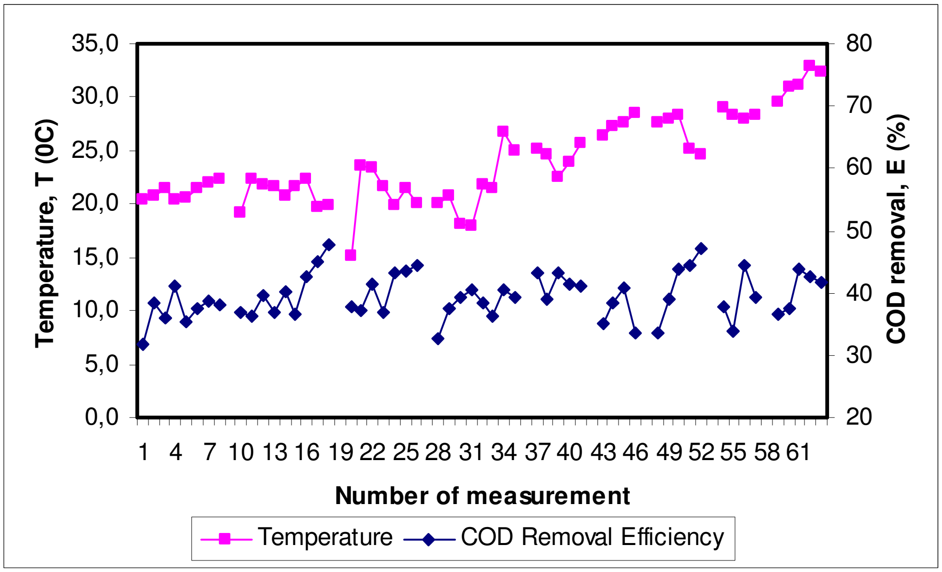


Figure 4.21 Temperature and COD removal efficiency values for the AFR 75 during experimental studies

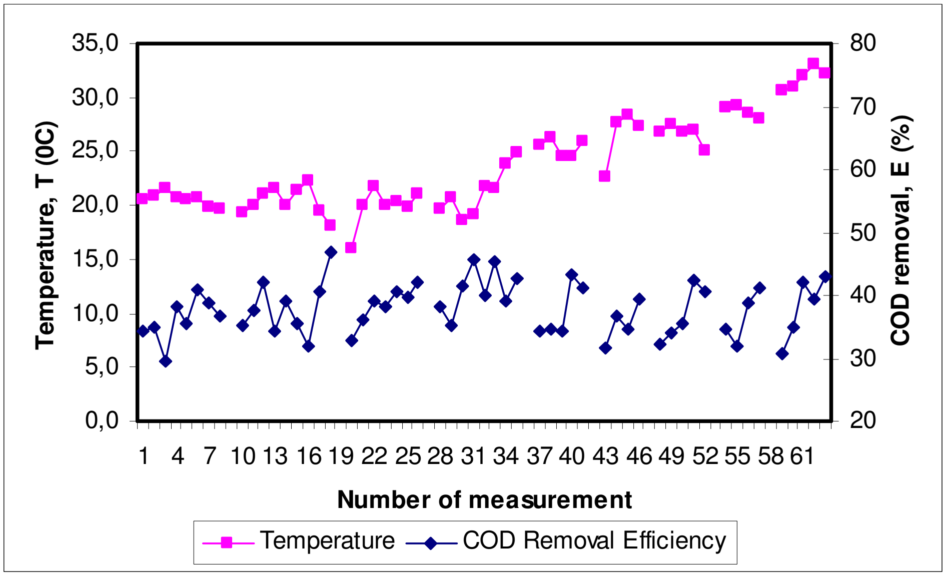


Figure 4.22 Temperature and COD removal efficiency values for the AFR 25 during experimental studies

4.1.4 pH and Alkalinity Alteration in Reactors

pH and alkalinity were monitored during the study. In the anaerobic filter model reactors used synthetic wastewater containing molasses for feeding, the pH control was achieved with NaOH.

In the studies made, NaOH was used for pH control. 0.8 – 1.0 g NaOH/L was applied as a buffer, and pH was tried to keep in ranged of 6.0 – 7.5.

When pH value of influent was observed in ranged 6.15 and 10.00, pH value of effluent of all reactors was kept in ranged 5.90 – 7.70 by the help of NaOH.

It is important that inlet pH values are achieved in the optimal range for anaerobic treatment. pH must be in ranged 6.5 – 8.5 for becoming anaerobic digestion as mentioned previous sections. That being the case, pH values were achieved in the above-mentioned values for being provided the optimum conditions. According to literature studies, it is vital important in terms of the system for pH to be over 10 and to be below 5. Therefore, necessary processes were done for providing optimum conditions.

As far as pH values collected from the systems are concerned, very high or low pH values are not observed except some value such as 10 or 5.90. Besides, outlet pH values as well are in ranged requisite values that the anaerobic filter reactors were operated at available conditions.

The inlet and outlet pH values for the reactors during experimental studies are given in Figures 4.23 to 4.26.

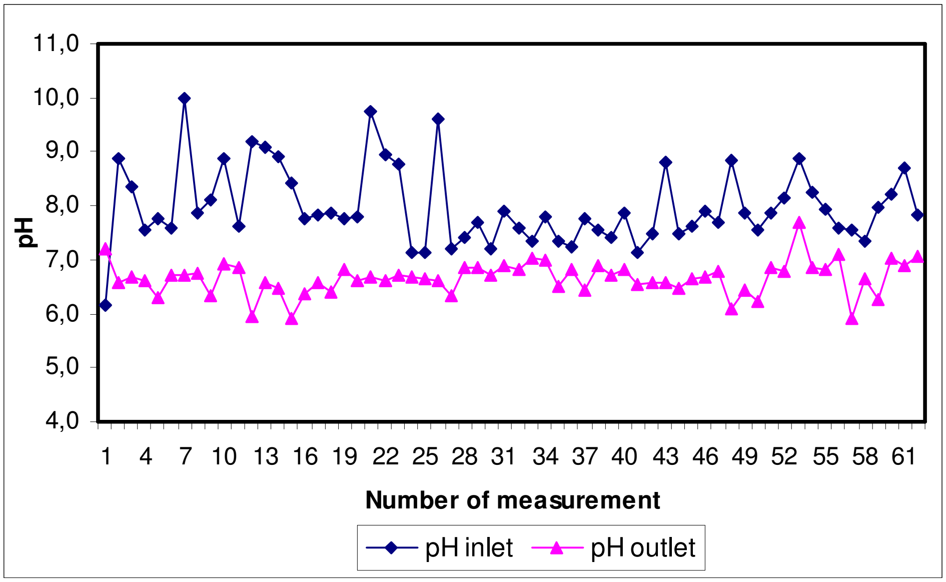


Figure 4.23 The inlet and outlet pH values for the AFR 100 during experimental studies

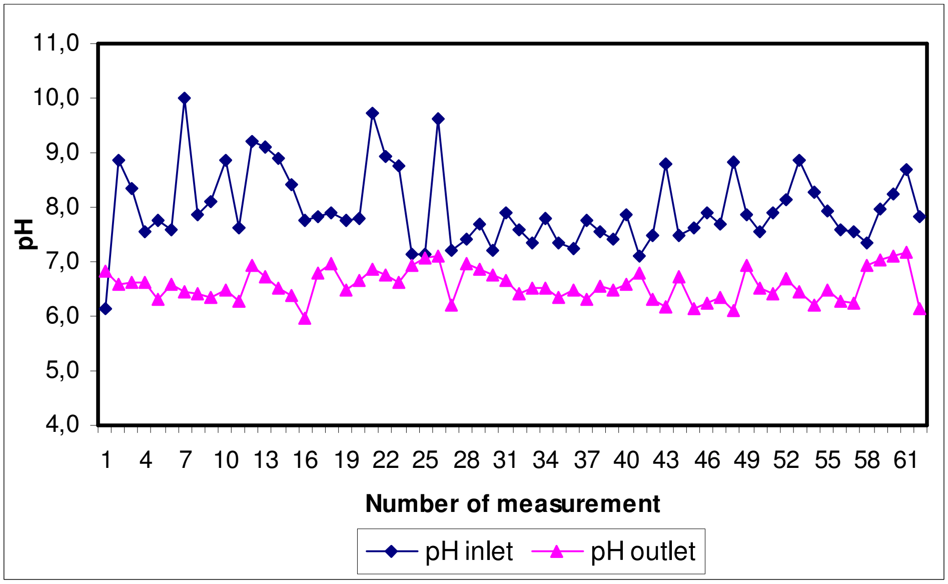


Figure 4.24 The inlet and outlet pH values for the AFR 50 during experimental studies

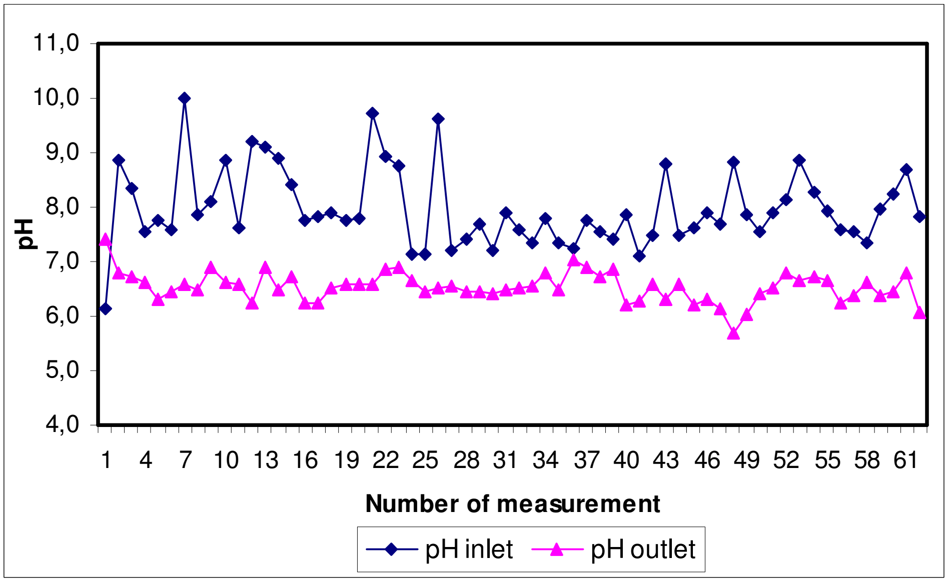


Figure 4.25 The inlet and outlet pH values for the AFR 75 during experimental studies

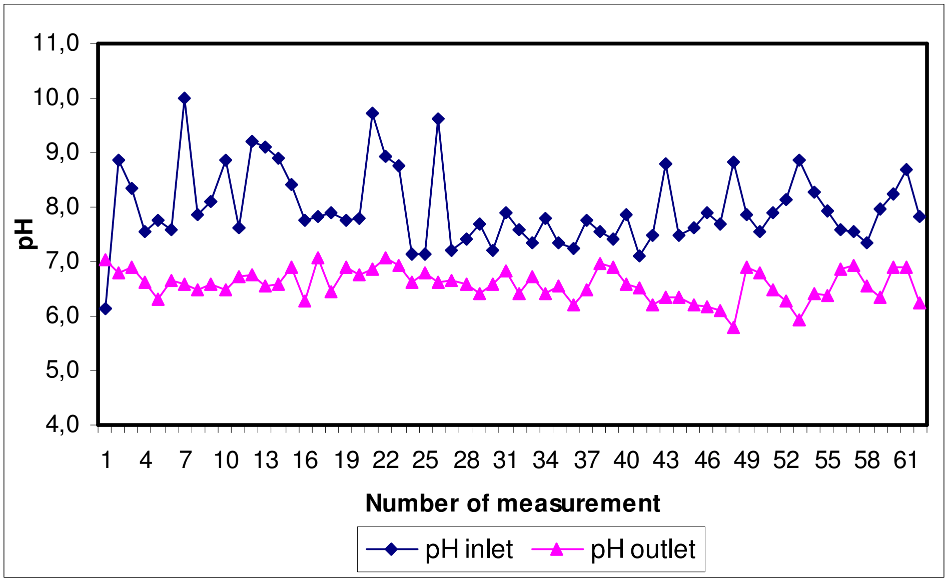


Figure 4.26 The inlet and outlet pH values for the AFR 25 during experimental studies

4.2 Kinetic Models Applied to Experimental Results

Some kinetic models were exerted to data obtained from the experimental studies. These kinetic models are Second Order Kinetic Model, DeWalle & Chian Model, Sundstorm et al Model (Lineweaver – Burk Plot) and Modified Stover-Kincannon Model. These models are generally related to biomass growth and biofilm formation. These kinetic models and kinetic constants are given as follows.

These data obtained from experimental studies and used for kinetic modeling are not statistically meaningful. Because, the least 6 or 7 data were not identified for every operation mode with standard deviation ±5. On other words, these data do not reflect steady-state conditions of the reactors.

Table 4.10 Model equations and linearilized model equations belong to kinetic models applied to data

Kinetic Model	**Model Equation**	**Linearilized Model Equation**
Second Order Model	$\frac{1}{\theta_C} = \left(Y\frac{S_o - S_e}{x * HRT} - K_d\right)$	$\frac{HRT * S_0}{S_0 - S_e} = b * HRT + a$ $\frac{HRT}{E} = b * HRT + a$
DeWalle & Chian Model	$\frac{d^2 S_Z}{d_Z^2} = \frac{1}{D}\left[U.S_Z.X/\left(K_S + S_S\right)\right]$	$\frac{1}{V}.\frac{df}{dt} = K_2\left(\frac{A}{V}\right).S_e$ $OLR = a.S_e$
Sundstorm et al Model (Lineweaver – Burk Plot)	$\frac{1}{V}.\frac{df}{dt} = \left[\frac{1}{V}.\frac{df}{dt}\right]_{\max}.\frac{S_e}{K_s + S_e}$	$\frac{1}{L} = \frac{K_S}{L_{\max}}.\frac{1}{S_e} + \frac{1}{L_{\max}}$ $\frac{1}{L} = a.\frac{1}{S_e} + b$
Modified Stover-Kincannon Model	$\frac{ds}{dt} = \frac{U_{\max}(QS_0/V)}{K_B + (QS_0/V)}$	$\frac{1}{OLR_{removal}} = \frac{K_B}{U_{\max}}.\frac{1}{OLR} + \frac{1}{U_{\max}}$ $\frac{1}{OLR_{removal}} = a.\frac{1}{OLR} + b$

4.2.1 Second Order Kinetic Model

The second order kinetic model was applied to data obtained from the experimental studies. A kinetic evaluation was done to the anaerobic filter reactors. Data and figures belong to all the reactors are given in Tables 4.11 to 4.14 and Figures 4.27 to 4.30.

When the second order kinetic is applied to the model, this equation is used,

$$\frac{1}{\theta_C} = \left(Y\frac{S_o - S_e}{x * HRT} - K_d\right) \qquad (4.1)$$

If this equation is linearilized, Eq 4.2 or Eq 4.3 is obtained,

$$\frac{HRT * S_0}{S_0 - S_e} = HRT + \frac{S_0}{K_2 . x} \qquad (4.2)$$

or;

$$\frac{HRT * S_0}{S_0 - S_e} = b * HRT + a \qquad (4.3)$$

Where; HRT; hydraulic retention time, (day)
So and Se; influent and effluent COD concentration, (kg/m³)
a; So/(K_S*X), (day)
b; constant
X; the average biomass concentration in the reactor, (mgVSS/L)
K_S; second-order substrate removal rate constant, (1/day)
S_{model}; expected effluent COD concentration depended on the model.

(So-Se)/So expresses the substrate removal efficiency and is symbolized as E. Therefore, the last equation can be written as follows:

$$\frac{HRT}{E} = b * HRT + a \qquad (4.4)$$

The following graphs were obtained by plotting HRT*So/(So-Se) versus HRT. The values a and b calculated from the intercept and slope of straight line on the graphs. And, HRT*So/(So-Se) values of model were estimated by the help of a and b values. Experimental and modeling value belong to systems are given in the following Tables 4.11 to 4.14.

Table 4.11 The data table of second order kinetic for AFR 100

Hydraulic Retention Time, HRT (d)	(HRT*So) / (So – Se)$_{Exp.}$	(HRT*So) / (So – Se)$_{Model.}$
3	4.824	4.531
3	4.427	4.531
3	4.451	4.531
2	3.152	3.047
2	2.797	3.047
2	2.971	3.047
1	1.462	1.563
1	1.582	1.563
1	1.756	1.563

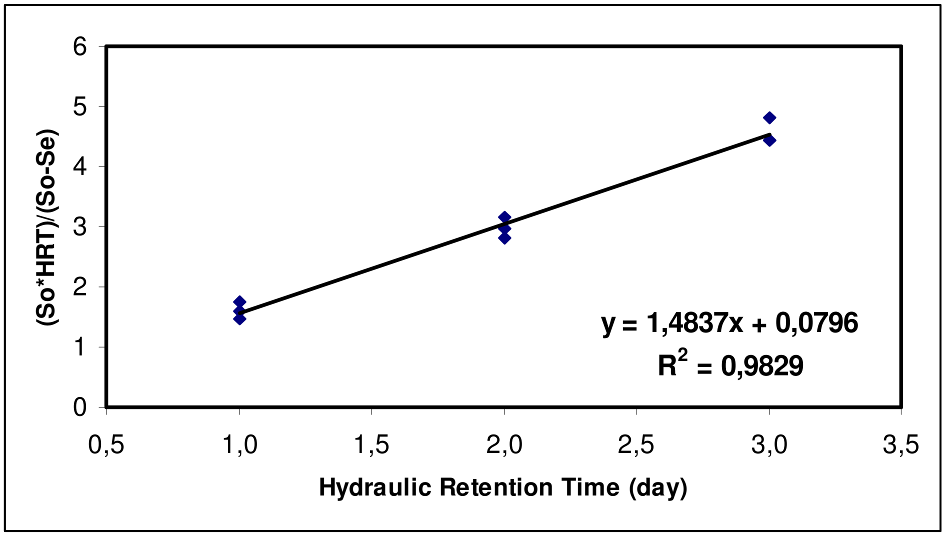


Figure 4.27 Evaluation of second order kinetic for AFR 100

Figure 4.27 shows the plot. The values a and b calculated from the intercept and slope of straight line on the graph were found to be 1.4837 and 0.0796 with correlation coefficient of 0.9829. The model equation for AFR 100 has found to be for the study.

$$S_{model} = S_0\left(1 - \frac{HRT}{1.4837 * HRT + 0.0796}\right) \quad (4.5)$$

Table 4.12 The data table of second order kinetic for AFR 75

Hydraulic Retention Time, HRT (d)	(HRT*So) / (So – Se)$_{Exp.}$	(HRT*So) / (So – Se)$_{Model.}$
3	8.126	7.718
3	7.529	7.718
3	7.431	7.718
2	5.273	5.126
2	4.811	5.126
2	5.432	5.126
1	2.443	2.533
1	2.597	2.533
1	2.489	2.533

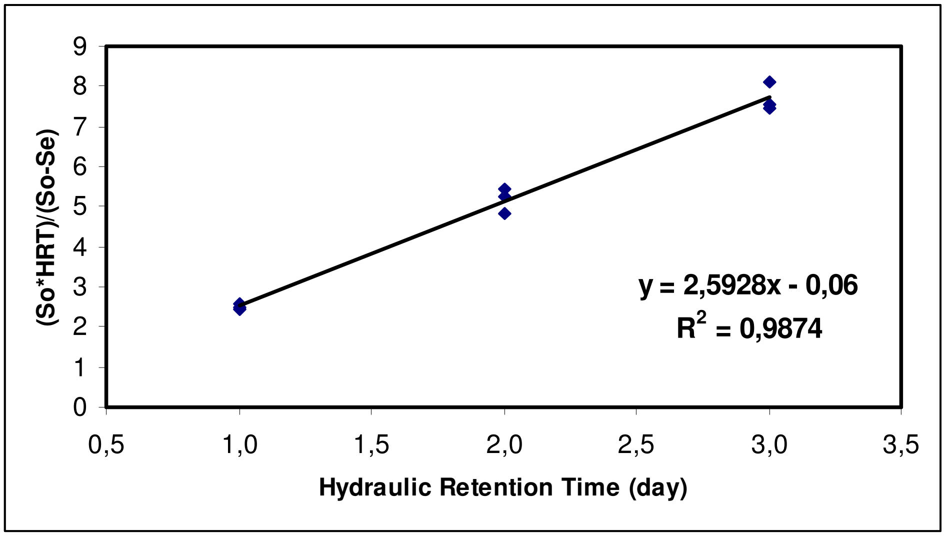


Figure 4.28 Evaluation of second order kinetic for AFR 75

Figure 4.28 shows the plot. The values a and b calculated from the intercept and slope of straight line on the graph were found to be 2.5928 and -0.060 with correlation coefficient of 0.9874. The model equation for AFR 75 has found to be for the study.

$$S_{model} = S_0\left(1 - \frac{HRT}{2.5928 * HRT - 0.06}\right) \qquad (4.6)$$

Table 4.13 The data table of second order kinetic for AFR 50

Hydraulic Retention Time, HRT (d)	(HRT*So) / (So – Se)$_{Exp.}$	(HRT*So) / (So – Se)$_{Model.}$
3	6.030	5.843
3	5.722	5.843
3	5.826	5.843
2	4.032	3.988
2	3.825	3.988
2	4.008	3.988
1	1.987	2.133
1	2.219	2.133
1	2.243	2.133

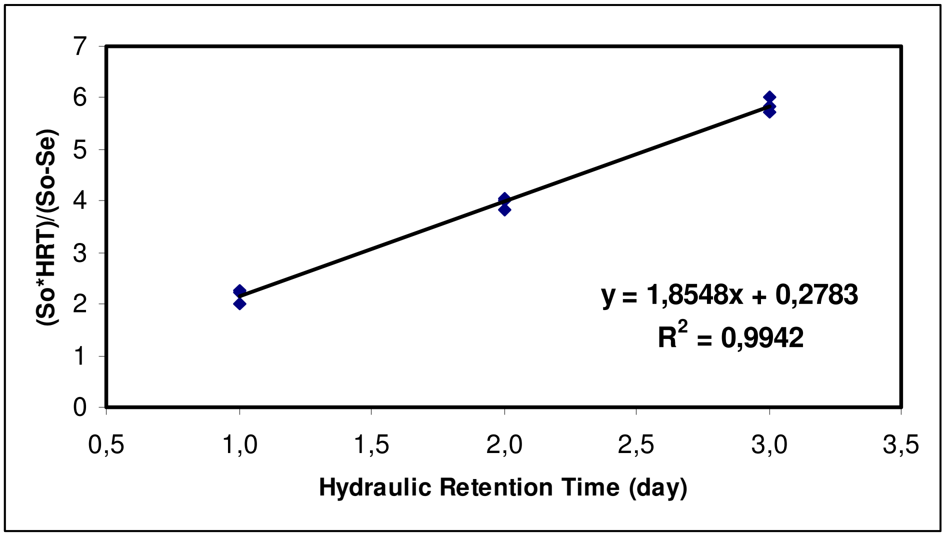


Figure 4.29 Evaluation of second order kinetic for AFR 50

Figure 4.29 shows the plot. The values a and b calculated from the intercept and slope of straight line on the graph were found to be 1.8548 and 0.2783 with correlation coefficient of 0.9942. The model equation for AFR 50 has found to be for the study.

$$S_{\mathrm{model}} = S_0\left(1 - \frac{HRT}{1.8548 * HRT + 0.2783}\right) \tag{4.7}$$

Table 4.14 The data table of second order kinetic for AFR 25

Hydraulic Retention Time, HRT (d)	(HRT*So) / (So – Se)$_{Exp.}$	(HRT*So) / (So – Se)$_{Model.}$
3	8.375	8.041
3	7.953	8.041
3	7.869	8.041
2	4.912	5.367
2	5.384	5.367
2	5.655	5.367
1	2.731	2.693
1	2.757	2.693
1	2.665	2.693

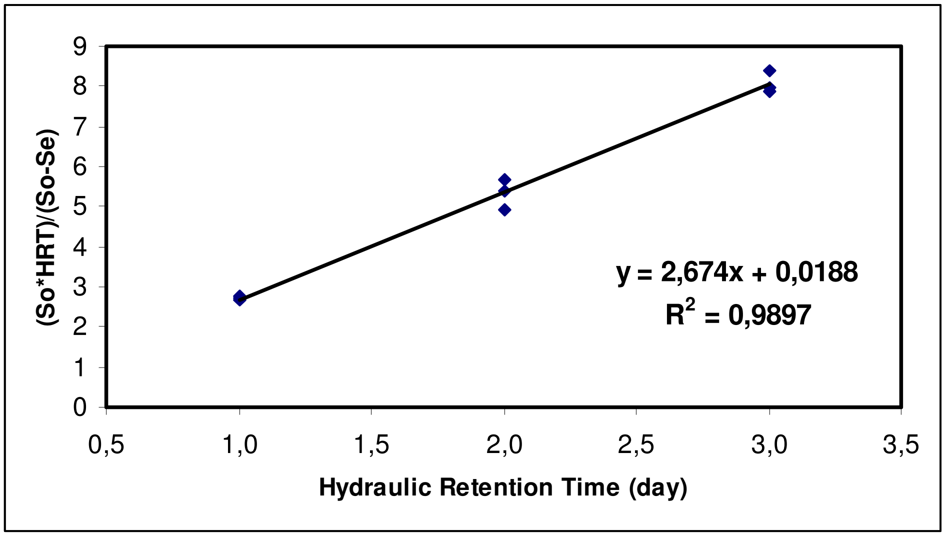


Figure 4.30 Evaluation of second order kinetic for AFR 25

Figure 4.30 shows the plot. The values a and b calculated from the intercept and slope of straight line on the graph were found to be 2.674 and 0.0188 with correlation coefficient of 0.9897. The model equation for AFR 25 has found to be for the study.

$$S_{model} = S_0\left(1 - \frac{HRT}{2.674 * HRT + 0.1488}\right) \tag{4.8}$$

Substrate removal constant was not possible to determine from this model because the total biomass could not determined.

4.2.2 DeWalle & Chian Model

The DeWalle & Chian model was applied to data obtained from the experimental studies. A kinetic evaluation was done to the anaerobic filter reactors.

When mass balance for the biofilm is done and "Fick's Diffusion Law" is applied, differential equation given in Eq. 4.4 is found (Nandy & Kaul, 1991).

$$\frac{d^2 S_Z}{d_Z^2} = \frac{1}{D}\left[U.S_Z.X/\left(K_S + S_S\right)\right] \tag{4.9}$$

$$\frac{df}{dt} = -A.D.S.\frac{ds}{dz} \tag{4.10}$$

Where; S_Z; substrate concentration at depth Z
U; specific substrate utilization rate, (kgCOD/m²d)
z; depth of biofilm starting from liquid-film interface, (m)

Using several assumptions given by DeWalle and Chian for the substrate concentration, When S_Z, substrate concentration, is less than Ks, equations 4.11 and 4.12 can be written as;

$$\frac{1}{V}.\frac{df}{dt} = K_2\left(\frac{A}{V}\right).S_e \tag{4.11}$$

$$OLR = a.S_e \tag{4.12}$$

Where; V; volume of the reactor, (m³)

A; area of the biofilm, (m²)

f; amount of substrate removed, (kg/d)

K_2(A/V); substrate removal rate constant, (1/day)

Se; effluent COD concentration, (kg/m³)

Df/(V*dt) or OLR; organic (substarate) loading rate, (kgCOD/m³d)

Linear regressions were used to determine the value of K_2 (A/V). The value of K_2 (A/V) was obtained from the slope of the line by plotting organic loading rate versus effluent substrate concentration.

Figures 4.31 to 4.42 show the plots between organic loading rate and effluent substrate concentration for all the reactors.

In this experimental study, average removal rate constant K_2 (A/V) in psychrophilic temperature was found to be 1.490 d^{-1} and 1.120 d^{-1} for AFR 100 and AFR 50 and was found to be 1.001 d^{-1} and 0.984 d^{-1} for AFR 75 and AFR 25, respectively.

The value for AFR 100 is higher than the values of other reactors; AFR 50 has second high value, because AFR 100 and AFR 50 were operated as continuous mode and the AFR 100 is full with the filter materials. On the other hand, temperature is effective on the removal rate constant K_2 (A/V), when temperature is increased, it will increase.

Removal rate constant K_2 (A/V) was determined as 2.05 d^{-1} for anaerobic filter treating synthetic wastewater containing molasses (Tokgöz, 1998). Similarly, the value was denoted as 0.910 d^{-1} in the study which Nandy & Kaul (1991) have worked with herbal pharmaceutical.

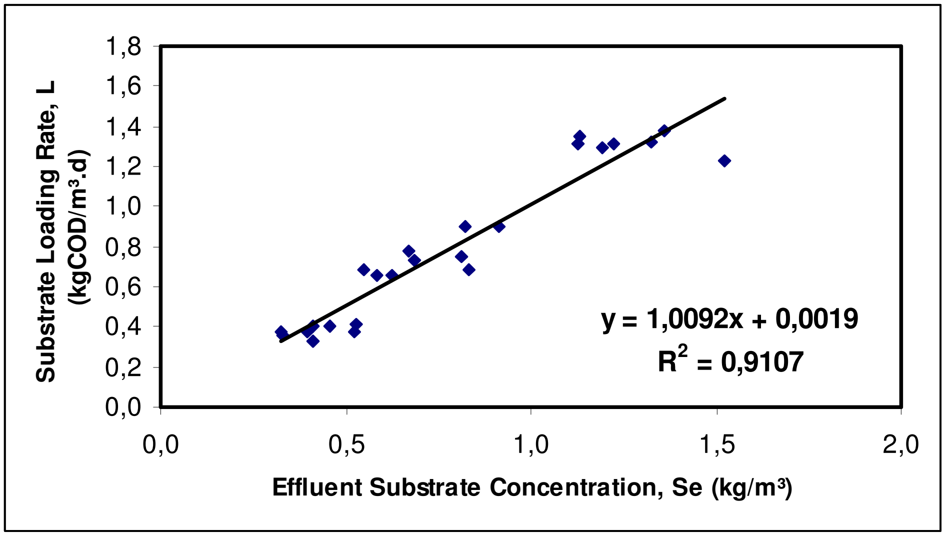


Figure 4.31 Plot of organic (substrate) loading rate as a function of effluent substrate concentration for COD, HRT = 3 days, evaluation of the DeWalle & Chian model for AFR 100

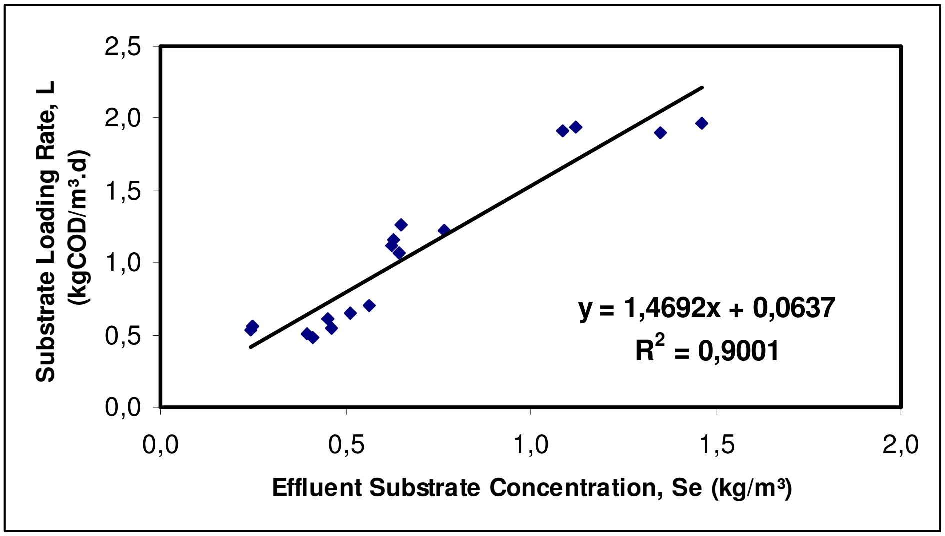


Figure 4.32 Plot of organic (substrate) loading rate as a function of effluent substrate concentration for COD, HRT = 2 days, evaluation of the DeWalle & Chian model for AFR 100

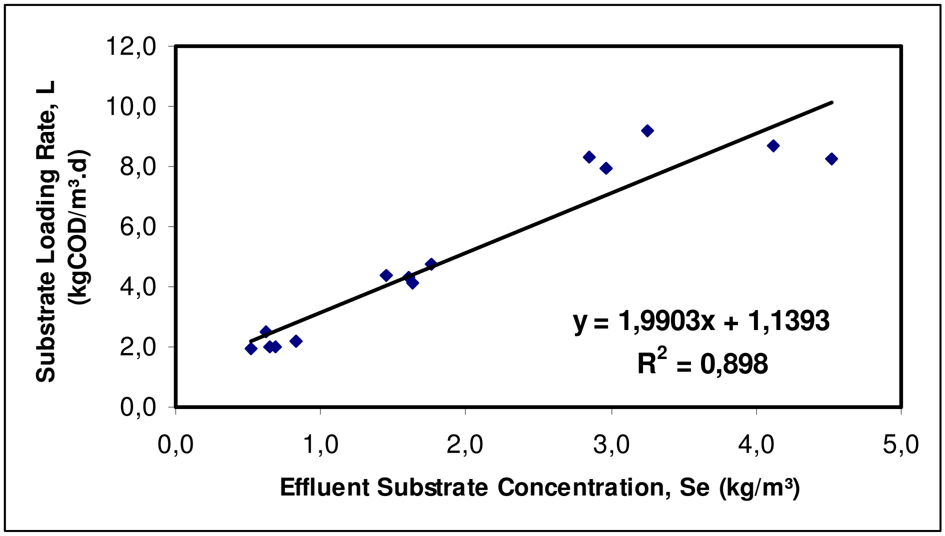


Figure 4.33 Plot of organic (substrate) loading rate as a function of effluent substrate concentration for COD, HRT = 1 day, evaluation of the DeWalle & Chian model for AFR 100

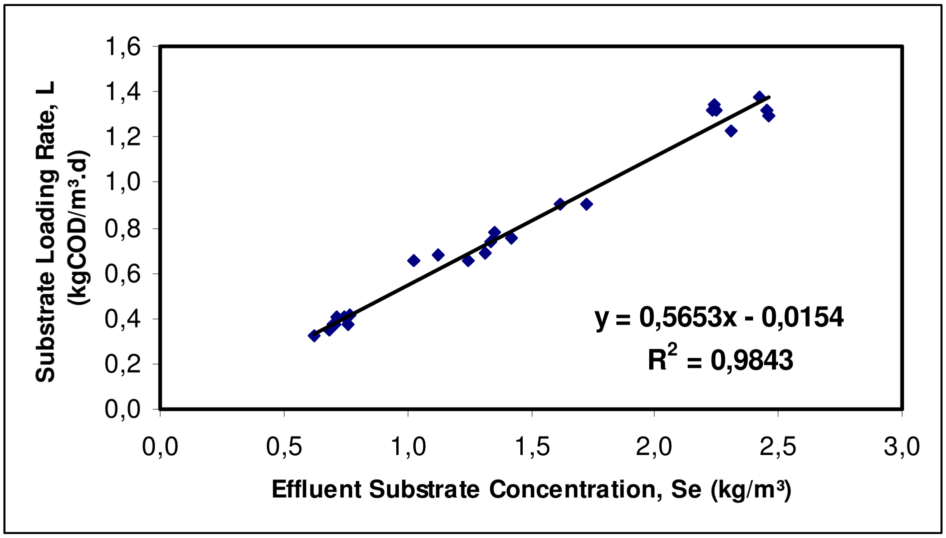


Figure 4.34 Plot of organic (substrate) loading rate as a function of effluent substrate concentration for COD, HRT = 3 days, evaluation of the DeWalle & Chian model for AFR 75

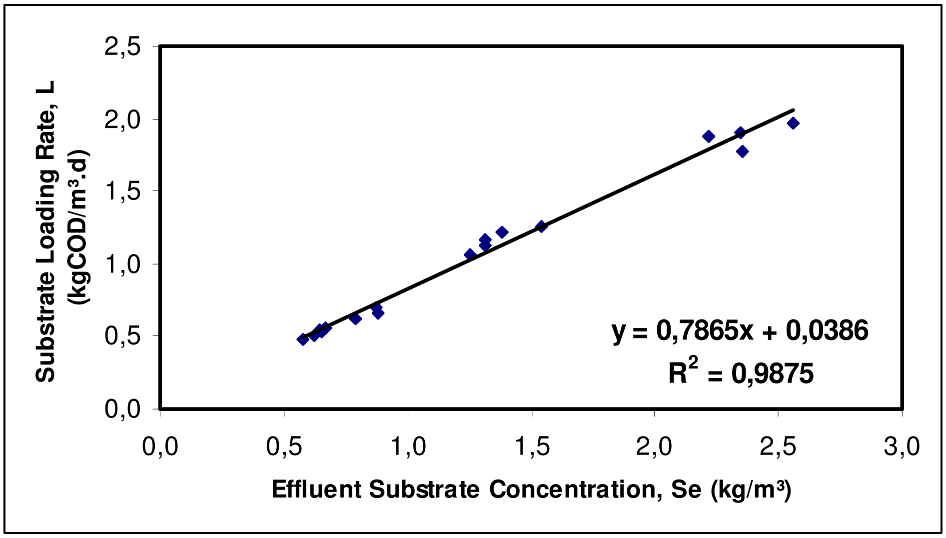


Figure 4.35 Plot of organic (substrate) loading rate as a function of effluent substrate concentration for COD, HRT = 2 days, evaluation of the DeWalle & Chian model for AFR 75

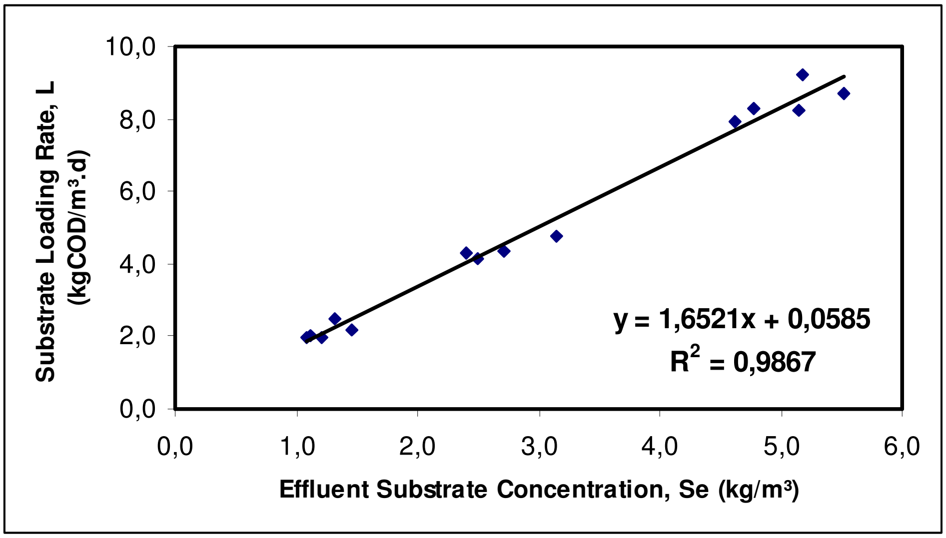


Figure 4.36 Plot of organic (substrate) loading rate as a function of effluent substrate concentration for COD, HRT = 1 day, evaluation of the DeWalle & Chian model for AFR 75

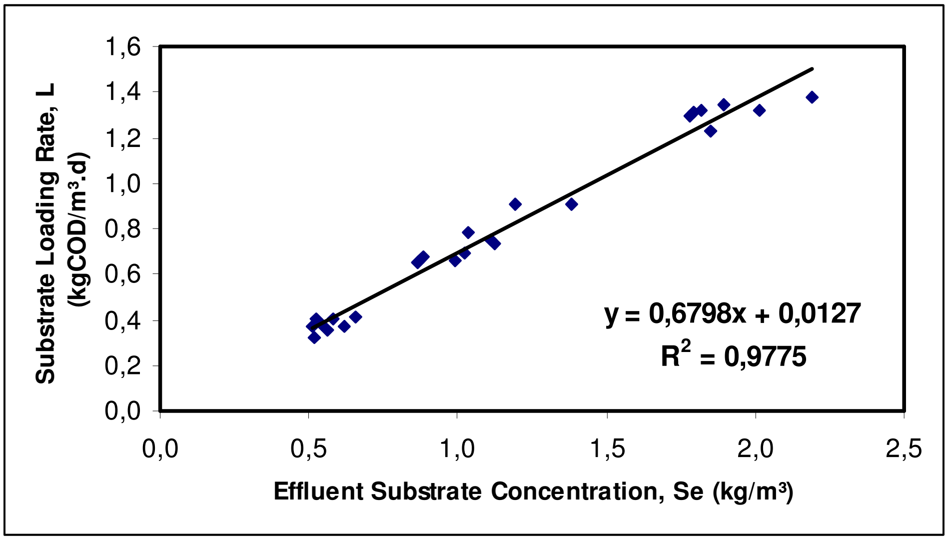


Figure 4.37 Plot of organic (substrate) loading rate as a function of effluent substrate concentration for COD, HRT = 3 days, evaluation of the DeWalle & Chian model for AFR 50

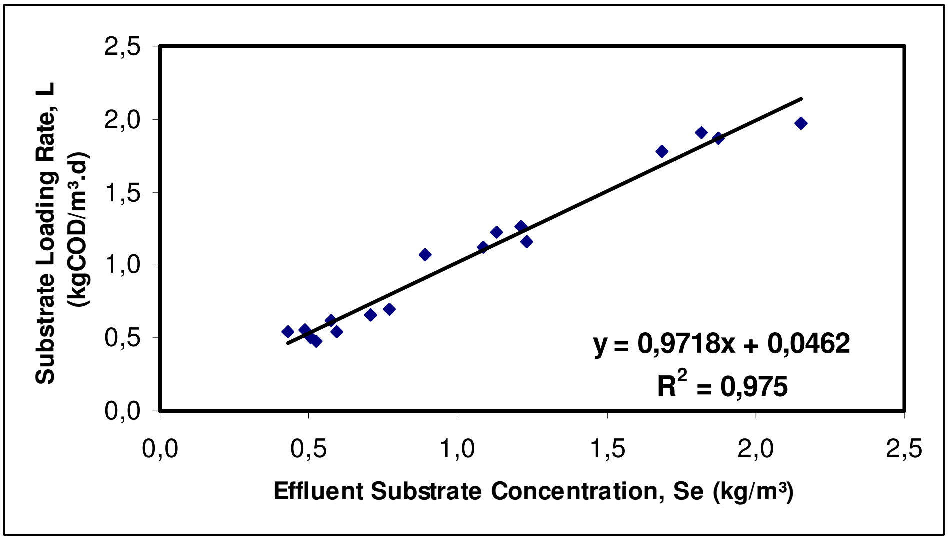


Figure 4.38 Plot of organic (substrate) loading rate as a function of effluent substrate concentration for COD, HRT = 2 days, evaluation of the DeWalle & Chian model for AFR 50

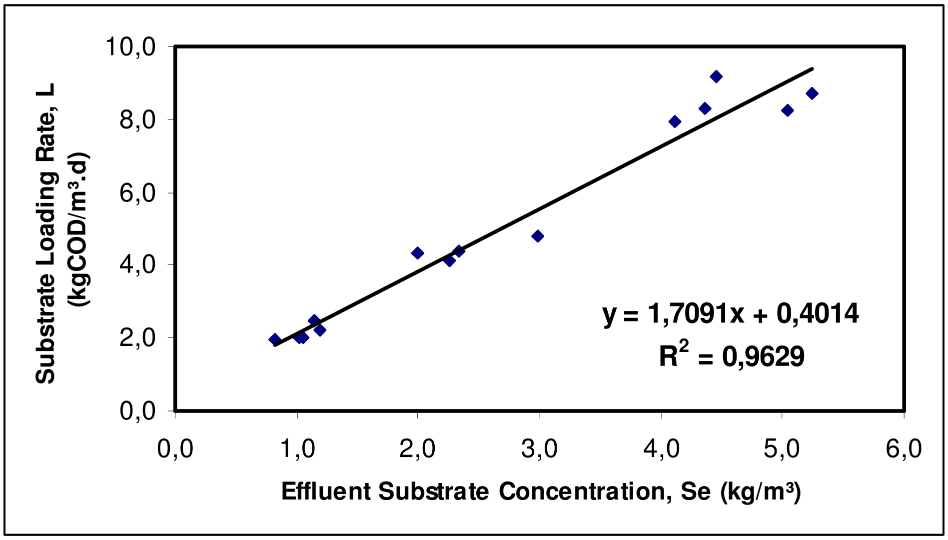


Figure 4.39 Plot of organic (substrate) loading rate as a function of effluent substrate concentration for COD, HRT = 1 day, evaluation of the DeWalle & Chian model for AFR 50

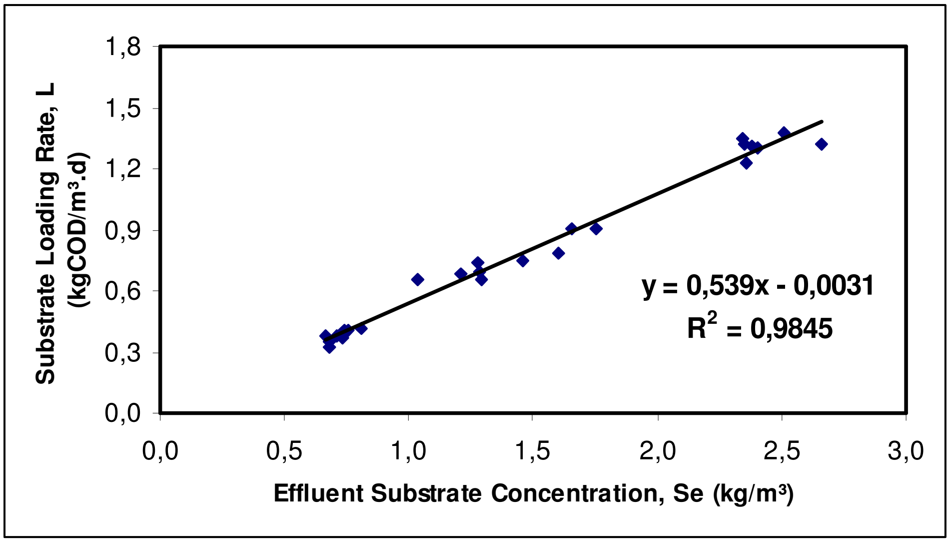


Figure 4.40 Plot of organic (substrate) loading rate as a function of effluent substrate concentration for COD, HRT = 3 days, evaluation of the DeWalle & Chian model for AFR 25

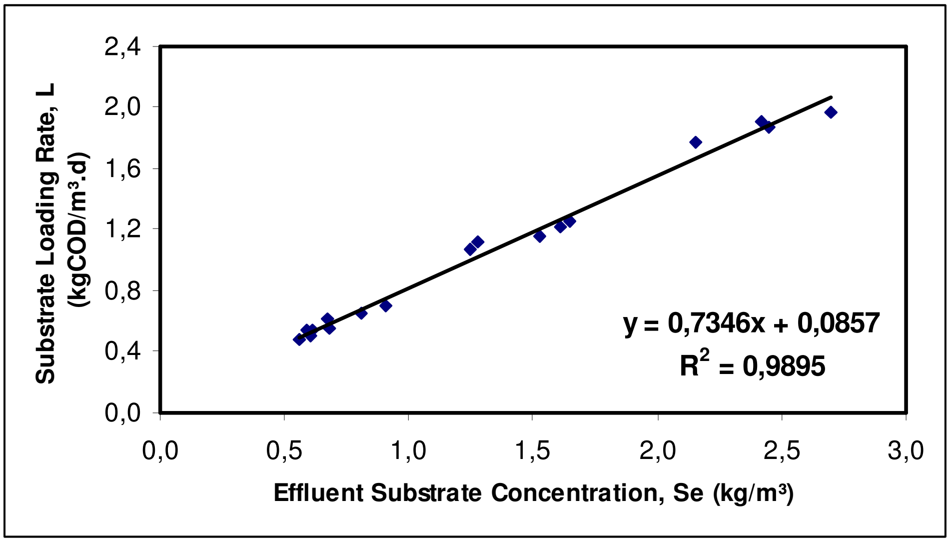


Figure 4.41 Plot of organic (substrate) loading rate as a function of effluent substrate concentration for COD, HRT = 2 days, evaluation of the DeWalle & Chian model for AFR 25

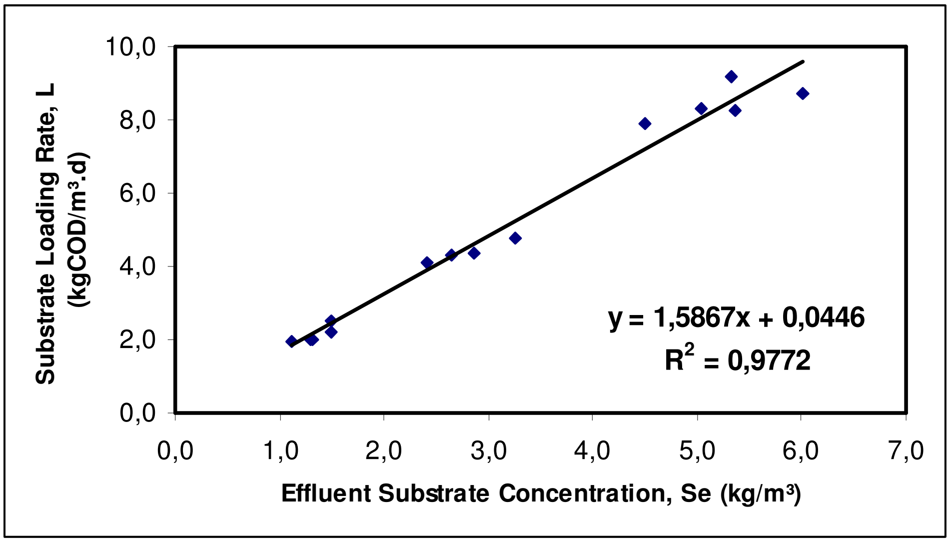


Figure 4.42 Plot of organic (substrate) loading rate as a function of effluent substrate concentration for COD, HRT = 1 day, evaluation of the DeWalle & Chian model for AFR 25

4.2.3 Sundstorm et al Model (Lineweaver – Burk Plot)

The Sundstorm et al Model (Lineweaver – Burk Plot) was applied to data obtained from the experimental studies. A kinetic evaluation was done to the whole reactors.

In defining maximum substrate removal ratio, Monod hyperbolic relation is followed and Se and organic loading rate (1/V.df/dt) were evaluated. Linear relation in this model known also as Lineweaver – Burk Graph is given by Eq. 4.13 and Eq. 4.14 (Nandy & Kaul, 1991).

$$\frac{1}{V}.\frac{df}{dt}=\left[\frac{1}{V}.\frac{df}{dt}\right]_{\max}.\frac{S_e}{K_s+S_e} \qquad (4.13)$$

$$L=L_{\max}\cdot\frac{S_e}{K_s+S_e} \qquad (4.14)$$

Linear regressions were used to determine K_s and L_{max} values. The equation 4.15 can be written by being linearilized Eq. 4.14.

$$\frac{1}{L}=\frac{K_S}{L_{\max}}.\frac{1}{S_e}+\frac{1}{L_{\max}} \qquad (4.15)$$

The values of K_s and L_{max} were obtained from the slope and intercept of the line by plotting $1/L$ versus $1/S_e$ on the graph.

Where; K_s; half saturation concentration, (mg/L)

L_{max}; maximum organic loading rate, (kg/m³.d)

Se; effluent COD concentration, (kg/m³)

L; organic loading rate, (kg/m³.d)

By the application of experimental data to The Sundstorm et al Model, the average maximum organic loading rates (L_{max}) applicable to the model reactor were calculated as 34.97 kgCOD/m³d and 26.21 kgCOD/m³d in AFR 100 and AFR 50, as 48.76 kgCOD/m³d, and 16.8 kgCOD/m³d in AFR 75 and AFR 25, respectively. But the values obtained have thought to be very high for these systems.

From the application of the model, Monod's half saturation values were averagely had as K_s 30756 mg/L and 25440 mg/L in AFR 100 and AFR 50, on the other hand, 36432 mg/L and 28825 mg/L in AFR 75 and AFR 25, respectively. According to data obtained, AFR 75 and AFR 25 have higher K_s values than AFR 100 and AFR 50. Since AFR 75 and AFR 25 achieved lower treatment performance.

The values of L_{max} and K_s for a system similar to our study at ambient temperature were found to be 12.90 kgCOD/m³d and 15325 mg/L on the studies made by Tokgöz, 1998.

Data and figures for all the reactors are given in Figures 4.43 to 4.54.

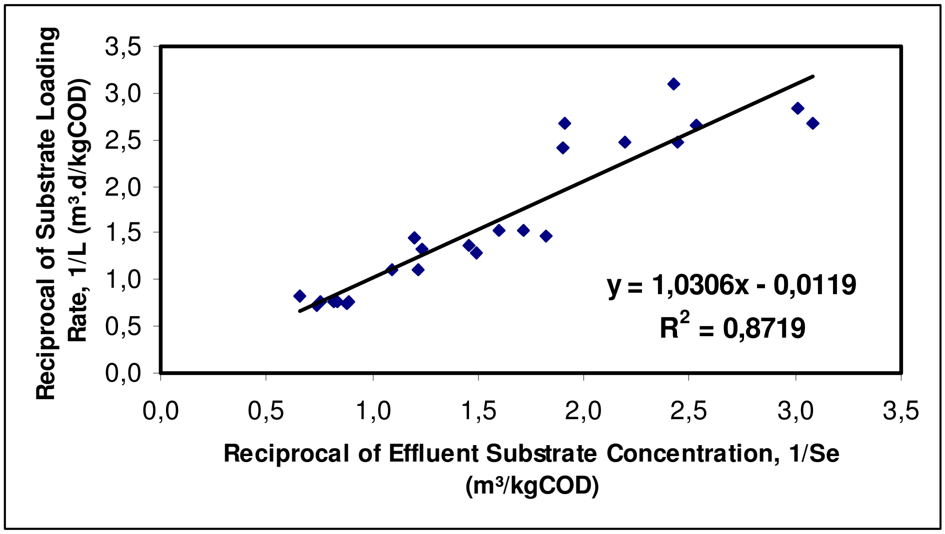


Figure 4.43 Evaluation of maximum organic loading rate for COD, HRT = 3 days, for AFR 100 (Sundstorm Model)

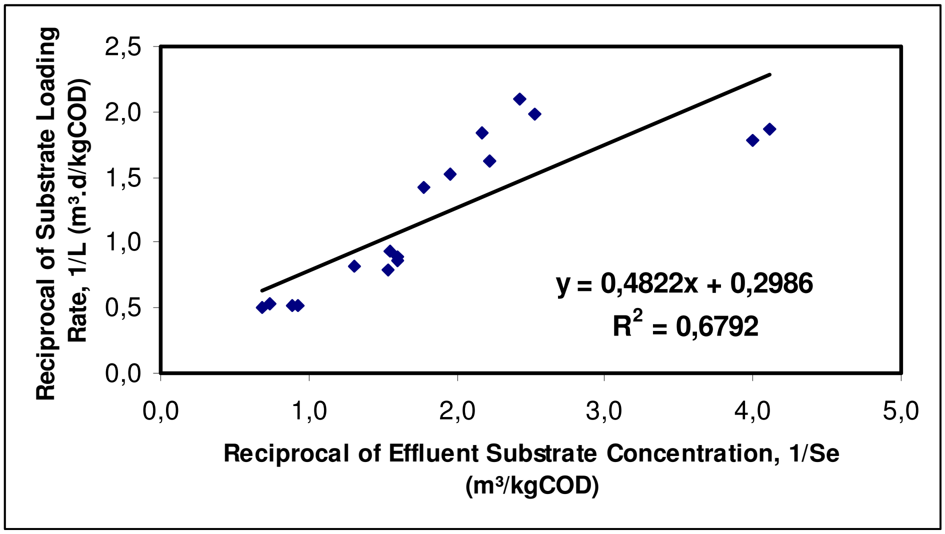


Figure 4.44 Evaluation of maximum organic loading rate for COD, HRT = 2 days, for AFR 100 (Sundstorm Model)

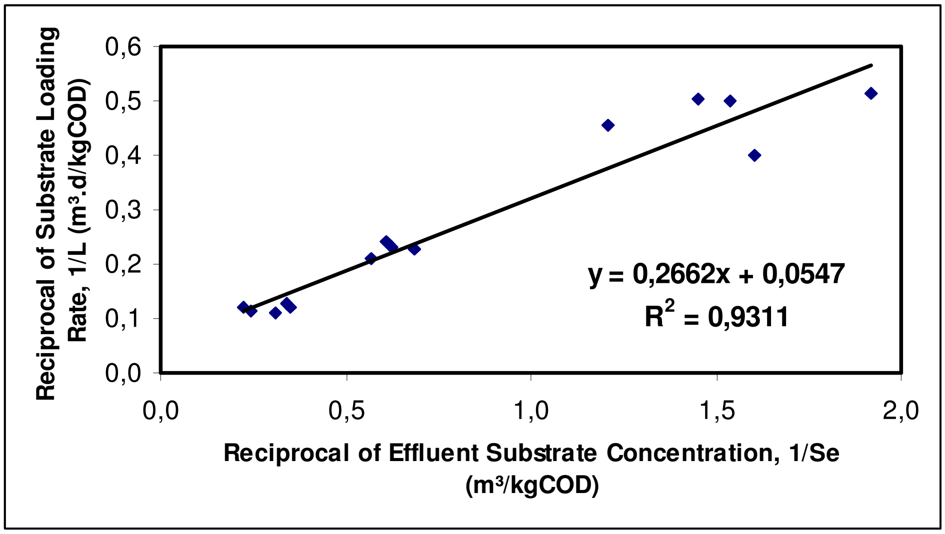


Figure 4.45 Evaluation of maximum organic loading rate for COD, HRT = 1 day, for AFR 100 (Sundstorm Model)

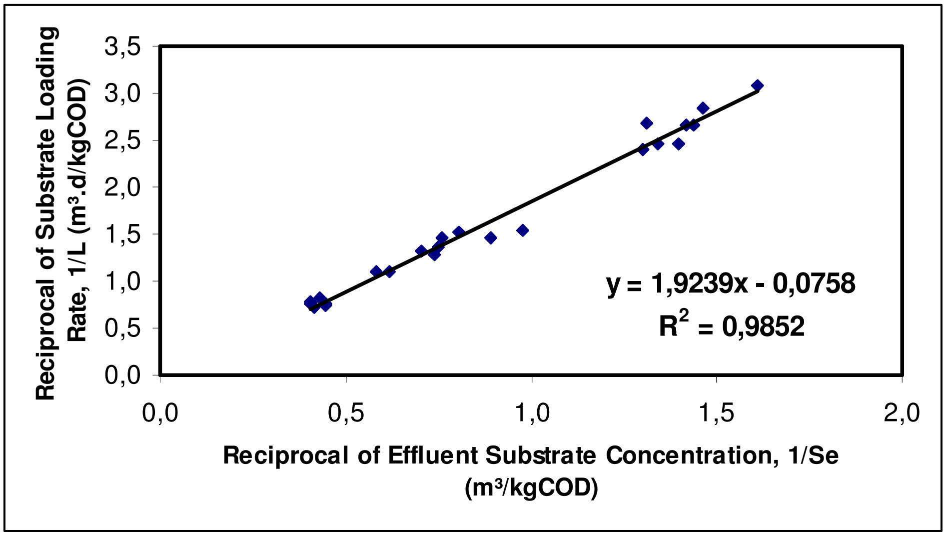


Figure 4.46 Evaluation of maximum organic loading rate for COD, HRT = 3 days, for AFR 75 (Sundstorm Model)

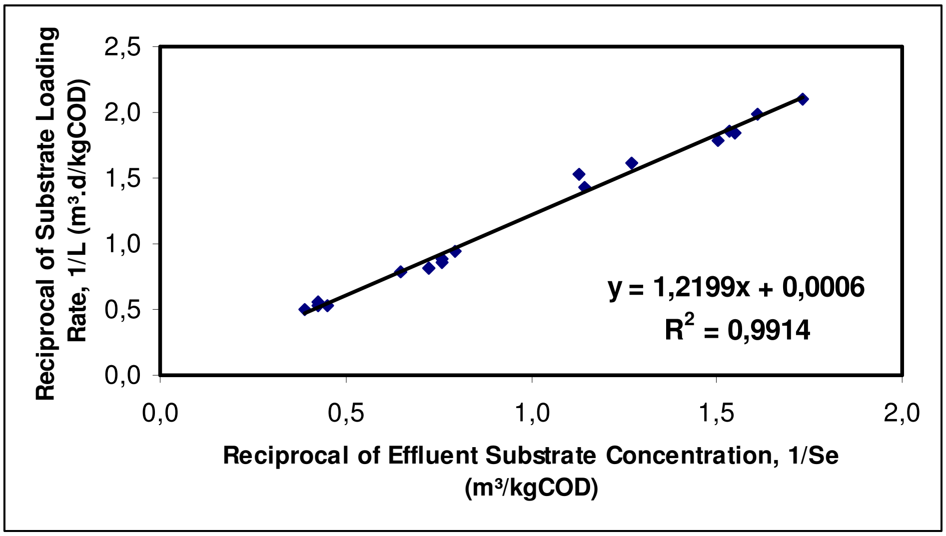


Figure 4.47 Evaluation of maximum organic loading rate for COD, HRT = 2 days, for AFR 75 (Sundstorm Model)

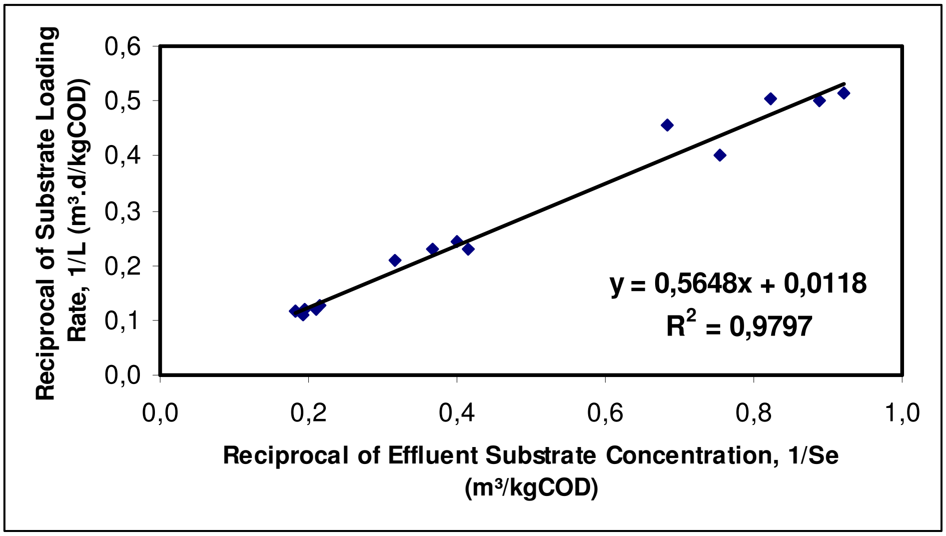


Figure 4.48 Evaluation of maximum organic loading rate for COD, HRT = 1 day, for AFR 75 (Sundstorm Model)

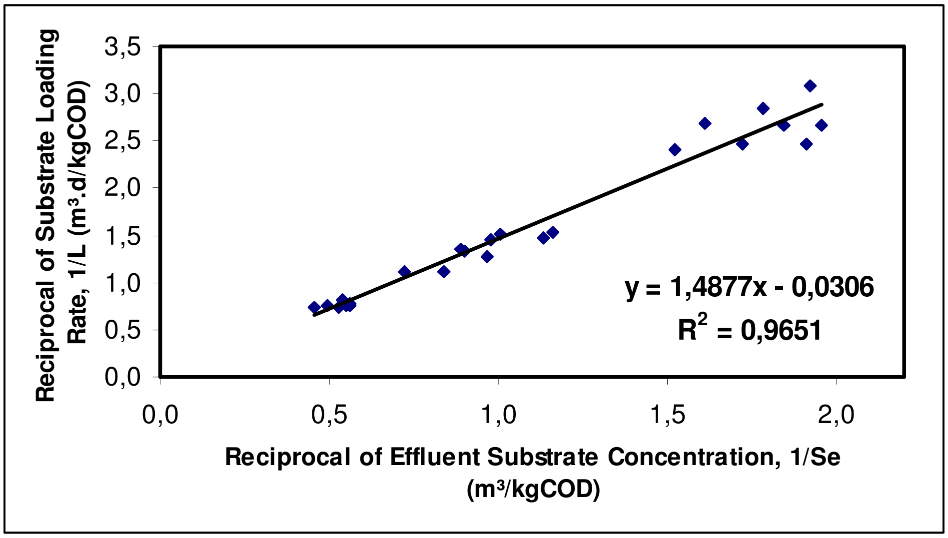


Figure 4.49 Evaluation of maximum organic loading rate for COD, HRT = 3 days, for AFR 50 (Sundstorm Model)

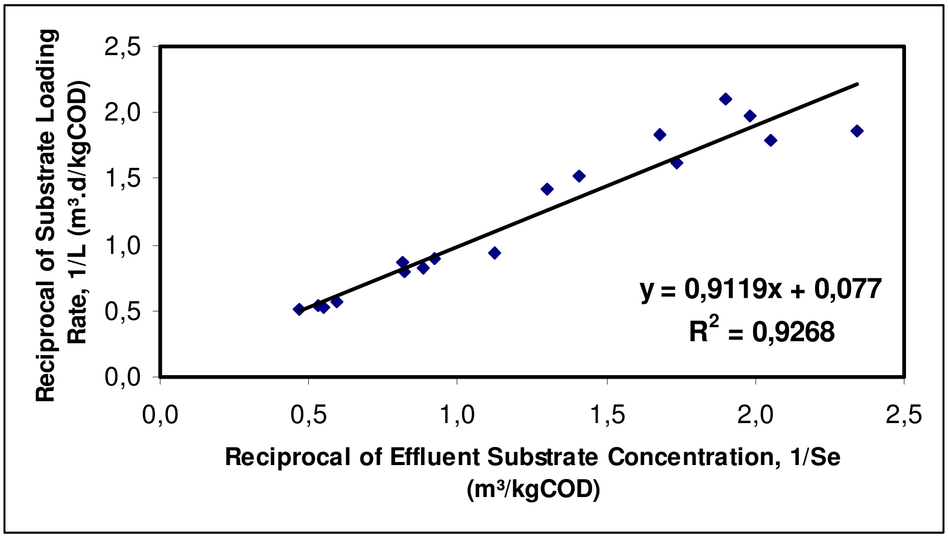


Figure 4.50 Evaluation of maximum organic loading rate for COD, HRT = 2 days, for AFR 50 (Sundstorm Model)

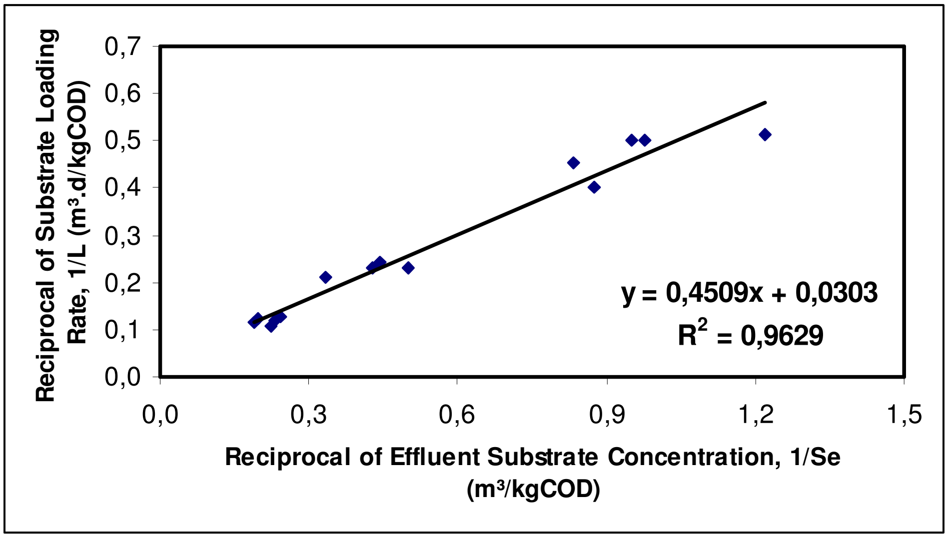


Figure 4.51 Evaluation of maximum organic loading rate for COD, HRT = 1 day, for AFR 50 (Sundstorm Model)

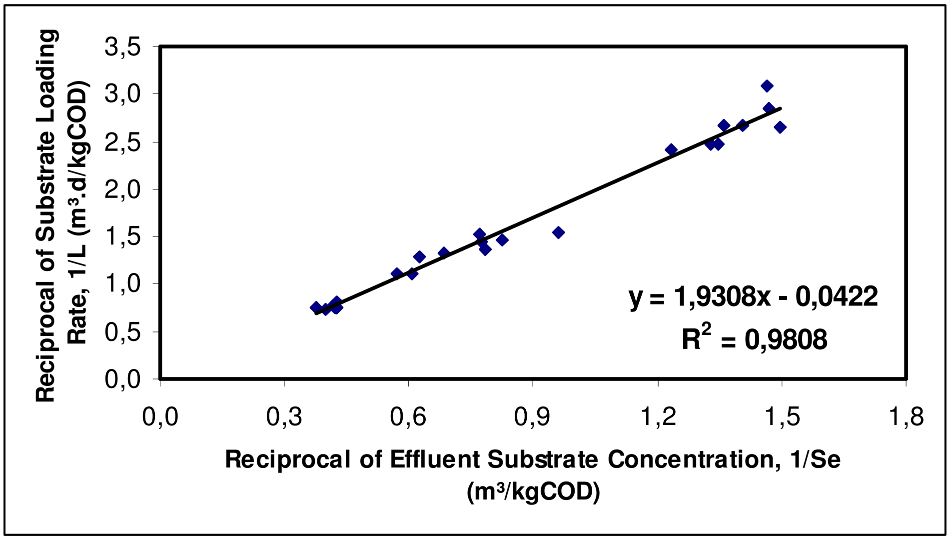


Figure 4.52 Evaluation of maximum organic loading rate for COD, HRT = 3 days, for AFR 25 (Sundstorm Model)

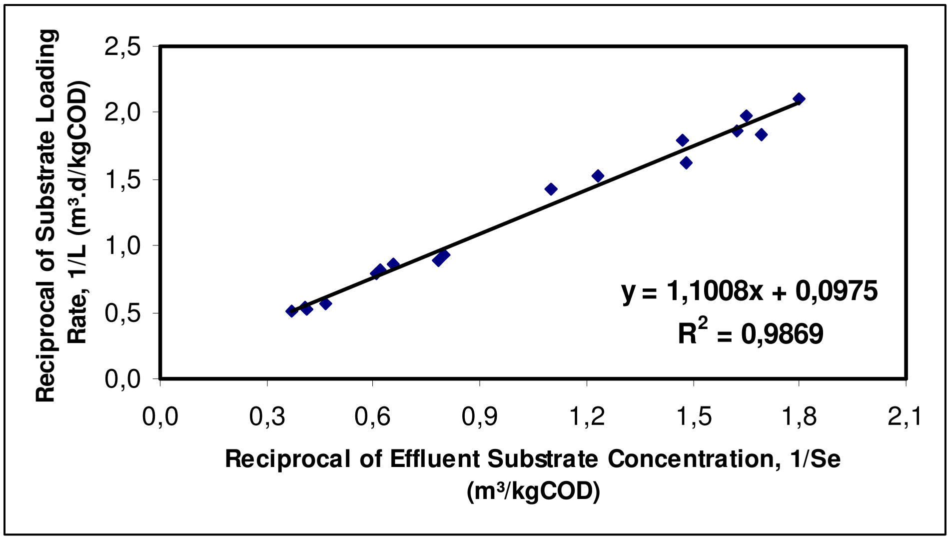


Figure 4.53 Evaluation of maximum organic loading rate for COD, HRT = 2 days, for AFR 25 (Sundstorm Model)

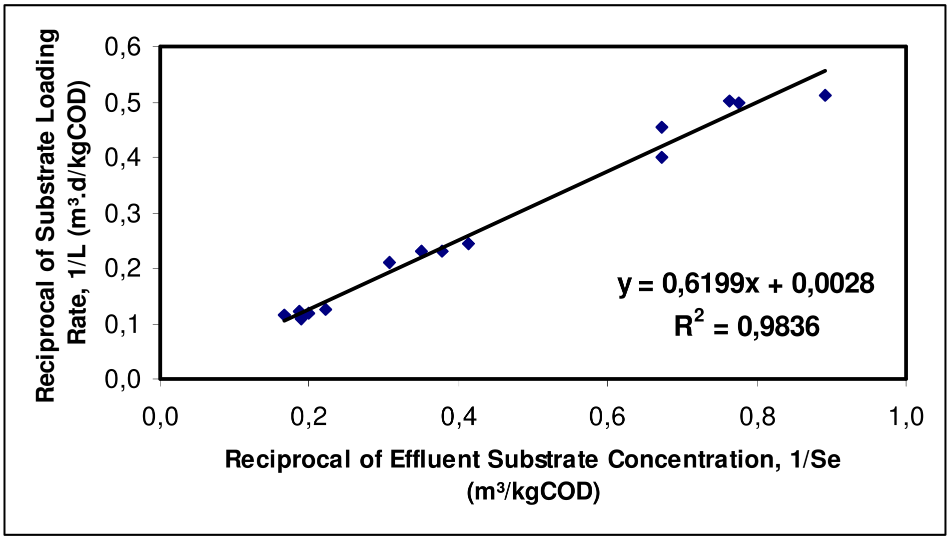


Figure 4.54 Evaluation of maximum organic loading rate for COD, HRT = 1 day, for AFR 25 (Sundstorm Model)

4.2.4 Modified Stover-Kincannon Model

Stover and Kincannon have proposed a design concept of total organic loading rate and established a kinetic model for biofilm reactor. In this model the substrate utilization rate is expressed as a function of the organic loading rate by monomolecular kinetics for biofilm reactors such as biological filters.

The Modified Stover-Kincannon Model was applied to data obtained from the experimental studies. A kinetic evaluation was done to the whole reactors. The mathematical model defines substrate consumption rate as a function of organic loading rate.

$$\frac{ds}{dt} = \frac{U_{\max}(QS_0/V)}{K_B + (QS_0/V)} \tag{4.16}$$

$$U = U_{\max}\cdot\frac{(QS_0/V)}{K_B + (QS_0/V)} \tag{4.17}$$

When the equation given in Eq.4.17 is linearilized, Eq. 4.18 and 4.19 can be written;

$$\frac{V}{Q(S_0 - S_e)} = \frac{K_B}{U_{\max}} \frac{V}{QS_0} + \frac{1}{U_{\max}} \tag{4.18}$$

$$\frac{1}{OLR_{removal}} = \frac{K_B}{U_{\max}} . \frac{1}{OLR} + \frac{1}{U_{\max}} \tag{4.19}$$

Where; U; the specific substrate utilization rate, (kg/m³.d)

U_{max}; the maximum specific substrate utilization rate, (kg/m³.d)

K_B; the model constant, (kg/m³.d)

$OLR_{removal}$; $V/Q(S_o\text{-}S_e)$, substrate utilization rate, (kg/m³.d)

The values of U_{max} and K_B were obtained from the slope and intercept of the line by plotting $1/OLR_{removal}$ versus 1/OLR on the graph.

By the application of experimental data to The Modified Stover-Kincannon Model, the maximum specific substrate utilization rate (U_{max}) applicable to the model reactors were calculated as 11.14 kgCOD/m³d and 13.61 kgCOD/m³d in AFR 100 and AFR 50, on the other hand, 41.85 kgCOD/m³d and 57.16 kgCOD/m³d in AFR 75 and AFR 25, respectively.

From the application of the model, model constant (K_B) was determined as 16.65 kgCOD/m³d and 26.86 kgCOD/m³d in AFR 100 and AFR 50 and was determined as 105.74 kgCOD/m³d and 156.09 kgCOD/m³d in AFR 75 and AFR 25, respectively. These values were calculated with correlation coefficient of about 0.960.

These results show that AFR 75 and AFR 25 which is operated in semi-continuous mode has a much higher maximum utilisation rate constant than AFR 100 and AFR 50 which is operated in continuous mode. On the study by Ahn and Forster, 2000, for anaerobic filters treating starch wastewater at mesophilic temperature, the values of U_{max} and K_B were obtained as 49.8 and 50.6 kgCOD/m³d, respectively.

Data and figures for all the reactors are given in Figures 4.55 to 4.66.

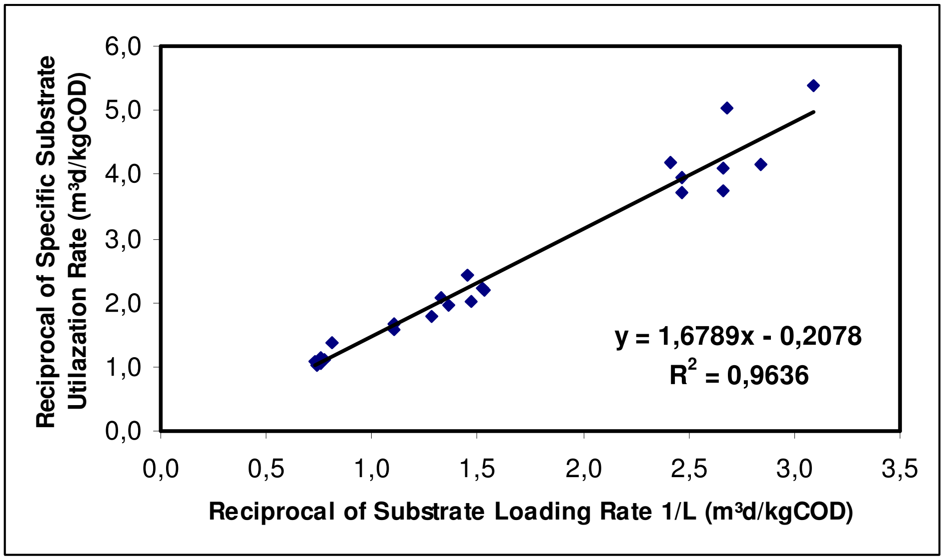


Figure 4.55 Evaluation of maximum specific substrate utilization rate for COD, HRT = 3 days, for AFR 100 (Modified Stover-Kincannon Model)

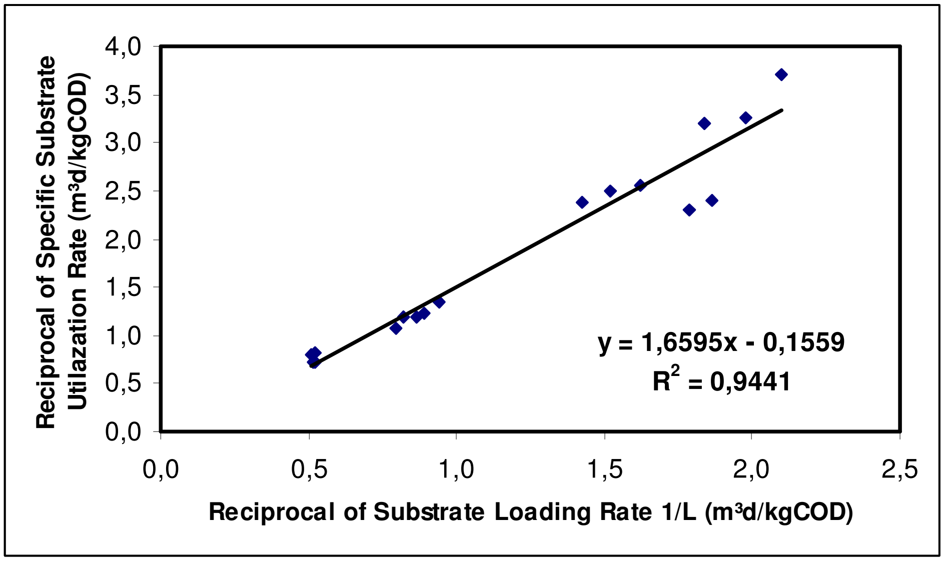


Figure 4.56 Evaluation of maximum specific substrate utilization rate for COD, HRT = 2 days, for AFR 100 (Modified Stover-Kincannon Model)

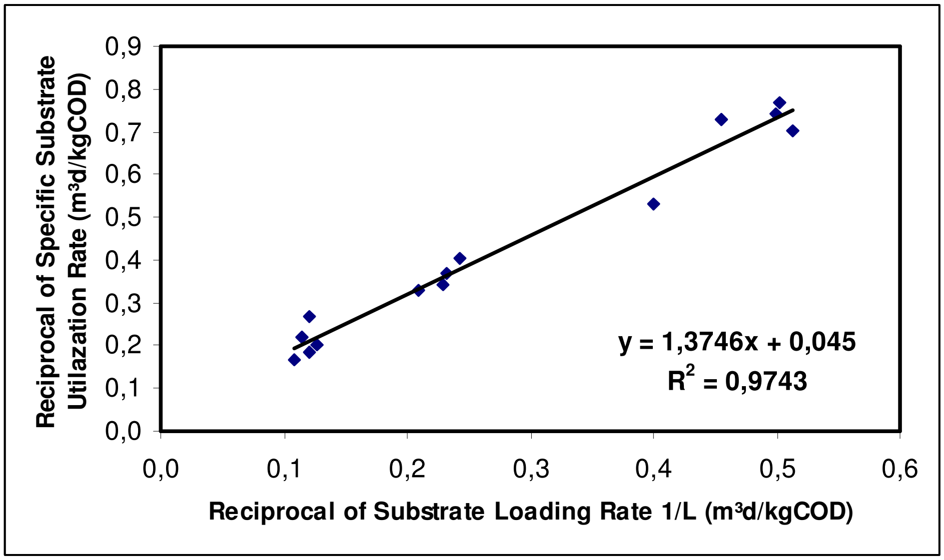


Figure 4.57 Evaluation of maximum specific substrate utilization rate for COD, HRT = 1 day, for AFR 100 (Modified Stover-Kincannon Model)

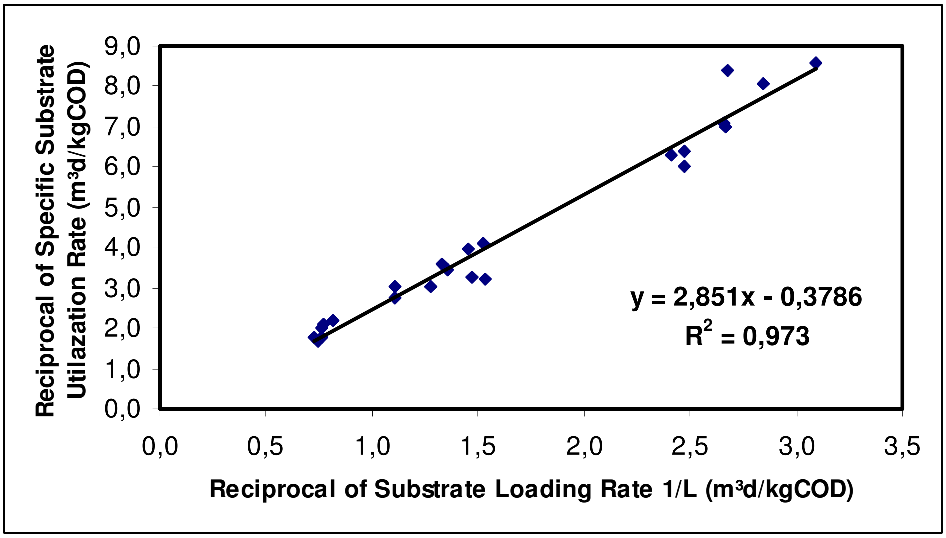


Figure 4.58 Evaluation of maximum specific substrate utilization rate for COD, HRT = 3 days, for AFR 75 (Modified Stover-Kincannon Model)

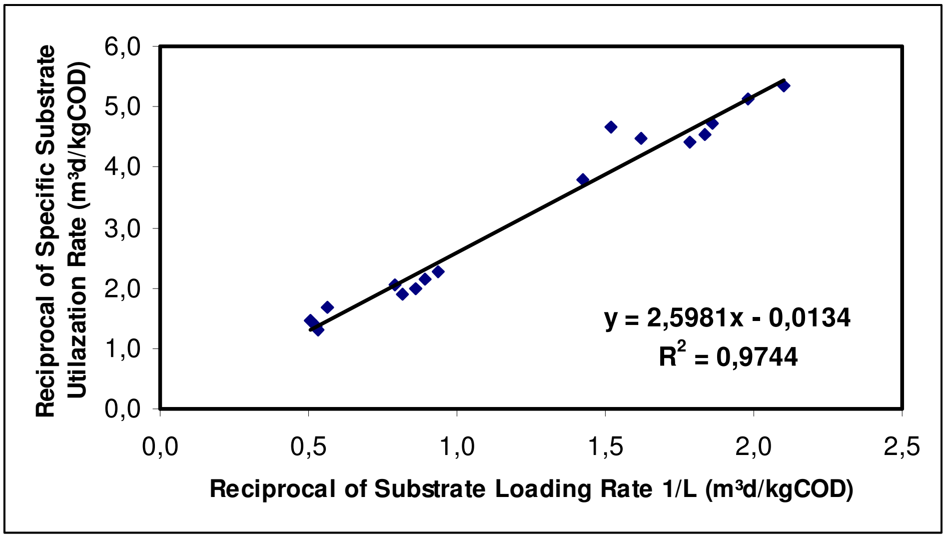


Figure 4.59 Evaluation of maximum specific substrate utilization rate for COD, HRT = 2 days, for AFR 75 (Modified Stover-Kincannon Model)

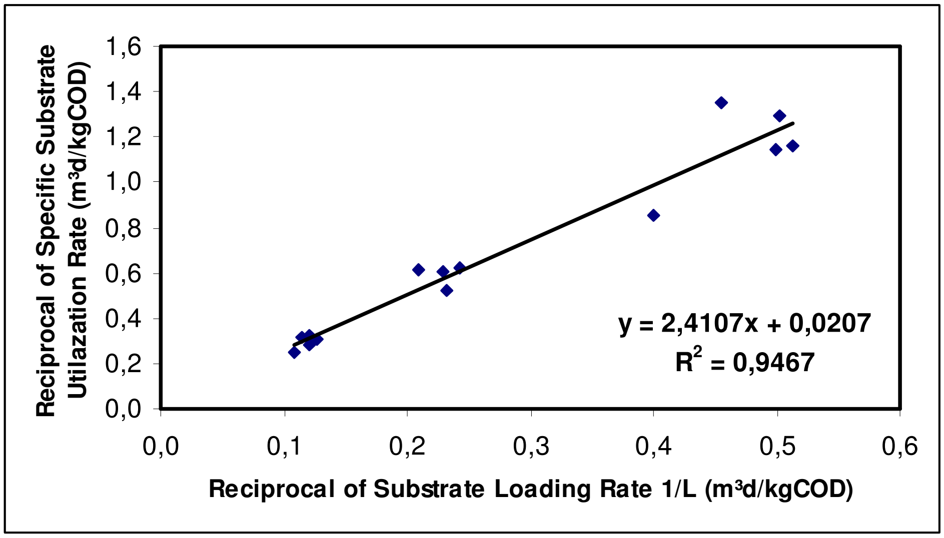


Figure 4.60 Evaluation of maximum specific substrate utilization rate for COD, HRT = 1 day, for AFR 75 (Modified Stover-Kincannon Model)

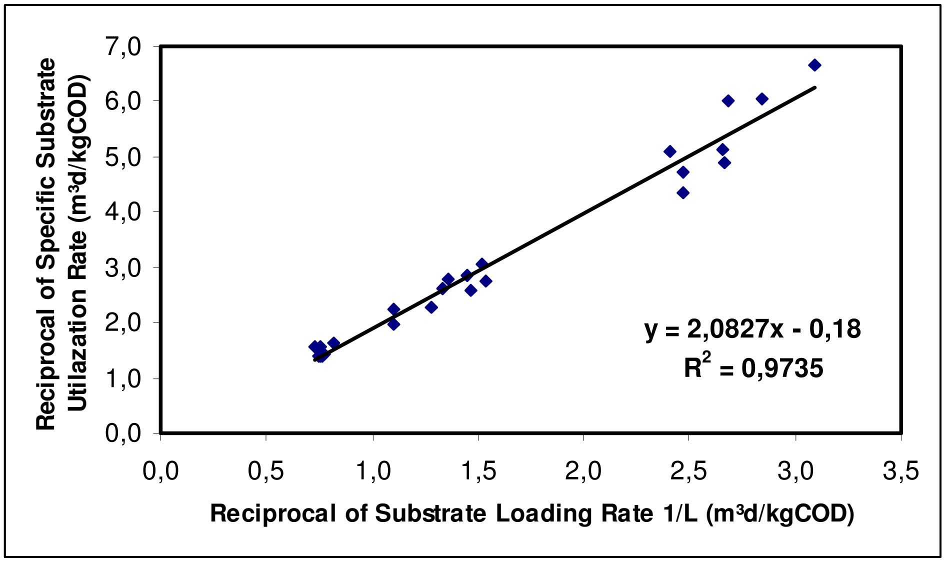


Figure 4.61 Evaluation of maximum specific substrate utilization rate for COD, HRT = 3 days, for AFR 50 (Modified Stover-Kincannon Model)

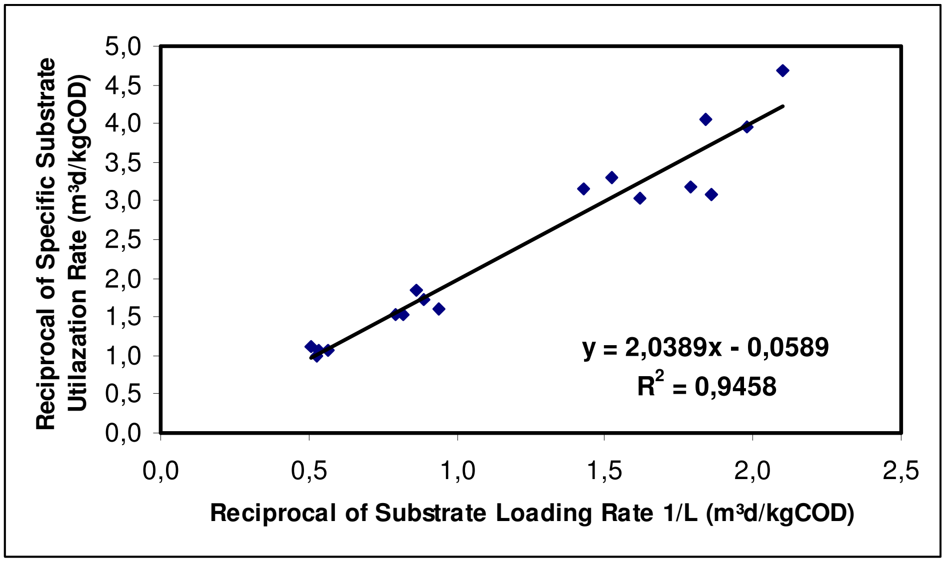


Figure 4.62 Evaluation of maximum specific substrate utilization rate for COD, HRT = 2 days, for AFR 50 (Modified Stover-Kincannon Model)

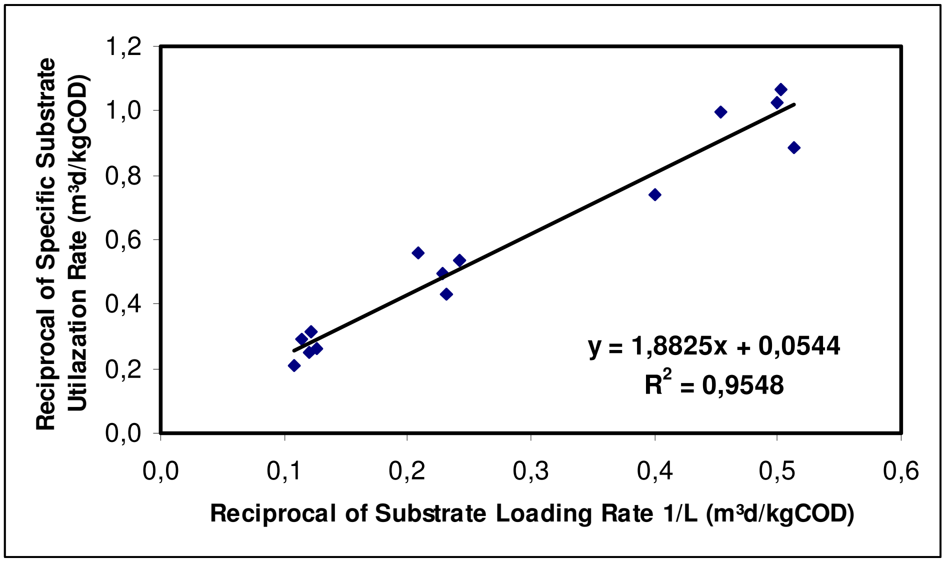


Figure 4.63 Evaluation of maximum specific substrate utilization rate for COD, HRT = 1 day, for AFR 50 (Modified Stover-Kincannon Model)

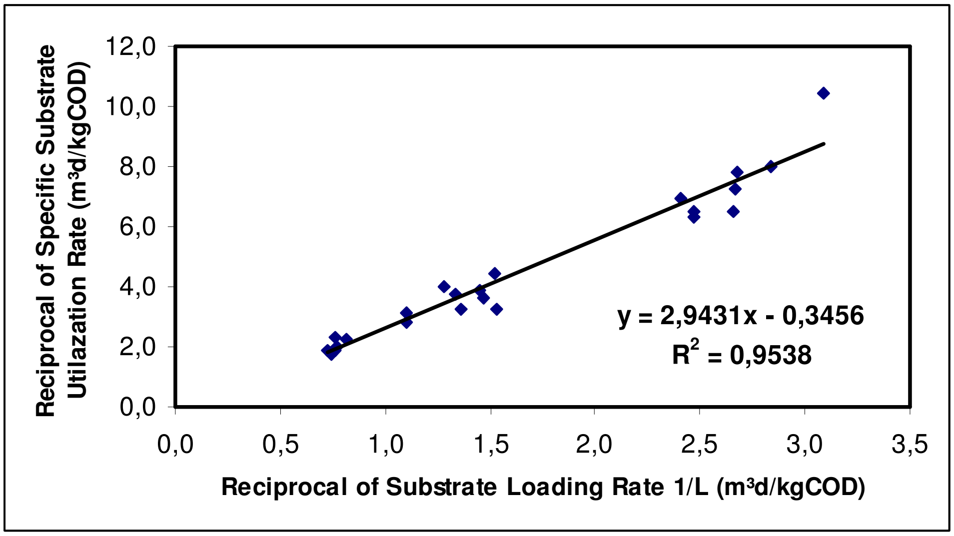


Figure 4.64 Evaluation of maximum specific substrate utilization rate for COD, HRT = 3 days, for AFR 25 (Modified Stover-Kincannon Model)

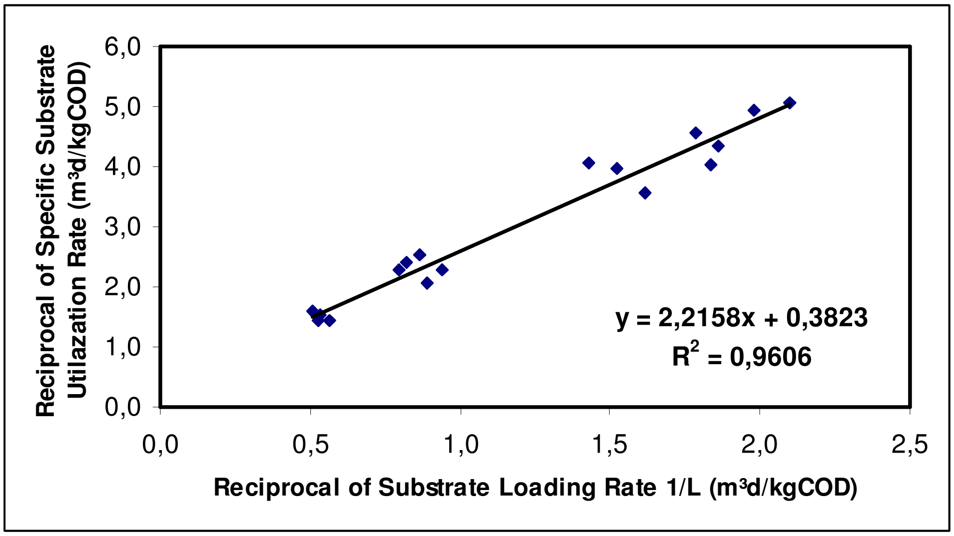


Figure 4.65 Evaluation of maximum specific substrate utilization rate for COD, HRT = 2 days, for AFR 25 (Modified Stover-Kincannon Model)

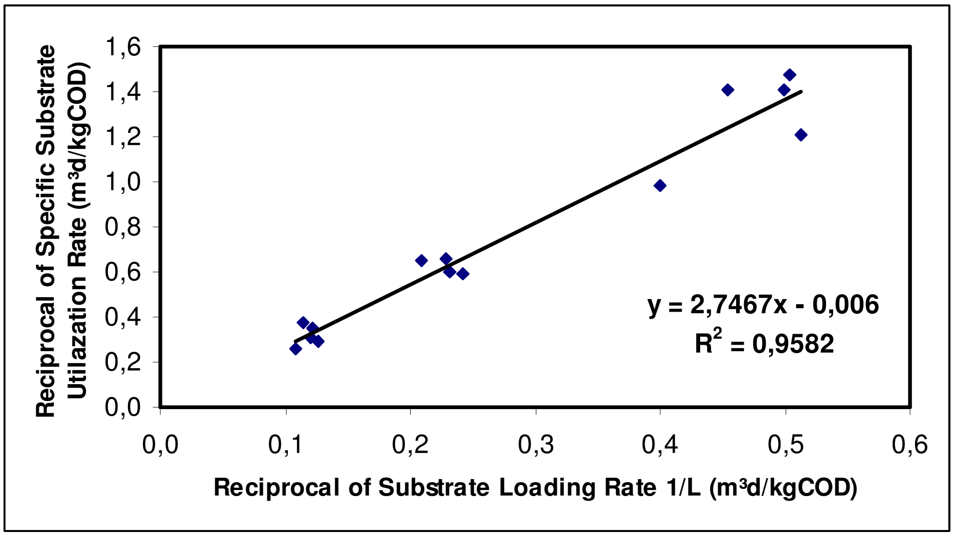


Figure 4.66 Evaluation of maximum specific substrate utilization rate for COD, HRT = 1 day, for AFR 25 (Modified Stover-Kincannon Model)

CHAPTER FIVE
CONCLUSION AND RECOMMEDATIONS

In this study, design and performance parameters such as filter material ratio, organic loading rate, hydraulic retention time and temperature were evaluated at four upflow anaerobic filter reactors having different filter material ratio.

The four anaerobic filter reactors having different filter material ratio, AFR 100, AFR 75, AFR 50 and AFR 25, were operated at HRT of 3 days, 2 days and 1 day, respectively. At three HRT values as well, the highest COD removal efficiencies were achieved in AFR 100 and the lowest COD removal efficiencies were obtained in AFR 25.

The filter reactors, AFR 100 and AFR 50, having the operation mode which was continuous mode reached better COD removal efficiencies than the filter reactors, AFR 75 and AFR 25, having the operation mode which was semi-continuous mode.

When organic loading rate applied to reactors were increased from 0.333 kgCOD/m^{3}d to 8.000 kgCOD/m^{3}d, the COD removal efficiency was observed to decrease. At the same time, being decreased of the hydraulic retention time as well negatively affected the reactors in terms of the COD removal efficiency. When studied COD removal efficiencies of the whole reactors, it can be seen that the COD removal efficiencies decrease in all the reactors at hydraulic retention time of 1 day. The reactor which the removal efficiency decreased at most is AFR 100. Decreasing removal efficiencies in other reactors are lower than AFR 100.

The four filter reactors were operated at psychrophilic temperature, which was controlled by the heater. It has understood that negative effects of the psychrophilic temperature interval were not too much. On the other hand, although the organic loading rate was increased, the COD removal efficiency did not alter because temperature as well increased.

In consequence of the experiments made, when discussed reactors which was AFR 100 and AFR 50 operated in continuous mode. The COD removal efficiencies of AFR 100 varied between 53 and 71% and the COD removal efficiencies of AFR 50 varied between 45 and 57% at HRT= 3 days and OLR = 0.333 kgCOD/m³d. Removal efficiencies of AFR 100 varied between 60 and 73% and COD removal efficiencies of AFR 50 varied between 49 and 57% at HRT= 3 days and OLR = 0.666 kgCOD/m³d. Removal efficiencies of AFR 100 varied between 59 and 72% and the COD removal efficiencies of AFR 50 varied between 47 and 55% at HRT= 3 days and OLR = 1.333 kgCOD/m³d.

The COD removal efficiencies of AFR 100 varied between 57 and 78% and the COD removal efficiencies of AFR 50 varied between 45 and 60% at HRT= 2 days and OLR = 0.500 kgCOD/m³d. Removal efficiencies of AFR 100 varied between 69 and 74%, the COD removal efficiencies of AFR 50 varied between 47 and 58% At HRT= 2 days and OLR = 1.000 kgCOD/m³d. Removal efficiencies of AFR 100 varied between 63 and 72%, the COD removal efficiencies of AFR 50 varied between 45 and 53% at HRT= 2 days and OLR = 2.000 kgCOD/m³d.

The COD removal efficiencies of AFR 100 varied between 62 and 75% and the COD removal efficiencies of AFR 50 varied between 46 and 58% at HRT= 1 days and OLR = 2.000 kgCOD/m³d. Removal efficiencies of AFR 100 varied between 60 and 67% and the COD removal efficiencies of AFR 50 varied between 38 and 54% at HRT=1 days and OLR = 4.000 kgCOD/m³d. Removal efficiencies of AFR 100 varied between 45 and 66% and the COD removal efficiencies of AFR 50 varied between 39 and 52% at HRT= 1 days and OLR = 8.000 kgCOD/m³d.

In consequence of the experiments made, when discussed reactors which was AFR 75 and AFR 25 operated in semi-continuous mode. The COD removal efficiencies of AFR 75 varied between 32 and 41% and the COD removal efficiencies of AFR 25 varied between 30 and 41% at HRT= 3 days and OLR = 0.333 kgCOD/m³d. The COD removal efficiencies of AFR 75 varied between 36 and 48% and the COD removal efficiencies of AFR 25 varied between 32 and 47% at

HRT= 3 days and OLR = 0.666 kgCOD/m³d. The COD removal efficiencies of AFR 75 varied between 37 and 45% and the COD removal efficiencies of AFR 25 varied between 33 and 42% at HRT= 3 days and OLR = 1.333 kgCOD/m³d.

The COD removal efficiencies of AFR 75 varied between 33 and 41% and the COD removal efficiencies of AFR 25 varied between 35 and 46% at HRT= 2 days and OLR = 0.500 kgCOD/m³d. The COD removal efficiencies of AFR 75 varied between 39 and 43% and the COD removal efficiencies of AFR 25 varied between 34 and 43% at HRT= 2 days and OLR = 1.000 kgCOD/m³d. COD removal efficiencies of AFR 75 varied between 34 and 41% and the COD removal efficiencies of AFR 25 varied between 32 and 39% at HRT= 2 days and OLR = 2.000 kgCOD/m³d.

The COD removal efficiencies of AFR 75 varied between 34 and 47% and the COD removal efficiencies of AFR 25 varied between 32 and 43% at HRT= 1 days and OLR = 2.000 kgCOD/m³d. the COD removal efficiencies of AFR 75 varied between 34 and 44% and the COD removal efficiencies of AFR 25 varied between 32 and 41% at HRT=1 days and OLR = 4.000 kgCOD/m³dthe COD removal efficiencies of AFR 75 varied between 37 and 44% and the COD removal efficiencies of AFR 25 varied between 31 and 43% at HRT= 1 days and OLR = 8.000 kgCOD/m³d.

According to the results and the data obtained form experimental and literature studies, filter material ratio affected COD removal efficiencies at the treatment performance of anaerobic filters. Especially, the removal efficiencies of anaerobic filter filled fully are more than the anaerobic filter having different filter material ratio. On the other hands, the operation mode of the anaerobic filters as well is significant from the point of COD removal efficiencies. The removal performance of filters operated as continuous mode is higher than anaerobic filter operated as semi-continuous mode. Moreover, it is incontestable that the temperature is effective on treatment performance. It follows from data obtained that temperature positively increases COD removal efficiencies.

By the application of experimental data to the second order kinetic model, model equation for AFR 100, AFR 75, AFR 50 and AFR 25, respectively, has found to be for the study. The model data were obtained by plotting HRT*So/(So-Se) versus HRT. HRT*So/(So-Se) values of model were estimated by the help of graphs plotted. Modeling values and equations belong to systems are given in the followings Eq. 5.1 to 5.4.

$$S_{\text{mod}\,el} = S_0\left(1 - \frac{HRT}{1.4837 * HRT + 0.0796}\right) \text{ for AFR 100.} \qquad (5.1)$$

$$S_{\text{mod}\,el} = S_0\left(1 - \frac{HRT}{2.5928 * HRT - 0.06}\right) \text{ for AFR 75.} \qquad (5.2)$$

$$S_{\text{mod}\,el} = S_0\left(1 - \frac{HRT}{1.8548 * HRT + 0.2783}\right) \text{ for AFR 50.} \qquad (5.3)$$

$$S_{\text{mod}\,el} = S_0\left(1 - \frac{HRT}{2.674 * HRT + 0.1488}\right) \text{ for AFR 25.} \qquad (5.4)$$

In this experimental study, average removal rate constant K_2 (A/V) in psychrophilic temperature was found to be 1.490 d^{-1} and 1.120 d^{-1} for AFR 100 and AFR 50 and was found to be 1.001 d^{-1} and 0.984 d^{-1} for AFR 75 and AFR 25, respectively, by the help of the DeWalle & Chian model.

The value for AFR 100 is higher than the values of other reactors; AFR 50 has second high value, because AFR 100 and AFR 50 were operated as continuous mode and the AFR 100 is full with the filter materials. On the other hand, temperature is effective on the removal rate constant K_2 (A/V), when temperature is increased, it will increase.

Removal rate constant K_2 (A/V) was determined as 2.05 d^{-1} for anaerobic filter treating synthetic wastewater containing molasses (Tokgöz, 1998). Similarly, the value was denoted as 0.910 d^{-1} in the study which Nandy & Kaul (1991) have worked with herbal pharmaceutical.

By the application of experimental data to The Sundstorm et al Model, the average maximum organic loading rates (L_{max}) applicable to the model reactor were calculated as 34.97 kgCOD/m³d and 26.21 kgCOD/m³d in AFR 100 and AFR 50, as 48.76 kgCOD/m³d, and 16.8 kgCOD/m³d in AFR 75 and AFR 25, respectively. But the values obtained have thought to be very high for these systems.

From the application of the model, Monod's half saturation values were averagely had as K_s 30756 mg/L and 25440 mg/L in AFR 100 and AFR 50, on the other hand, 36432 mg/L and 28825 mg/L in AFR 75 and AFR 25, respectively. According to data obtained, AFR 75 and AFR 25 have higher K_s values than AFR 100 and AFR 50. Since AFR 75 and AFR 25 achieved lower treatment performance.

The values of L_{max} and K_s for a system similar to our study at ambient temperature were found to be 12.90 kgCOD/m³d and 15325 mg/L on the studies made by Tokgöz, 1998.

By the application of experimental data to The Modified Stover-Kincannon Model, the maximum specific substrate utilization rate (U_{max}) applicable to the model reactors were calculated as 11.14 kgCOD/m³d and 13.61 kgCOD/m³d in AFR 100 and AFR 50, on the other hand, 41.85 kgCOD/m³d and 57.16 kgCOD/m³d in AFR 75 and AFR 25, respectively. Model constant (K_B) was determined as 16.65 kgCOD/m³d and 26.86 kgCOD/m³d in AFR 100 and AFR 50 and was determined as 105.74 kgCOD/m³d and 156.09 kgCOD/m³d in AFR 75 and AFR 25, respectively. These values were calculated with correlation coefficient of about 0.960. In a same way, the values of U_{max} and K_B were obtained as 49.8 and 50.6 kgCOD/m³d, respectively, on the study by Ahn and Forster, 2000, for anaerobic filters treating starch wastewater at mesophilic temperature

These results show that AFR 75 and AFR 25 which is operated in semi-continuous mode has a much higher maximum utilisation rate constant than AFR 100 and AFR 50 which is operated in continuous mode.

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