UNIVERSITY OF NAIROBI

STUDY OF TREATMENT OF HIGH-STRENGTH INDUSTRIAL WASTEWATER BY A RECYCLED BIOMASS ANAEROBIC PROCESS

A CASE STUDY OF THIKA BREWERY)

BY

DANIEL MURIITHI MIGWI

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ABSTRACT

Performance and effectiveness of anaerobic process with biomass recycle, analogous to activated sludge process, in the treatment of high-strength brewery wastewater was investigated. Using laboratory bench scale anaerobic digester, at organic loading rate in the range of 0.29 to 10 kg COD $m^{-3}d^{-1}$ which was much higher than the theoretical values in the conventional anaerobic process (completely stirred tank reactor), that ranges between 0.25 to 3.00 kg COD $m^{-3}d^{-1}$.

The experimental results showed the recycled process achieved a percentage COD removal of between 86% and 95% while the conventional anaerobic process achieved between 66% and 84.2% for the same range of volumetric loading rate. The recycled process had a shorter start-up time and responded much better to changes in both hydraulic and organic loading rates.

Gas production was higher in the recycled process than in the conventional process. The methane yield at standard temperature (20°C) ranged between 0.25 and 0.32 m^3/kg COD removed for the recycled process while it was between 0.19 and 0.30 m^3/kg COD removed for the conventional process. Comparing the experimental results most of the COD removed was converted to methane as opposed to biomass synthesis. This also resulted in less sludge production for the recycled process.

The results of the study show that anaerobic process with biomass recycle holds potential for treatment of high-strength industrial wastewater like brewery effluent. However, a pilot plant study would be necessary in order to obtain operational and design parameters for a full-scale operation.

DECLARATION

I certify that this thesis is my original work and it has not been submitted for a degree in any other university.

D. Muriithi Migwi

CANDIDATE

This thesis has been submitted for examination with my approval as the university supervisor.

Dr. B. N. K. Njoroge

SUPERVISOR

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DEDICATION

Winnie, my fiancée, observed that it is a good idea to give your efforts time to compound before you quit, success may be just after your next single action. She took the project as her own and put extraordinary hours and matchless concern into its completion. Her words of encouragement still remain a source of continuing inspiration.

To Winnie, a lovely lady, who caught my eye long time back, and has held my heart ever since, this is dedicated.

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NOTATIONS

WHO	:	World Health Organisation
UNEP	:	United Nations Environmental Programme
UNEP-IE	:	United Nations Environmental Programme Industry and Environment
BOD_5	:	Five-day Biological Oxygen Demand at 20^0c
COD	:	Chemical Oxygen Demand
SS	:	Suspended Solids
VSS	:	Volatile Suspended Solids
VS	:	Volatile Solids
MLSS	:	Mixed Liquor Suspended Solids
MLVSS	:	Mixed Liquor Volatile Suspended Solids
θ	:	Hydraulic Retention Time
θ_c	:	Mean Cell Residence Time
HRT	:	Hydraulic Retention Time
MCRT	:	Mean Cell Residence Time
SRT	:	Solid Retention Time
CMFR	:	Completely Mixed Flow Reactor
CSTR	:	Completely Stirred Tank Reactor
PFR	:	Plug Flow Reactor
UASB	:	Upflow Anaerobic Sludge Blanket
kg	:	Mass, kilograms
mg/l	:	Milligrams per litre
^0C	:	Temperature, degrees centigrade
d^{-1}	:	per day
t^{-1}	:	per time
m^3	:	Volume, cubic metre
m^{-3}	:	per cubic metre
$m^3/kg/d$	:	cubic metre per kilogram per day
CO_2	:	Carbon Dioxide
O_2	:	Oxygen
H_2O	:	Water
CH_4	:	Methane
N	:	Nitrogen
P	:	Phosphorus

1 INTRODUCTION

1.1 General

Rapid industrial development has not only brought prosperity to mankind, but has resulted in environmental pollution which is now a major threat to the very prosperity it is intended to advance. Prime to this, is the pollution of fresh water sources caused by domestic and by industrial wastes. Domestic wastewater treatment is generally well appreciated and has continued to receive the necessary attention mainly from local authorities. In developing countries, industrial wastewater has been receiving relatively little attention and its more often than not discharged into existing municipal sewage system or directed into surface water bodies. With the increased demand of fresh water, which is relatively scarce, more attention is being focused on the conservation of the limited fresh water sources. This has therefore lead to a general campaign aimed at reduction of the pollution load to the environment. Consequently industries in many parts of the world are being called upon to meet a minimum pre-treatment level before releasing their wastewater into the municipal system for further treatment. The alternative is to meet the set minimum standards if they are to discharge directly into the surface water bodies.

Unlike the past, public awareness on environmental conservation is increasing, a situation that will prompt authorities in the world to be duty bound to initiate more stringent waste management regulations in order to be more responsive to the prevailing world standards. The current world trend is to empower the public with more responsibilities in various aspects of development that affects them. Environmental issues are part and parcel of this initiative. The aforementioned not withstanding, the already established environmental protection agencies such as UNEP and WHO, among others, are creating awareness to both the environmentalist and the general public. With this collective approach to environmental protection, industries will of necessity have to be more vigilant in their waste management strategies. It is instrumental to note that the rate of industrialisation is by itself not a measure of the degree to which the environment will be polluted. If the waste can be effectively managed by way of proper treatment at a rate commensurate with its generation before its eventual disposal into the receiving water bodies, pollution would not result. It is when this waste management strategy is either not in place or fails to function effectively that the dangers of pollution are imminent. In essence, therefore, proper treatment and disposal of wastewater will become an increasingly important aspect of the design and operation of all industrial plants. To fully achieve and sustain a comprehensive waste management program, it is prudent to evaluate and understand in greater details the various treatment processes in relationship to the flow and quality characteristics of liquid wastes.

Industrial wastewater are characterised by high pollution loads and wide variability in both flow and composition which may result in shock loads in the unit process if not properly balanced. Biological processes have been used quite extensively in the treatment of industrial wastewater with varying degree of success. The aerobic process responds quite well and is more cost effective in handling wastewater of low BOD, but their performance in treatment of high-strength waste (BOD_5 greater than 2000mg/l) is relatively inferior (Curi, 1980). Furthermore, many aerobic processes are sensitive to shock loads and have high chances of sludge bulking.

As the concept of clean production continues to receive recognition, research is being geared towards reduction in volume of waste mainly by encouraging resource recovery (UNEP-IE, 1995 and Bunyagidj et. al., 1996). This will inevitably result in higher strength waste, which cannot be handled effectively by aerobic treatment process alone. Consequently, anaerobic processes must be considered as an alternative in the industrial wastewater management. Anaerobic digestion was first applied to the stabilisation of sludge resulting from treatment of municipal wastewater (Curi, 1980). Proper application results in considerable destruction of putrescible organic, significant reduction in pathogens, conversion of hydrophilic solids to water resulting in humus like residue and gas (Gunnerson, 1986). As a result of its successful application to municipal sludge treatment and its several advantages, it has been applied to the treatment of industrial sludge. Most recently process modification have been devised which make the application of these processes to the treatment of dilute organic wastewater practical (Metcalf and Eddy, 1979). Anaerobic microoganisms produce high energy end products than aerobic microoganisms, consequently less energy is available per unit of organic processed for synthesis of cells than with an aerobic system (Holder, 1978). This in effect results in lower volumes of sludge. Anaerobes can more easily solubilize complex organic matter such as cellulose and various fats than aerobes (Bruce et. al., 1986).

The economic advantages of high rate anaerobic process is basically restricted to very strong waste (Mosey, 1977), hence their use in sewage sludge. However, provided it is possible to maintain sufficiently high biological solids within the system industrial wastewater can be treated anaerobically at low hydraulic retention time. To maintain this high biological mass there is need to incorporate microorganism concentration by either recycle or retention, analogous to activated sludge process.

The development of high rate anaerobic reactor, defined as retained biomass reactors have greatly advanced the potential of anaerobic wastewater treatment processes (Pol et. al., 1986). The reactors have decreased the investment and operation costs of anaerobic processes as compared to conventional anaerobic digesters. High loading rates are achieved by retaining a high concentration of active biomass in the reactor (Rintala, 1987).

1.2 Significance of the Study

In an agricultural based economy like that of Kenya, small industries such as tea, coffee, dairy and slaughterhouses play a significant role in the rural economy. Mostly in these areas energy is limited and any research aimed at reduction on energy consumption and possible ways of resource recovery and reuse would greatly contribute to industrial sustainability. In the urban areas, land use and its conservation are pertinent issues and every effort should be made to maximise the land use.

As cost of waste treatment facilities continues to rise, treatment has become a significant factor in determining economic success in the industries. In recent times there has been a growing concern over the amount of product and energy going to waste, hence reducing anticipated profits. This has resulted in research towards resource conservation and recovery. From an economic point of view, benefits can accrue from recycling recovered resources and these can partially offset the increasing production costs. With the widening scope of pollution legislation, there is need for more research into low cost treatment methods.

The appropriateness of the digester can be justified due to the following advantages: -

- High degree of stabilisation is expected due to the production of gases that can easily be separated from the liquid phase, hence shifting the equilibrium towards more waste digestion.
- Proper land utilisation per unit load as a result of reduced reactor volume, yet higher degree of digestion.
- Oxygen limitation problems can be avoided.
- Low sludge production due to production of high-energy end products.
- Low nutrient requirement relative to aerobic process.
- The resulting methane gas can be recovered and used as a source of energy.
- Odour nuisance is reduced due to use of airtight reactor.
- Access of the waste to vermin like fries is limited due to digester sealing.

1.3 Research Objective

The overall research objective was to investigate the performance and assess the efficiency of anaerobic process with biomass recycle, analogous to activated sludge process, in the treatment of high-strength brewery wastewater. The unique characteristic of the process is a batch recycle of anaerobic sludge while maintaining a continuous flow of the incoming wastewater. The specific research goals are: -

1 To determine start-up time for the digesters.
2 To assess the performance of the recycled biomass digester against the conventional anaerobic process by a comparison of the percentage COD removal.
3 To determine methane gas production in the system.
4 To establish the operational conditions of the process.

In order to achieve these objectives, bench scale models for both the proposed digester and a conventional anaerobic digester were set up and used for performance comparison under the same environmental conditions. The time needed to attain steady state conditions was determined for the two reactors and this was an indicator of start up phase. The difference in percentage COD reduction between the two reactors was used as a measure of the performance variation between the two, while the actual COD reduction between the influent and the effluent is a good measure of the effectiveness of the treatment process. The amount of gas produced can be an indicator of the potentials in terms of resource recovery. The digester were seeded with domestic sewage sludge and placed in a water-bath at 35^0C. The wastewater was continuously fed into the reactor by gravity flow. The strength of the waste was varied by dilution or addition of beer, to enable an investigation of the digester behaviour for a loading rate between 0.29 and 10 kg COD m^{-3} d^{-1}. The daily amount of return and wasted sludge was determined mathematically, while the gas was collected by displacement method.

2 LITERATURE REVIEW

2.1 General Characteristics of Industrial Wastewaters

Industries by their very nature regardless of their manufacturing processes, their end products and their sizes, generate wastewater. The operations of industries are so varied that there is no general solution to their waste disposal problems (Kilani et. al., 1989). Almost all industries are characterized by extensive use of water for various purposes, for example water is used:

- As an integral part in the industrial process as in the chemical, brewery and other fermentation industries.
- As a vehicle for the carriage of raw materials as in paper making and the sugar beet industries.
- For washing in the food and metal industries and the agricultural industries.
- For cooling purposes as in power generation.

Industrial wastes are characterized by great variability in both flow and strength. Economy in the use of water leads to a reduction of the volume of wastewater discharge in all industries (Dart et. al., 1980). Wastewater flow rate varies with the type and size of the industry, the supervision, the degree of water reuse and the wastewater treatment methods employed on site. Flow may be regulated by use of detention tank or equalization basins (Metcalf and Eddy, 1979). For proper wastewater management, it is of prime importance that a comprehensive data collection is undertaken to enable classification and determination of wastewater characteristics of specific industrial effluent (Curi 1980; Kilani et. al., 1989).

Wastewater disposal is an additional burden on the cost of production. The primary aim is to keep wastewater volume to a minimum while adhering to the requirements of pollution prevention. In most cases the most satisfactory solution to the problem of industrial wastewater disposal is by discharge to the municipal sewer after complying with requirements, relating to volume of wastewater, waste strength, temperature, pH, maximum concentration of certain substances and BOD load. The trend in the charging by the municipal authority is to peg the charges to the volume, strength and concentration of suspended matter (Dart et. al., 1980). However not all industries are located in the proximity of sewer lines and a proper assessment of on site treatment must be taken into consideration.

Economy in treatment costs may also be achieved by segregation of difficult wastes such as sulphide liquors for special treatment. On the other hand, mixing of liquors such as acid and alkaline water or chrome and lime liquors will result in an improvement in treatability. If flow and composition vary substantially a considerable saving in cost of treatment will result from the installation of adequate mixing and balancing tank with constant flow weirs.

2.2 Brewery Wastewater

2.2.1 Brewing Process

Generally steps in beer production include (Koziorowski et. al., 1972):

- The conversion of barley into malt.
- The preparation of mash, by mixing malt with hot water.
- Conversion of starch to sugar by the addition of hops.
- Draining and washing the 'sweet' waters from the mash to fermentation tanks.
- Fermentation of sugar to alcohol by yeast.
- Skimming, Cooling and Clarification of the fermented liquor.
- Locking in casks.

The basic ingredients in the manufacture of beer are barley, rice or corn and hops. Barley is first induced to germinate by steeping in water in a malting plant. This process enables the barley to produce roots and leaflets. The germinated barley (malt) is stored in silos, after which the dry malt is ground and mashed using pure water under controlled temperature. A small portion of the ground malt is then introduced into the cooker, along with the rice or corn and pure brewing water. In the cooker, the mash is heated at controlled temperature, and enough growth time is allowed, which enable the enzymes in the malt to hydrolyze starch into fermentable sugars. Water additives like gypsum are added. The resulting solution of fermentable sugars and protein is known as "wort" (Isaac et. al., 1978).

After mashing, the wort is dropped into the strainmaster where it is separated from the grains by means of filtration through the slotted area of the vessel. The residues obtained after extraction is complete, are mainly the spent grains, which are conveyed into a hopper. The wort enters the brew-kettle from the strainmaster. Here, the wort is boiled as hops are added. The hops impart the characteristic aroma and taste to the finished beer. The boiling process extracts the necessary aromatic and bitter components from the hops and the contents of the kettle are then pumped through a hop strainer which removes the spent hops and allow the wort to pass on. The wort enters the whirlpool tank, which acts as a cleaning or straining vessel. Solid wastes, mostly from hops, are separated from the useful liquid. The clear wort is then pumped through a stainless steel cooler into collecting tanks where pure culture yeast is injected as the fermentation process occurs.

Fermentation takes place under controlled temperature in the range of 10^0C and 15^0C. During the fermentation process, the yeast converts most of the fermentable sugars present into alcohol and carbon dioxide. The carbon dioxide is collected, purified liquefied and stored for later use where it is re-introduced into the beer for use in the carbonation stage. At the end of the process, the yeast will have settled at the bottom of the vessel and it is filtered off for re-use in subsequent fermentation.

The beer is then placed in a primary storage tank where the carry over yeast slowly settles. At the same time the overall flavour and character the beer matures. The beer is then drawn off and pumped through a chiller and a filter, which removes the remaining yeast and haze-forming proteins. The beer becomes optically bright and carbon dioxide collected previously is injected back into the beer. The beer is stored in bright beer tanks for a period of 3 - 5 days and then it is finally pumped through fine polish filters to the keg filling machine and bottling.

2.2.2 Source of Brewery Effluent

The organic compounds found in brewing are mostly carbohydrates (starch, sugar and cellulose), proteins and alcohol. The liquid phase of a brewery effluent consist mainly of carbohydrates, proteins and ethanol resulting from wort and beer losses and sodium hydroxide from washing operations (Painter, 1960; Newton et. al., 1962). The solid components comprise of cellulose from spent grains, silica from diatomaceous earth, carbohydrate-protein complexes found in yeast cells and proteins from the trub (Newton et. al., 1962). Since wort, beer, trub and yeast are concentrated forms of organic compounds, they constitute very high source of oxygen demand. The CO_2 emitted, can be recovered and re-used in carbonation. The other pollutants result mainly from cleaning and lubrication operations, that is, detergents, sterilizes and lubricants. The temperatures of brewery effluent are normally higher than domestic wastewater. Wide pH variations are as a result of product losses, change over, caustic detergents used in the bottle-washer and acid Cleaning in Place (CIP). Typically, the pH values range from 4 - 12. The actual sources of the effluent can be detailed as follows:

Brewhouse: The steep water emanating from the wet-milling operation as well as the rinsing of the brewhouse vessels are discharged to drain together with the rinsing of the tanks that store adjuncts. The start-up and shutdown liquors from the strainmaster or mesh filter are also disposed off into the drain. The spent grains are collected in a hopper and transferred, during which operation inevitable spillage to drain occur. In addition, should the spent grains be dewatered in a filter press for instance, the resulting liquor is discharged to drain. Normally the trub is discharged to drain only when the brewhouse stops for Cleaning-in-Place (CIP) operations, otherwise, it is transferred back to the strainmaster, and thereafter disposed together with the spent grains.

Cellars: The surplus yeast generated during fermentation is either collected for beer recovery, sold directly in wet form is dried in a spray or drum dryer. However, the yeast remaining in the maturation tanks is normally disposed directly to the drain. When water is used to transfer beer from the brewhouse to fermentation tank or from fermentation to storage, there is also beer lost to drain at the end of the transfer operation.

Filtration: At the end of a filtration run, the filter cake consisting of diatomaceous earth, yeast and beer, is either discharged to drain or collected in waste bins and disposed off. However, the start-up and shutdown of the filtration process goes to the drain.

Packaging: The effluent is contaminated with beer that is lost in the filter operation as well as from bottles broken during the packaging process. The drip beer resulting from the over -filled bottles is normally poured down the sewer. The overflow and soak solutions of the bottle-washers contain organic residues from the dirty bottles, detergent additives and label glue. Keg washing and filling also results in some beer going down the drain. Occasionally, beer from market rejects is also released here.

Cleaning and lubrication: A wide variety of detergents are used in a brewery industry and can be classified into three categories; alkaline (containing caustic soda), acids (such as nitric and phosphoric acids) and neutral detergents

Sterilizes are used after CIP to kill beer spoilage bacteria and wild yeast and comprise mostly of strong oxidizing agents such as hypochlorite and peroxide. Caustic soda and acids are responsible for shifting the pH and increasing the amount of total dissolved solids. However, they have no effect on the oxygen demand. Anti foaming and complexing agents used as detergent additives, as well as conveyor lubricants, are organic compounds and contribute to the oxygen demand. The overflow from bottle-washers is probably the largest source of effluent strength

2.2.3 General Characteristics of Brewery Wastewater

The brewery industry wastewater just like wastes from all food-processing industries not only contains a high level of organic matter, but also is produced in relatively large volumes. In addition, certain processes operate on a batch basis both in terms of volume of effluent produced and its polluting load. (Tomlinson, 1976). The major brewery wastestream are the malting, brew-house, bottling and washings.

Malting: Barley is induced to germinate by steeping in water. While methods may vary considerably, the average volume of water used is $2.4m^3/1000$ kg of barley steeped. An average BOD_5 of the combined steep water and washings from malting associated with distilleries has been reported to be about 1500 mg/l

Brewhouse: Brewery wastewater have a high BOD: N ratio and can have a beneficial effect to the overall nitrogen regime. The waste is readily oxidized biologically and an 80% reduction in BOD for the treatment in plastic filter in series at a loading rate of 2 kg BOD_5 $m^{-3}d^{-1}$ has been reported (Dart 1980).

The brewery industry is a major water consumer. The combined volume of water needed for the various operations is in the range of 4.85 to $11.3m^3$ per m^3 of beer produced. Even in very comprehensive in-house waste reduction measures, at least 2.35 m^3m^{-3} of beer still goes to waste, hence must be treated (Barnes et al, 1984). Studies of five different breweries showed that the volume of wastewater range from 4.6 to 23.2 m^3 of used water to a m^3 of beer produced with a BOD_5 ranging from 445 to 1200 mg/l (Barnes et al, 1984). The amount of water that goes to waste largely depends on the in-house efforts to reduce waste. The main quantity comes from the washing of casks, bottles and equipment. The most polluting waters are the press liquor, wort and spilt beer. (Dart 1980). Other literature also gives a range of 2.4 to 9.0 m^3m^{-3} beer.

Review of the organic strength shows considerable variation with the BOD: COD ratio of between 1:3 and 1:8. The literature data report BOD_5 of brewery wastewater between 70 mg/l and 119000 mg/l, COD can varies between 120 mg/l and 184000 mg/l. The average temperature in the range of 13°C to 29°C has been recorded

(Nzainga, 1989). A summary of characteristics of the effluent from the Tusker Brewery at Ruaraka carried out in 1989 is shown in Table 2.1 below.

Table 2.1 **Characteristics of Tusker Brewery at Ruaraka (Kilani, 1989)**

PARAMETER	FERMENTATIONS & BREWING		BOTTLING & WASHING		COMBINED EFFULENT	
	Range	Average	Range	Average	Range	Average
pH	3.6–8.0	5.3	5.2–11.1	8.2	4.7-9.8	6.3
Alkalinity	34-165	73	185.5-286	212	37-245	117.4
Nitrate Nitrogen	None	-	None	-	None	-
Nitrate Nitrogen	None	-	None	-	None	-
Ammonia	3.2-152	69.8	0.8-28.8	9.9	19.2-160	64.5
Chloride	3.0-72	16.4	2.0-22	10.4	4-52	24.2
SS	12-5216	1729	20-409	106	96-4824	1928
DS	344-3268	1499	256-948	699	892-5480	2360
BOD_5	1000-10,800	3621	230-1100	624	800-6600	3555
COD	1943-16653	7153	628-2569	1093	1204-12950	6453
All parameters in mg/l except pH						

Besides carbon, microorganisms require nitrogen and phosphorous for cell growth. Brewery wastewater containing 106 mg/l of total nitrogen and a BOD: Nitrogen ratio of 44:1 and a BOD: Phosphorous ratio 120:1 has been reported (Curi, 1980). In terms of nutrient requirements, the most economical way of treating brewery wastes is to treat them in combination with domestic sewage which has a BOD: N ratio of less than 17:1 (Curi, 1980).

2.2.4 Thika Brewery Brewing Process

In the Brewhouse, the ready made malt is milled to form ground barley malt (grist) in a process called mashin-in. Maize is combined with water creating a thick mixture called "the Mash". The mash is then pumped to a mash tun, where under a monitored heating procedure the starch in the mash tun is converted into simple sugars. Varying the time and temperatures in the mashing programme influences the body and colour of the beer and determines the potential alcohol content. The mash is then transferred to a lauter tun (strainmaster), which acts as a giant sieve and filter, separating the rich methods. Pre-treatment by equalization and aeration is essential to avoid acidification, sludge deposits and odour emissions. Partial biological treatment is known to achieve upto 80% BOD_5 reduction. Addition of excess sewage sludge coupled with equalization and mixing can improve the effectiveness of partial biological methods (Barnes et al., 1984). The nutrient requirement for biological treatment can be met by addition of domestic sewage, cleaning water and bottle washing liquors. Aerobic oxidation ponds have been used where land is not a limiting factor. Barnes et al (1984) reported use of anaerobic treatment with a COD reduction in the range of 72% to 90% at a volumetric loading rate of upto 5.55 kg BOD_5 $m^{-3}d^{-1}$.

2.3.1 Conventional Treatment System

On setting up the objectives of a treatment facility, the degree of treatment can be determined by comparing the influent-wastewater quality to the required effluent-wastewater characteristics. Treatment is achieved through physical, chemical and biological means. These methods are classified as physical unit operations, chemical unit processes and biological unit processes (Barnes et al., 1983). Unit operations are the phenomena of contaminant removal by physical means, while unit processes are phenomena of contaminant removal by either chemical or biological means. However chemical and biological are conversion process rather than removal processes. The contaminant may be changed but the product remains in the system until a physical operation removes them from suspensions by sedimentation or by transfer to the atmosphere (Peavy et. al, 1985; Ferrero et. al., 1987).

Unit operation and processes are grouped together to form what is known as primary, secondary and tertiary treatment as referred to in the conventional treatment processes. Primary treatment process refer to unit operations, secondary refer to chemical and biological unit processes, while tertiary refer to the combination of all three (Metcalf and Eddy, 1979)

2.3.1.1 Physical Unit Operations

These are techniques where wastewater treatment is achieved through application of physical forces. Unit operations commonly used in wastewater include screening, flow equalization, mixing, flocculation, sedimentation, flotation and filtration. The process analyses of these units are well detailed in Metcalf and Eddy (1979) and Peavy et al (1985).

2.3.1.2 Chemical Unit Process

Removal or conversion of contaminants is brought about by the addition of chemical or by other chemical reactions. The most common examples include precipitation, gas transfer, absorption and disinfection. In chemical precipitation, treatment is accomplished by producing a chemical precipitate that settles. The settled precipitate contains both the added chemical and the constituents that were swept out of the wastewater as the precipitate settled. Gas transfer involves the movement of gas from one phase to another mostly from the gaseous phase to the liquid phase to enhance conversion. A good example is the aerobic process where oxygen is transferred to the liquid (wastewater) phase for biological oxidation. The efficiency of the system depends on the availability of oxygen. Another example is conversion of nitrogen to ammonia and transferring the ammonia gas from water to air. Adsorption involves the removal of specific compounds from wastewater on solid surfaces using the forces of attraction between bodies. Activated carbon is the most commonly used adsorbent. However, unlike physical unit operation and biological unit process, chemical unit processes have a disadvantage in that they are additive processes. In chemical process, a chemical is added to the wastewater to achieve conversion or removal of contaminant, consequently there is a net increase in the dissolved constituents in the wastewater. These dissolved constituents play a significant role especially if the treated wastewater is to be reused (Metcalf and Eddy, 1979; Kakabadse, 1978). Chemicals may be used for wastewater treatment either to enhance biological treatment or as an alternative to the same. However chemical oxidation is not very popular and is normally applied only in exceptional circumstances because of its high cost (Kakabadse, 1978).

2.3.1.3 Biological unit processes

This is the process where treatment is brought about by microorganism activities in the system. It is used primarily to remove biodegradable organic substances in wastewater. These biodegradable substances are converted into gases that can escape to the atmosphere and into biological cell mass (biomass) that can be removed by physical means such as sedimentation. A high percentage of waste matter can be biologically treated as long as the right environmental conditions are maintained (Peavy et al., 1985).

2.3.2 High Rate Systems

High rate processes are based on the principle of a high viable biomass retention. The principle aim is immobilization of the acclimatized microbial mass within the system. This may be achieved by, the formation of highly settleable sludge aggregates, attachment to high density inert particulate carrier material or to immobile support structures supplied to the reactor or by the entrapment of microorganism flocs between packing material supplied to the reactor. Different high rate processes are in use today especially for the treatment of municipal sludge. However various processes exhibit difference with respect to their hydraulic and organic loading potentials, kinetics, level of contact achieved, start-up procedures and stability. Generally the merits of the high rate processes is the high loading potentials as compared to the conventional systems. Studies performed with raw domestic sewage in a granular sludge UASB - reactor recorded 65-85% COD reduction at temperatures in the range 8-20^{0}C at 12 hours liquid detention time (Lettinga, 1984). Studies carried out by Wanjau (1986) in the thermophilic temperature range indicated enormous potentials up to an organic loading rate of 12kg COD $m^{-3}d^{-1}$. With such a wide temperature spectrum the high rate systems are destined to gain more recognition in both domestic and industrial wastewater treatment.

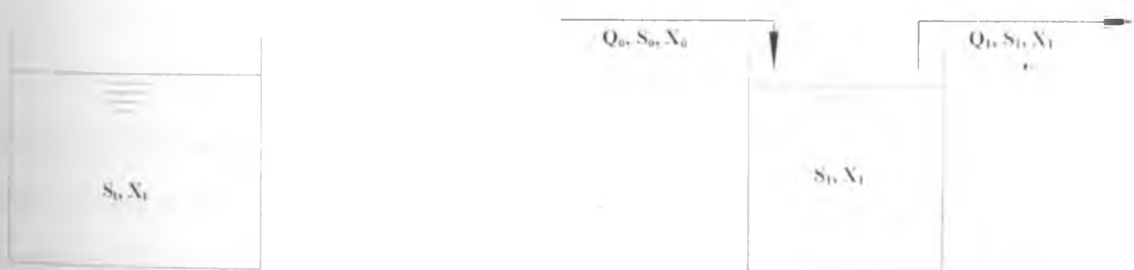
2.4 Wastewater Treatment Facilities

2.4.1 Reactor

Microorganisms involved in wastewater treatment are basically the same that degrades organic matter in natural fresh water systems. Unlike in the natural system the processes in wastewater treatment are not allowed to proceed in their natural behaviour. but are controlled in carefully engineered facilities (reactor) to optimize both the rate and completeness of organic removal. A rector can therefore be defined as the vessel or structure together with the necessary equipment. in which the unit operations or processes take place (Peavy et.al. 1985). Many types of reactors exist, and the best alternative for any objective can best be determined by developing a model for the several types (Curds et.al., 1983). The two broad types of classification commonly used are in terms of flow and mixing.

2.4.1.1 Classification by Flow

The two extremes in this case are the batch and the continuous flow reactors. In a batch reactor as shown in Figure 2.1 (a) the reactants are placed in the reactor and the reaction allowed to proceed to completion without outflow for a time, after which the resulting products are taken to the next stage. Under batch conditions the concentration of the reactants are constantly changing with respect to time.



(a) Batch Reactor (b) Continuous-flow Reactor

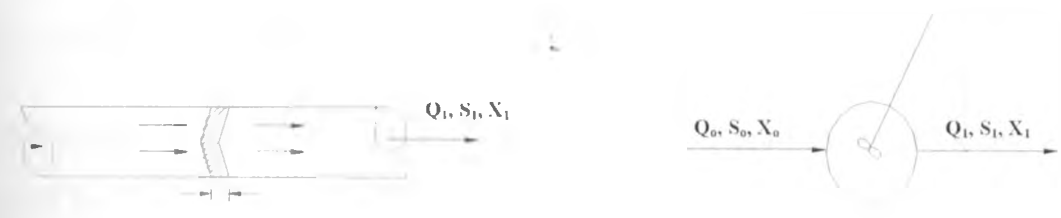
Figure 2.1 Reactor classification by flow

In a continuous flow reactor shown in Figure 2.1 (b) reactants are continuously added and removed from the reactor. The flow may be steady (constant with respect to time) or unsteady (varies with time). At steady state in a continuous flow reactor the concentration is uniform throughout the reactor and is equal to the effluent concentration.

In practical operation there are reactors, which are neither fully, batch or fully continuous, where both the influent and the effluent flow rates are intermittent. This is commonly encountered in many anaerobic digesters. In some cases where more than one phase is involved a reactor may be batch with respect to one phase and continuous flow with respect to another. Many laboratory reactors are batch with respect to liquid phase and continuous flow with respect to gas phase where supply of oxygen and removal of carbon dioxide is involved (Curds et.al., 1983).

2.4.1.2 Classification by Mixing

Reactors can be classified in terms of mixing characteristics and the two extremes are plug flow and completely mixed. In a plug flow reactor shown in Figure 2.2 (a) no attempt is made to induce mixing (Curds et.al., 1983). The flow is perfectly radial and the reactants are assumed to move through the reactor as a plug

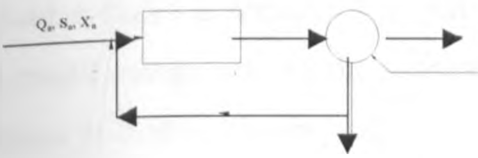


(a) Plug flow Reactor (b) Completely mixed Reactor

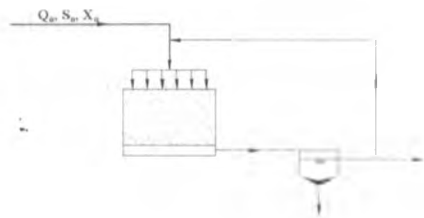
Figure 2.2 Reactor classification by mixing

In a completely mixed flow reactor shown in Figure 2.2 (b), it is assumed that there is complete mix conditions, hence the influent concentration is immediately dispersed throughout the reactor. However, the above conditions are idealization with respect to mixing characteristics. In practice complete mixing conditions are not very difficult to attain, but plug flow is much more difficult since there is almost always some mixing introduced due to inlet and outlet disturbances, wind, thermal, and density induced currents. Real reactors therefore usually exhibit an intermediate between complete mixing and plug flow conditions (Curds et.al., 1983).

Advancement on the above reactors has included recycle process and fixed film reactors as shown in Figure 2.3, as a way of increasing the concentration of the microorganisms in the reactor and therefore permitting the use of smaller reactors. This is possible since the rate of substrate utilization is a function of both substrate and organism concentration (Curds et.al., 1983).



(a) A biomass recycle process



(b) A fixed film reactor

Figure 2.3 Recycle process and fixed film reactor

Generally the reactors in practical use take into account both the flow and the mixing characteristics and can be classified as: -

a) Completely mixed Batch Reactor (CMBR)
b) Plug Flow Reactor (PFR)
c) Completely Mixed Flow Reactor (CMFR)
d) Completely mixed Flow Reactor with recycle.

By application of the concept of material (mass) balance, mathematical models can be developed for the purpose of analysis and design of the above reactors.

2.4.2 Settling Tank

The settling tank has three major tasks namely the production of an effluent relatively free from suspended solids, production of concentrated suspension of biological mass (biomass) for recycle or subsequent digestion and provision of sufficient solids storage capacity to handle daily fluctuation in flow to the treatment facility. Although high microorganism concentration in the recycle system can be highly beneficial for substrate digestion, too high biomass concentration in the recycle flow can result in poor quality effluent due to excessive solids in the clarified effluent (Curds et.al., 1983). While biomass concentration and recycle has been extensively used in the activated sludge process, it is not yet widely used in the anaerobic process.

2.5 Principles Of Microorganism Growth And Biological Oxidation

Biological digestion of waste matter is a natural process brought about by microorganism activities. Microorganisms use the organic matter in wastewater as a food supply and convert them into gases and biological mass (biomass). Since wastewater contains a wide variety of organic matter, a wide range of microorganisms (mixed culture) is required for complete treatment. Each type of microorganisms in the mixed culture utilizes the substrate most suitable for its metabolism. Most mixed cultures will also contain grazers, or organisms that prey on other species. The newly created biomass must be removed from the wastewater to complete the treatment process. Design of biological systems requires the understanding of the theory of biological growth, its microbiology, kinetic of metabolism, mass balance and physical operations necessary to control the environment in the reactors (Peavy, et. al., 1985)

2.5.1 Biological Reaction

Biological reactions of interest to wastewater treatment range from specific enzymatic reactions to empirical expressions for the gross reactions carried out by mixed culture of microorganisms (Curds et al., 1983). However, there are basic principles common to all microbial activities. A source of cellular building block such as carbon, oxygen, hydrogen, nitrogen and phosphorus must be transported into the cell in a soluble form. Hydrogen acceptor must be present and aerobic microorganisms use oxygen for this purpose, while anaerobic microorganisms use such compounds as sulphates, nitrates and carbon dioxide. Energy source must equally be available either chemically from the substrate or a radiant energy from the sunlight (Curds et al., 1983).

The digestion in the cell takes place in both respiration and synthesis reactions. The energy released during respiration is used in the synthesis reaction for the production of more cells with the remainder being dissipated as waste products or heat. Being organic in nature the resulting microorganisms can exert a pollutional burden on the receiving waters. It is therefore desirable that any biological process should result in flocculant microorganisms that can be easily separated from the liquid phase by physical means (Curds et.al., 1983). Microorganisms undergo decay (endogenous respiration) forming soluble and insoluble waste products; some of which are non biodegradable, while others can support the growth of additional microorganisms.

Bacteria growth and their subsequent activities play the most significant role in the biological treatment relative to other forms of microoganisms. However, it must be born in mind that a biological treatment unit is composed of a complex mixture of microorganisms exhibiting different growth behaviour (Metcalf and Eddy, 1979). The relationship of bacteria growth and substrate utilisation in a mixed culture of microorganisms and a given amount of substrate (waste) containing the necessary nutrients can be illustrated by a simple batch reactor. The cell growth pattern has four distinct phases as shown in Figure 2.4

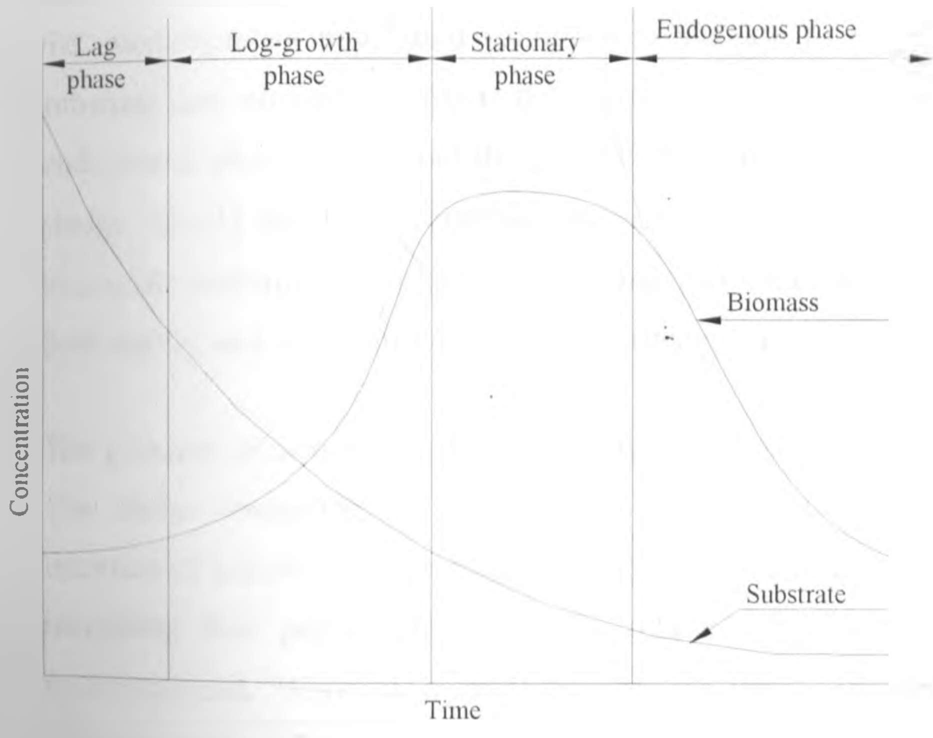


Figure 2.4 The biological growth curves (Peavy et. al., 1985)

The exact shape of the curve is dependent upon many factors such as environmental conditions in the batch reactor, the type of substrate, species of microorganism, physiological conditions of the inoculum and initial concentration of the microorganism and substrate. One or more of the distinct phases in Figure 2.4, say, the lag-time stage may be completely absent or greatly suppressed in time with respect to the other phases (Curds et.al., 1983). On addition of an inoculum to a culture medium, the microorganisms need some time (lag time) to acclimatise to the new environment before decomposition of the organic matter can commence. The lag phase represents the acclimatisation of the microorganisms to the substrate with the bacterial cells having long generation times and zero growth rate (Gray, 1989). The lag phase varies in length depending on the conditions of the seeding biomass and type of substrate. If the microorganisms have been accustomed to a similar environment and similar substrate the phase is reduced considerably and growth will be initiated earlier, hence waste stabilisation will be achieved in less time. Once growth has been initiated, microorganisms reproduce quite rapidly (Peavy, et. al., 1985). Initially there is an excess amount of substrate surrounding the microorganisms and the rate of metabolism and growth is only a function of the ability of the microorganisms to process the substrate. Consequently, the higher the microorganism population the higher the rate of metabolism. In the process of digestion the substrate decreases but the microorganism population continues to increase to a limit where the available substrate can no longer sustain the whole population. It is at this stage that the endogenous phase sets in and the population decreases through death and forms the sludge. Should the sludge containing the starving (activated) bacteria be reintroduced to a waste similar to the original one the bacteria would act quite fast in that they are both starved and acclimatised to the waste (Peavy, et. al., 1985).

The principle of activated sludge is based on the understanding of the above theory. The sludge containing active microorganisms is returned to the reactor with the intention of introducing the already accustomed microorganisms and at the same time increasing their population in that the return sludge has higher concentration of microorganism. While it is important to achieve a high rate of organic matter decomposition in the reactor, it is equally important to ensure formation of stable flocs, which enhance settlement in the solid separation unit. Research has show that the settling characteristics of the biological flocs can be enhanced by increasing the mean cell residence time (sludge age) in the system (Peavy et. al., 1985). This has been explained on the basis of surface charge reduction and production of extra cellular polymer by the microorganisms as the sludge age increases. This results in the formation of a slime layer. presence of which promote the formation of flocs that can readily settle by gravity (Peavy et. al., 1985).

Consequently, the effect of sludge return is a reduced lag time due to the accustomed microorganisms, higher metabolism as a result of higher activated microorganism and indeed improved sludge quality due to enhanced settling characteristics.

2.5.2 Stoichiometry of Biological Oxidation

The Stoichiometry of biological reactions is strongly influenced by the species of microorganisms present and the environmental conditions prevailing on the process. The reactions are autocatalytic, in that microorganisms both participate and are produced in the reactions. Very simplified net reactions are as illustrated below (Curds et. al., 1983).

Aerobic Reaction

$$\textit{Organic} + O_2 \xrightarrow[\textit{as catalyst}]{\textit{Aerobic Micro-organisms}} \text{Aerobic Microorganisms} + CO_2 + H_2O$$

Anaerobic Reaction

$$\textit{Organic} \xrightarrow[\textit{as catalyst}]{\textit{Anaerobic Micro-organisms}} \text{Anaerobic Microorganisms} + CO_2 + CH_4 + H_2O$$

Photosynthetic

$$CO_2 + H_2O \xrightarrow[\textit{as catalyst}]{\textit{Aerobic Micro-organisms}} \text{Photosynthetic Microorganisms} + O_2$$

It is possible to develop balanced equations if an elemental analysis is performed on the organic substrate and microorganisms produced. In applying the stoichiometry analysis in biological processes, the equation of organism decay cannot be ignored since the organism residence time is sufficiently long for this to have an influence. It equally should be remembered that this simplification does not consider that some portions of the organic substrate and microbial mass are not biodegradable and that some of the waste products formed can serve as an additional source of substrate.

2.6 Kinetics of Biological Oxidation

2.6.1 Basic Kinetic Relationships

Most reactions in biological processes are autocatalytic and it is usually assumed that the relationship between waste concentration and organism growth rate can be expressed by a hyperbolic function proposed by Monod as shown in Figure 2.5 (Walter et. al., 1981).

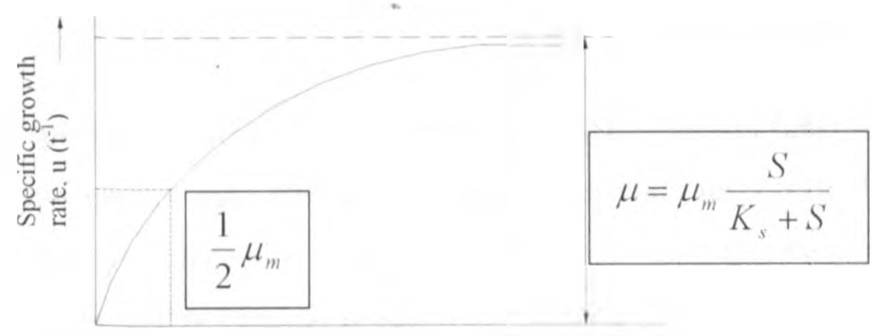


Figure 2.5 Monod growth rate function

Where μ = specific growth rate, time^{-1}

μ_m = maximum growth rate constant, time^{-1}

S = concentration of growth-limiting substrate in solution, mass/unit volume.

K_s = half saturation constant, i.e. concentration of limiting substrate at half the maximum growth rate ($\mu = \frac{1}{2}\mu_m$), mass/unit volume.

In the log-growth phase the rate of bacteria growth is catalysed by different enzymes and a relationship involving enzyme utilisation may be expressed in terms of Michaelis-Menten kinetics for enzyme-substrate interaction. The enzymes are supplied by the microbial mass, the overall chain being governed by the slowest step in the chain. The system is essentially biomass-limited and is a first order in respect to biomass, that is, the growth rate R_x, is proportional to the first power of the biomass concentration, X.

$$R_x = \mu X$$

$$\frac{dX}{dt} = \mu X \tag{2.1}$$

Where $\frac{dX}{dt}$ = R_x = the growth rate of the biomass per time

X = concentration of biomass (microorganisms), mass/unit volume

The rate of cell growth is given empirically by the Monod equation (Walter et. al., 1981).

Monod function

$$\mu = \frac{\mu_m S}{K_s + S} \tag{2.2}$$

Substitution of the specific growth rate in equation (2.1) by the Monod function result in an expression for growth rate which is a first order with respect to biomass concentration and variable order (zero or first) with respect to substrate concentration (Curds et. al., 1983). The rate of biomass production can therefore be expressed as: -

$$R_x = \frac{dX}{dt} = \frac{\mu_m SX}{K_s + S} \tag{2.3}$$

If all the substrate were converted to biomass, then the rate of substrate utilisation would equal the rate of biomass production. However catabolism convert part of the substrate into energy, hence the rate of substrate utilisation will be greater than the rate of biomass production (Peavy et al., 1985). By using experimentally determined yield coefficient, the respiration and synthesis equations are combined to relate the mass of biomass produced to the mass of substrate consumed (Curds et al., 1983)

$$R_x = -\frac{YdS}{dt} = -YR_s$$

$$R_s = -\frac{R_x}{Y} = -\frac{\mu_m SX}{Y(K_s + S)} \tag{2.4}$$

Y = True yield (maximum yield coefficient) – ratio of biomass formed to mass of substrate consumed, mass/mass.

R_s = $\frac{dS}{dt}$ = rate of substrate utilisation, mass/unit volume/time.

The factor Y varies depending on the metabolic pathway used in the conversion process. Typical values of Y for anaerobic reactions range from 0.08 to 0.2 Kg biomass per Kg of BOD_5 (Peavy, et. al., 1985).

The distribution of cell ages is such that not all the cells in the system are in the log-growth phase. An account must also be allowed for depletion of biomass through endogenous respiration. Endogenous decay is taken to be a first order in respect of biomass concentration (Peavy, et. al., 1985).

$$\frac{dX}{dt}(end.) = -k_e X \qquad (2.5)$$

Where k_e = endogenous decay rate constant, time $^{-1}$

Consequently in correction for endogenous decay equation. (2.3) becomes

$$\frac{dX}{dt} = \frac{\mu_m SX}{K_s + S} - k_e X \qquad (2.6)$$

2.6.2 Mass Balance Analysis

Mathematical model for the different types of reactors can be developed by applying material (mass) and energy balances using the fundamental stoichiometric, thermochemical and kinetics relationships within the system. At steady state the concentration at various stages can be obtained by a mass balance analysis for biomass and the substrate in the influent and the effluent. This is an application of the principle of continuity to any component in a reactor such as substrate, biomass and product. Since matter can neither be created nor destroyed, a mass balance analysis within a defined system boundary illustrates the changes as a function of time and a general form is as follows (Metcalf and Eddy 1979): -

Inflow + Utilization - Outflow = Accumulation

Symbolic representation

$$QC_o \pm VR_a - QC = V\frac{dC}{dt} \qquad (2.7)$$

Where Q = Flow rate, V = Volume of reactor, C_o = Influent concentration, C = Effluent concentration, R_a = Rate of reaction.

In case of uniform concentration of material within the system boundary as in the CMFR, the material balance may be taken over the whole reactor. When the concentration is not uniform as for a plug flow reactor the mass balance must be made over a differential element of reactor volume and then integrated. Mathematical complexity can be greatly simplified by assuming steady state conditions and first order reaction.

2.6.2.1 Completely mixed Batch Reactor (CMBR)

In a batch reactor, the concentration of reactants and products are constantly changing with time. At some intermediate time greater than zero and less than completion time the input and output are zero.

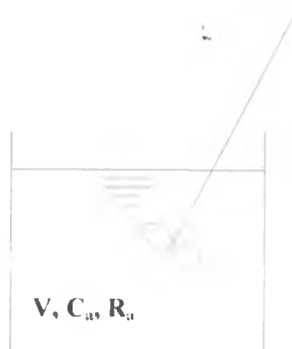


Figure 2.6 Completely mixed batch reactor

Material Balance

Input - output ± Rate of reaction = Rate of accumulation

$$0 - 0 \pm R_a V = V \frac{dC_A}{dt}$$

Assuming first order reaction, the above equation can be simplified thus,

$$\int_{C_o}^{C_t} \frac{dC_A}{C_A} = -k\int_0^t dt$$

$$C_t = C_o e^{-kt} \tag{2.8}$$

2.6.2.2 Plug Flow Reactor (PFR)

The concentration is not uniform, hence the mass balance must be made over a differential element of the tube taking into account there is no accumulation at steady state.

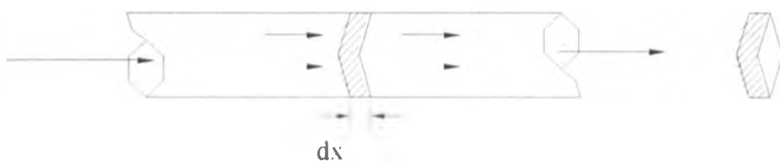


Figure 2.7 Plug flow reactor

Input – Output + Rate of Reaction = Rate of accumulation

$$QC_A - Q(C_A + dC_A) - dVkC_A = 0$$

$$C_t = C_o e^{-kt} \tag{2.9}$$

2.6.2.3 Completely mixed Flow Reactor (CMFR)

At steady state the concentration of reactants and products in the reactor effluent do not change with time and there is no accumulation. Material balance can be applied to both the biomass, X, and substrate, S concentration

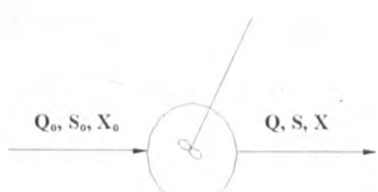


Figure 2.8 Completely mixed reactor

Influent ± Reaction = Accumulation + Effluent

Biomass balance

$$QX_o + \mu VX - k_e XV = QX + V\frac{dX}{dt}$$

$$\mu = \frac{1}{\theta} + k_e \qquad (2.10)$$

Since θ is a function of flow rate equation 2.10 shows that specific growth rate can be controlled by varying the flow rate in a fixed volume reactor.

Substrate balance

$$QS_o - \frac{\mu}{Y}XV = QS + V\frac{dS}{dt}$$

$$\frac{\mu X}{Y} = \frac{(S_o - S)}{\theta} \qquad (2.11)$$

From the Monod function and the above equations the steady state substrate concentration in the effluent can be determined by equating equation 2.2 to equation 2.10, thus eliminating the specific growth rate.

$$\mu = \frac{\mu_m S}{K_s + S} = \frac{1}{\theta} + k_e \qquad (2.12)$$

$$S = \frac{K_s(1 + k_e\theta)}{\theta(\mu_m - k_e) - 1} \qquad (2.13)$$

From the substrate balance equation and substituting the specific growth rate (equation 2.10), the biomass concentration in the reactor effluent at steady state can be determined thus;

$$\frac{\mu X}{Y} = \frac{(S_o - S)}{\theta} \qquad X = \frac{Y}{\mu}\frac{(S_o - S)}{\theta}$$

$$X = \frac{Y(S_o - S)}{1 + k_e\theta} \qquad (2.14)$$

2.6.2.4 **Completely mixed Flow Reactor with recycle**

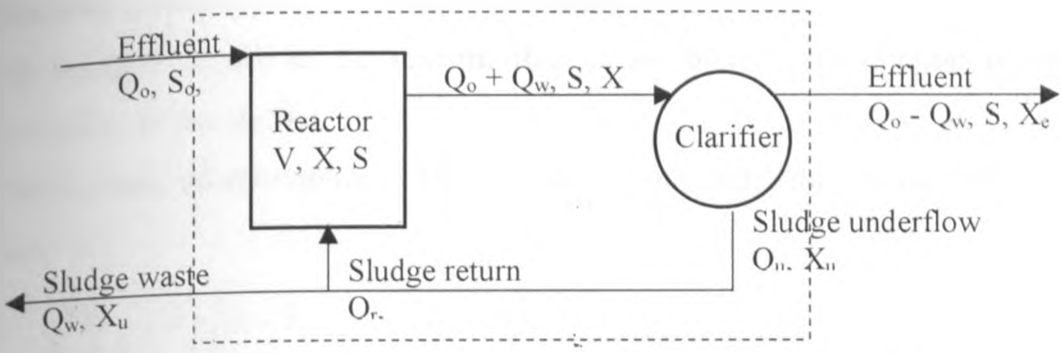


Figure:2.9 **Typical completely mixed flow reactor with recycle**

For a completely mixed flow reactor (CMFR), mass balance equations can be developed with reference to Figure 2.9. Mass balance equations are written around the entire system (dotted line) at steady-state conditions.

Biomass balance

$$Q_oX_o + VR_x = (Q_o-Q_w)X_e + Q_wX_u$$

$$Q_oX_o + V\left(\frac{\mu_m SX}{K_s+S} - k_eX\right) = (Q_o-Q_w)X_e + Q_wX_u \qquad (2.15)$$

Substrate balance

$$Q_oS_o - VR_s = (Q_o-Q_w)S + Q_wS$$

$$Q_oS_o - V\frac{\mu_m SX}{Y(K_s+S)} = (Q_o-Q_w)S + Q_wS \qquad (2.16)$$

Where Q_o, Q_w = Influent and waste sludge flow rate, respectively, volume/time

X_o, X, X_e, X_u = biomass concentration in influent, reactor, effluent, and waste sludge, respectively, mass/unit volume

S_o, S = soluble substrate concentration in the influent and reactor, respectively, mass/unit volume

V = volume of reactor

K_s, u_m, k_e, Y = kinetic constants, mass/volume, time^{-1}, time^{-1}, mass/mass.

By making the following assumptions the above equations can be simplified

1. The influent and effluent biomass concentrations are negligible.

2. The influent substrate concentration, S_o, is immediately diluted to the reactor substrate concentration, S, because of complete mix regime.
3. All reaction occurs in the reactor, that is, no biomass production or substrate utilisation in the clarifier.
4. On the basis of assumption 3 the volume, V represents the volume of the reactor only.

$$\frac{\mu_m S}{K_s + S} = \frac{Q_w X_u}{VX} + k_e \tag{2.17}$$

$$\frac{\mu_m S}{K_s + S} = \frac{Q_o Y(So - S)}{VX} \tag{2.18}$$

On combining the two equations

$$\frac{Q_w X_u}{VX} = \frac{Q_o Y(So - S)}{VX} - k_e \tag{2.19}$$

The inverse of the expression, $Q_w X_u/VX$ is the mean cell residence time (MCRT), and represent the average time microorganisms spend in the reactor, while the inverse of Q_o/V is the hydraulic retention time (HRT) based on influent flow rate. The two factors have a physical significance in reactor design. The MCRT will be greater than the HRT since sludge from the clarifier is returned to the reactor.

$$\frac{V}{Q} = \theta \tag{2.20}$$

$$\frac{VX}{Q_w X_u} = \theta_c \tag{2.21}$$

Where θ = Hydraulic Residence Time

θ_c = Mean Cell Residence Time

On substitution

$$\frac{1}{\theta_c} = \frac{Y(So - S)}{\theta X} - k_e \tag{2.22}$$

The concentration of biomass (mixed-liquor suspended solids – MLSS) in the reactor is related to mean cell residence time and hydraulic retention time and can be got by solving for X in the above equation.

$$X = \frac{\theta_c}{\theta} \frac{Y(So - S)}{1 + k_e \theta_c} \tag{2.23}$$

$$S = \frac{Ks(1 + k_e\theta_c)}{\theta_c(\mu_m - k_e) - 1} \quad (2.24)$$

In a recycle system the effluent substrate concentration is independent of both the influent substrate concentration and the HRT. The limiting HRT is when it approaches the regeneration time of the microorganism and cells are wasted out of the reactor before growth occurs. At this point S approaches S_o, meaning the treatment is very poor (Peavy et al., 1985).

The time a cell remains in the treatment system must be sufficient for growth, otherwise it would be washed out of the system before it has a chance to multiply in which case the process of digestion would fail (Gashaw, 1984). This is the washout residence time, θ_w. it can be calculated by setting S equal to S_o in Equation 2.12, since no substrate consumption occur at washout.

$$\theta_w = \frac{K_s + S_o}{S_o(\mu_m - k_e) - K_s k_e} \quad (2.25)$$

At washout the microorganisms are swept out of the reactor faster than they can grow (reproduce), hence there is no substrate utilization.

2.6.3 Design criteria

Design variables for reactors include; volumetric loading rates, food to microorganism ratio and mean cell residence time.

The volumetric loading rate, V_l, is the mass of BOD_5 in the influent divided by the volume of the reactor.

$$V_l = \frac{QS_o}{V} \quad \text{Kg of BOD}_5\text{/ unit volume} \quad (2.26)$$

The food to microorganism ratio, F/M, is the mass of BOD_5 removed divided by the biomass in the reactor.

$$\frac{F}{M} = \frac{Q(S_o - S)}{VX} \quad \text{Kg of BOD}_5\text{/Kg of biomass .day.} \quad (2.27)$$

The mean cell residence time, θ_c is the mass of viable cells in the reactor divided by mass of viable cells lost per unit time.

$$\theta_c = \frac{VX}{Q_w X_u} \qquad \text{time}^{-1} \qquad (2.28)$$

The mean cell residence time is the most commonly used approach and it allows a trade-off between reactor volume and concentration of the MLSS in the reactor.
The five day biological oxygen demand (BOD_5) or chemical oxygen demand (COD) is usually used as a measure of substrate concentration, while the concentration of suspended solids (SS) or volatile solids (SS) is normally used as an index of biomass concentration (Peavy, et. al, 1985).

2.7 Anaerobic Digestion Process

2.7.1 Concept of Anaerobic Digestion

The fermentative process in which biological oxidation of complex organic matter take place in the absence of oxygen and result in the production of methane and carbon dioxide gases is referred to as anaerobic digestion. In activated sludge process waste is mixed with biomass containing large quantities of microorganisms and with enough supply of oxygen to ensure aerobic conditions. The digestion process results in stabilisation of the soluble organic matter into new cells that can be removed by physical means such as sedimentation (McCarty, 1964). However, the new cells are not fully stable, and thus the problem is simply translated from one of soluble organic matter to solid or semi-solid matter in form of sludge, which needs further treatment before eventual disposal. Oxygen is a limiting factor for all processes whose operation depend on dissolved oxygen due to the relatively low rate of its transfer from the air to the liquid phase. This oxygen transfer limitation is usually the basis of poor performance of aerobic processes in treatment of high-strength organic loading which requires a lot of oxygen for degradation. At this high concentration the anaerobic processes become economical (Curi, 1980).

Natural and a large proportion of synthetic organic compounds can be anaerobically digested and the end products are methane and carbon dioxide from carbonaceous matter and ammonia from organically combined nitrogen, which are stable products (Curi, 1980). In the stabilisation of sludge from municipal wastewater treatment plants, the objective of anaerobic digestion is to convert as much of the sludge as possible to end products such as liquids and gases while producing as little residual biomass as possible (Peavy, et. al., 1985). Anaerobic processes have considerable potential in the treatment of industrial wastewater. Unfortunately, unlike domestic sludge, which is semi-solid and contains large quantities of active micro-organism, most industrial wastes contain soluble organic matter with no active biomass; hence long retention time would be necessary to develop a biologically active environment (Curi, 1980).

2.7.2 Microbiology of Anaerobic Digestion

The biological conversion of organic matter in anaerobic process is a complicated interaction of microorganism which are either strict obligate and are unable to grow in the presence of oxygen, or facultative and can adapt to environmental either with or without oxygen. The latter forming the bridge between the obligate aerobes and obligate anaerobes (Gray, 1989). The microbiological species that co-exist in an anaerobic digestion with their associated substrate have been identified and are summarised in Table 2.2.

The process is broadly considered as two-phase process; the non-methanogenic phase followed by the methanogenic phase. Specifically it can be described as comprising three discrete stages which occur simultaneously; hydrolysis and acid formation being the first phase and the methane formation the second phase as illustrated in Figure 2.10.

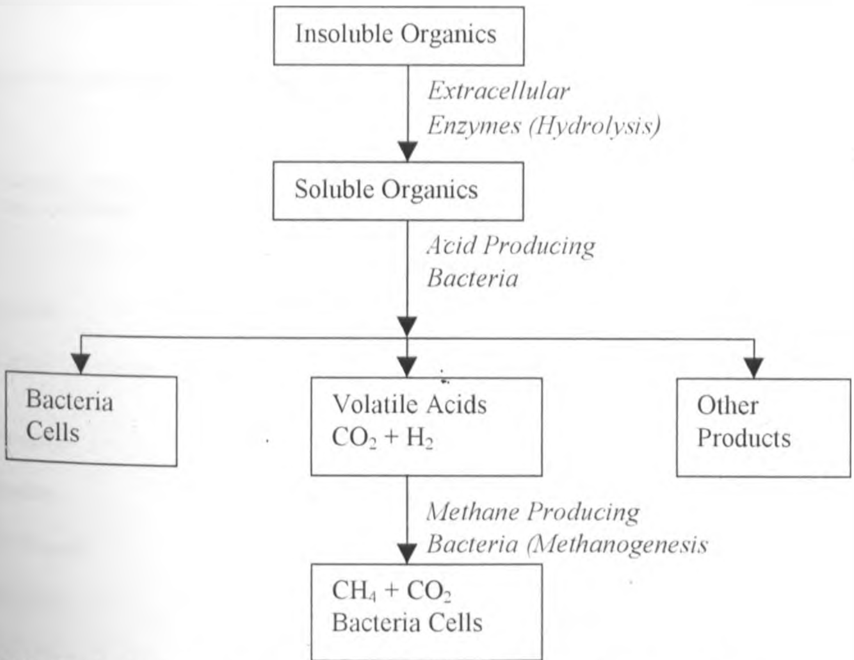


Figure 2.10 Biological activities in anaerobic digestion (Curds et.al., 1983)

Table 2.2 **Main genera in anaerobic digestion with the associated substrate (Bruce, 1986)**

		Substrate degraded	Fermentation products
1 Hydrolysis and acidogenesis			
Aerobes	Pseudomonas Micrococcus	Nutritionally highly versatile starch	Lactate
Facultative Bacillus **Anaerobes**	Streptococcus Lactobacillus Escherichia	Starch maltose numerous sugars numerous sugars	Lactate Acetate
Anaerobes	Clostridia Ruminococcus Bacteroides Butyrivibrio	Cellulose, cellobiose Hemicellulose, pectin Starch	Succinate, acetate Ethanol, hydrogen Formate Butyrate, lactate
	Megasphera Selenomonas Desulfobibrio Bifidobacteria Propionibacterium Peptostreptococcus Anaerovibrio	Lactate, glucose Other sugars Lactate, malate Proteins Amino-acids	Branched VFA hydrogen Acetate, propionate, lactate, hydrogen Acetate VFA Propionate
2 Acetogenesis			
2.1 Non obligate proton reducing bacteria	Desulfovibrio Selenomonas	Lactate, malate Other sugars	Acetate (when associated with methanogens)
	Ruminococcus Clostridium	Cellulose, cellobiose	
2.2 Obligate proton reducing Bacteria		Fatty acids neutralend products	
	Syntrophobacter wolinii Syntrophobacter wolfii	Monocarboxylic C_4-C_8 fatty acids	Acetate
2.3 Homo acetogenic bacteria	Clostridium aceticum C formicoaceticum C thermoautotrophicum Acetobacterium woodii Acetogenium kivui	$CO_2 + H_2$	Acetate
3 Methanogenic bacteria		$CO_2 + H_2$ Formate acetate Methanol methylamines	CH_4
Methanobacterium	Formicicum, Bryantii Thermoautotrophicum		
Methanobrevibacter	Ruminantium,Smithii, Arboriphilus		
Methanococcus	Vannielii, Voitae Thermolithotrophicus, Mazei		
Methanomicrobium	Mobile		
Methanobacterium	Cariaci, Marisnigri		
Methanospirillum	Hungatei		
Methanosarcina	Barkeri		
Methanothrix	Soehngenii		
Methanoghermus	Fervidus		

Hydrolysis: It is an enzyme conversion of complex molecular compounds into simpler compounds suitable for use as a source of energy and cell carbon. The process is carried out by a complex interaction of bacteria, several of which degrade organic polymeric material like polysaccharides, lipids and proteins by means of extracellular enzymes (Novaes, 1986). This results to sugars and amino-acids, which are then fermented to lactase, succinate, pyrurate, propionate, butyrate, valerate, acetate, ethanol, ammonia, sulfide, H_2 and CO_2. The diversity of substrate and intermediary metabolites involved encourage a great variety of microorganisms (Bruce et. al., 1986). As shown in Table 3.1 species acting on cellulose for example are of the genera *clostridia, Ruminococcus, Butyrivibrio,* and *Cellobacterium.*

The hydrolytic step of anaerobic digestion is achieved by mixed group of strict obligate and facultative anaerobic microorganisms. The species and the population of each will vary depending on the composition of the substrate. However research has shown that obligate anaerobes are much more numerous than the facultative anaerobes (Curds et. al., 1975). Therefore the hydrolytic activity of the mixed culture rely principally on obligate anaerobes leading to the production of the intermediate products, which lead to volatile fatty acids fermentation (Bruce et. al., 1986). Heavy production of volatile fatty acids tends to lower the pH, which in effect is inhibitory to other microorganisms, especially the methanogens. However the acidogenic microorganisms will themselves not be affected by a low pH until it reaches about 4.5 (Bruce et. al., 1986). Hydrolysis and acidogenesis lead to formation of: -

- Intermediary metabolites (lactate, succinate, pyruvate)
- End products such as acetate
- Substrates that can be utilized by sulfate reducing bacteria and denitrifying bacteria
- Hydrogen and carbon dioxide

Acid formation: The second step is a bacterial conversion of the resulting compounds into identifiable lower molecular intermediate compounds, namely volatile acids, and ultimately to acetic acid. This is characterized by three groups of microorganisms that are able to produce acetate from various substances namely: -

Non-obligate hydrogen producing acetogenic bacteria are of a genera *Selemomonas, Clostridium, Ruminococcus* and *Desultovibria* can yield higher volatile fatty acids, alcohols, acetate and hydrogen when grown in pure culture. When in a mixed culture with methanogens, the metabolism shifts towards production of more acetate and hydrogen (Bruce et. al., 1986).

Obligate hydrogen producing acetogenic bacteria (syntrophic bacteria) are of the genera *syntrophobacter wolinii* and syntrophomonas *wolfei*. They can co-exist with methanogens to form stable association and they convert fatty acids to acetate and hydrogen (Bruce et. al., 1986).

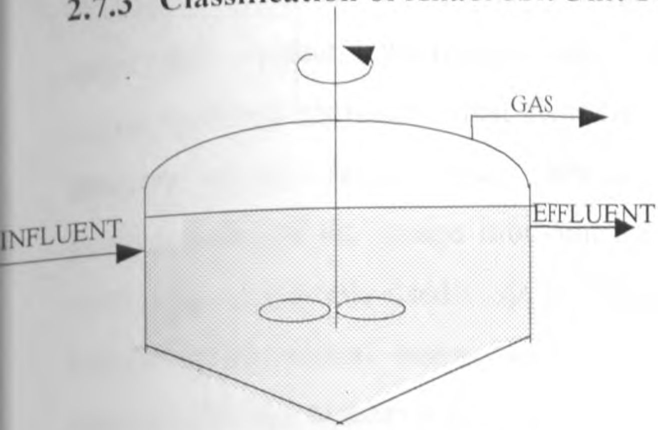
Homoacetogenic bacteria are of the genera *Clostridium formicoaceticum, Clostridium thermoautotrophicum, Acetobacterium woodii* and *Acetogenium kivui*. They can produce acetate from fructose, but are equally able to oxidise hydrogen and reduce carbon dioxide into acetic acid. Therefore, when in a mixed culture with methanogens they can act either as competitors or as donors of acetate, hydrogen and carbon dioxide (Bruce et. al., 1986).

Methanogenesis: Obligate anaerobic bacteria convert the intermediate matter (organic acids) into simpler end products, principally methane and carbon dioxide (Metcalf and Eddy, 1979). This stage is characterized by a very distinct group of microorganisms with respect to their physiology and ecology existing in strictly anaerobic environments (Curds et.al., 1975). They are the last link in the anaerobic transformation of the substrate available in such environments. A common feature in this group of microorganism is that all the members are able to reduce carbon dioxide into methane as final product of their energetic metabolism. Most can even obtain their cell carbon directly from carbon dioxide. They are able to grow on end product of the metabolism of other microorganisms with which they exist in a mixed culture. As they synthesis the end products of these microorganisms they heavily influence the composition and the chemical activity of the whole ecosystem to which they belong. Methanogens show a great affinity for hydrogen since they obtain their energy from the oxidation of hydrogen and reduction of carbon dioxide (Bruce et. al., 1986).

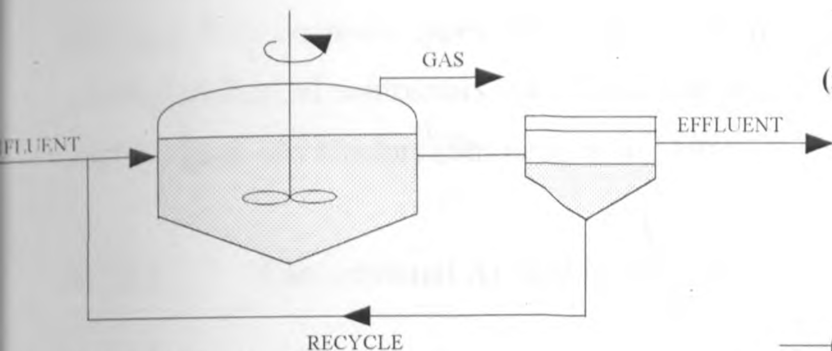
The microorganisms involved at each stage are metabolically dependent on each other for survival. For example the methanogenic bacteria requires the catabolized end-products of the acid formers. However the acid formers would eventually become inhibited by their own end products (acids) if these were not degraded by the methane formers (Gray, 1989). The acid formers (nonmethanogenic) are facultative bacteria, while the methane formers (methanogenic) are strictly anaerobes similar to those found in the stomachs of ruminant animals and in organic sediments taken from lakes and rivers (Desouza, 1986). The most important bacteria of the methanogenic group are the ones that degrade acetic and propionic acids. They have a very slow growth rate. As a result, their metabolism is considered the rate-limiting stage in anaerobic treatment of organic matter (Metcalf and Eddy, 1979).

To maintain an anaerobic treatment system that will stabilise an organic waste efficiently, the nonmethanogenic and methanogenic bacteria must be in a state of dynamic equilibrium. To establish and maintain such a state, the reactor should be void of dissolved oxygen and free from inhibitory concentration of such constituents as heavy metals and sulphides. The two types of microorganisms differ considerably in terms of nutritional requirements, growth kinetic capability and environmental variation. In the same physical and chemical environment the methanogenic population dictates the design and operation of the process (Wanjau, 1986). Anaerobic process is sensitive to acid pH conditions and requires careful control. The pH of the aqueous environment should be in the range of 6.5 to 7.5, a fall below this range means the process is becoming unbalanced (Tebbutt, 1991). Sufficient amount of nutrients (nitrogen and phosphorus) must also be available to ensure the proper growth of the biological community. Due to the low synthesis yields of anaerobes, nutrient requirements are relatively low. Stuckey (1981) suggested a C.N.P. ratio of 150:5:1 for optimal digestion, and these nutrients can be added in the form of ammonium phosphate and ammonium chloride. The optimum temperature ranges between 30^0c to 38^0c and 49^0c to 57^0c for the mesophilic and thermophilic microorganisms respectively (Metcalf and Eddy, 1979).

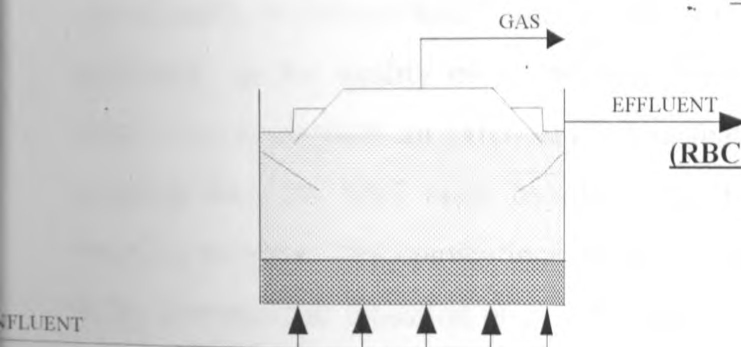
2.7.3 Classification of Anaerobic Unit Processes



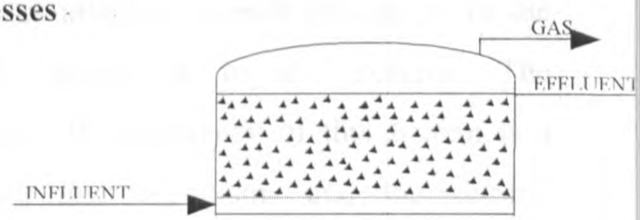
The Continuously Stirred Tank Reactor



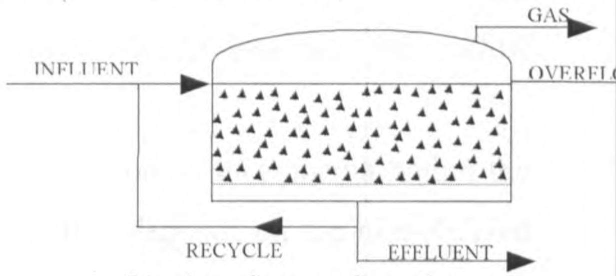
(ii): **The Contact Process**



(iii): **TheUpflow Anaerobic Sludge Blanket Reactor**

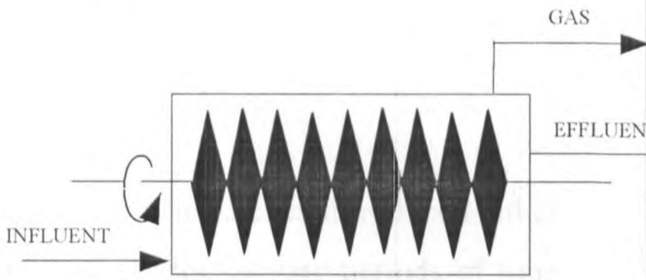


(a) upflow configuration

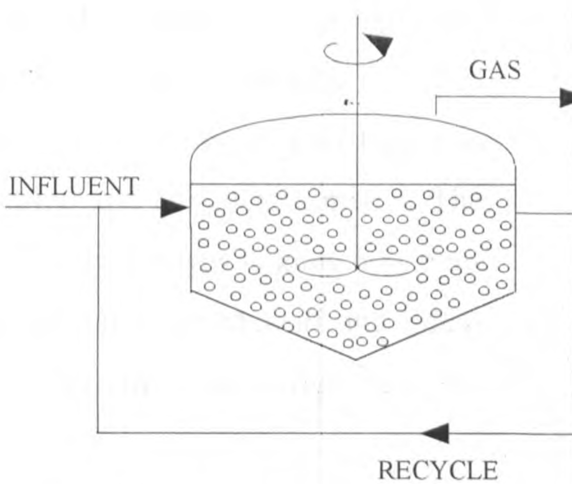


(b) downflow configuration

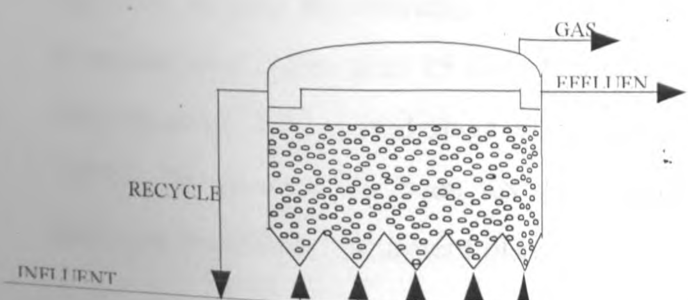
(iv): **Anaerobic Filter Reactors**



(v): **Rotating Biological Contactors (RBC)**



(vi): **The Carrier-assisted Contact Reactors**



(vii):**The Expanded Bed / Fluidised Bed Reactor**

Figure 2.11 Anaerobic unit processes

Anaerobic processes can either be suspended or attached growth processes. In the suspended system, microorganisms remain suspended in the reactor. The microorganisms therefore must form flocs, hence the efficiency of this system is a function of the floc-forming abilities of the microorganisms and the settling characteristics of the sludge inoculum used to initiate the digestion process (Kiama, 1992). The commonly used suspended growth processes are; continuously stirred tank reactor (conventional anaerobic process), anaerobic contact process and upflow anaerobic sludge blanket reactor.

In the attached growth system, microorganisms are held on an inert media within the reactor and the efficiency of organic matter stabilisation depends on the immobilized biomass. The common types of attached growth reactors include; anaerobic filter, rotating biological contractors, carrier-assisted contact reactors, expanded bed reactors and fluidized bed reactors (Stronach, et. al., 1986.

2.7.3.1 Conventional Anaerobic Process

The process is carried out in an airtight reactor, where wastewater is introduced either continuously or intermittently and retained in the reactor for varying periods of time depending on the quality of influent and the required degree of stabilisation. The reactor design requires an extended HRT in that it has no specific means of biomass retention thus the SRT must be sufficiently high to permit biological conversion reactions to occur. The conventional process could either be standard rate or high rate. In the standard rate digestion process, the contents of the digester are usually unheated and unmixed. Detention time for this system varies from 30 to 60 days. In high rate digestion process the contents of the digester are heated and completely mixed. The detention time is less than 15 days. A combination of the two stages is known as two-stage process. The second stage acts as a solid-liquid separation (Metcalf and Eddy, 1979). The process has been used extensively in the treatment of sludge from the domestic wastewater treatment plants.

The anaerobic digester is technically a continuous microbial culture and as such requires a continuous input of medium that is balanced by a continuous outflow of digested wastewater and excess biomass. Unfortunately the normal pumps have too great a pumping volume to permit the continuous feeding of the small volumes necessary for long detention periods within the reactor. Input is therefore usually intermittent. Mixing in these reactors tend to be equally intermittent (Stronach et.al. 1986). Activities and efficiencies of ten anaerobic full-scale digesters were investigated, eight of which were of the stirred tank configuration, and the loading rates employed varied from 0.7-3.2 kg VS $m^{-3}d^{-1}$ and the waste contained 4.7-11.3% total solids. Reduction of 27-44% VS were reported and methane production ranged from 53-70% of the total gas (Stronach et.al. 1986).

2.7.3.2 Anaerobic Contact Process

In a system without sludge recycle the limiting retention time is reached when the microorganisms are being removed from the system faster than they can reproduce. To ensure microorganism reproduction especially in industrial wastewater treatment, long hydraulic residence time would be necessary to control bacteria washout, thus requiring very large reactors. The long hydraulic residence time stems from the slow growth of the methanogenic bacteria (Koziorowski et. al., 1972). As a result the solid retention time need to be controlled independent of the hydraulic residence time. By using the concept of mean cell residence time (sludge age) as applied in activated sludge process, attempts have been made to activate the anaerobic bacteria to improve the performance of the conventional anaerobic process. This is the basic principle in anaerobic contact process where process settling of microbial flocs and other suspended solids are contacted with the raw waste (Van den Berg et. al., 1978). In this process sludge rich in acclimatized microorganisms is recycled to the reactor from the settling tank. This has an overall effect of reducing the long hydraulic residence time for the same quality of effluent (Curi, 1980). Re-inoculation of a well-acclimatized sludge can maintain optimum stabilization of industrial wastewater, which, unlike sewage sludge do not contain a high proportion of microflora. The microorganisms are maintained in suspension by mechanical agitation. Separation of flocs and treated wastewater occurs in a separator unit such as a sedimentation tank. The contact process comprises a continuously fed, completely mixed flow reactor stage followed by a solid-liquid separation stage at which the settled biomass is recycled back to the reactor. COD reduction of between 90 and 95% has been achieved with wastewater of COD values in the range of 2000 to 10000mg/l (Stronach et. al, 1986).

2.7.3.3 Up-flow Anaerobic Sludge Blanket (UASB)

In this type of reactor the biomass is retained as a blanket and kept in suspension by controlling the upflow velocity. The process relies on the development of a highly settleable granular sludge within the reactor, and requires no inert support media. Creating a quiescent zone within the digester can reduce washout from the sludge blanket. The wastewater flows through an expanded bed of active sludge while the upper part of the reactor contains a three-phase separation system, allowing gas collection and sludge recycle. Long solids retention time can be maintained with short HRT. hence the volume of reactor can be greatly reduced. The limitation of the process is based on problems associated with the development of the granular sludge. UASB are particularly suitable for the treatment of wastewater with low suspended solids (less than 500 mg/l) and high dissolved organic substances. Initial seeding with active digester sludge is necessary for effective start-up of the reactor. At an organic loading rate of 11.15 kg COD m^{-3} d^{-1} and HRT of 7 days, 95% COD removal have been recorded (Stronach et. al., 1986).

2.7.3.4 Anaerobic Filter

It is a fixed bed system where the microorganisms in the filter get attached or become entrapped to an inert medium. The vertical flow can be either up-flow or down-flow. The process was developed because of difficulties experienced with the treatment of dilute soluble organic industrial wastewater (Stuckey et. al. 1981). By carrying out extensive laboratory studies, Young and McCarty (1969) illustrated the potentials of upflow anaerobic filter for the treatment of dilute organic wastestreams and production of gas of methane content of up to 75% (Stronach, et.al, 1986). A substantial percentage of the biomass remains as suspended flocs in the spaces between the media particles. The process operation and efficiency is well documented by Stronach et al

(1986). Upto 85% COD removal of both strong and weak organic matter, while 90-99% COD removal from dairy wastes was achieved using anaerobic filters.

2.7.3.5 Rotating Biological Contactors (RBS)

The Microorganisms attach to the inert plastic medium to form a fixed film. The partly or fully submerged disc array rotates slowly on a horizontal axis in the reactor. A plug flow condition prevails and the excess sludge leaves the reactor with the treated wastewater. The high hydraulic shear induced on the biofilm enhances mass transfer from substrate to microbial film. The mode of attachment of the biomass provides adequate cell retention in the reactor, hence promoting the development of long mean cell residence times (Stronach, et. al. 1986). Floating solids present few problems as a large liquid gas interface exists within the reactor. At loading of 10-20 kg COD $m^{-3}d^{-1}$ a COD reduction of 60-80% have been recorded (Stronach et. al., 1986).

2.7.3.6 Carrier-Assisted Contact Reactors.

The process is basically similar to the contact process except the incorporation of an inert media into the reactor. Small inert particles with a low settling velocity are used. These can be maintained in suspension with relatively low degree of mixing. The microorganisms in the system attach to those inert particles enabling a substantial percentage of the active biomass to exist as suspended flocs. The reactor bed is maintained in suspension by mechanical agitation. The low volumes of carrier media in this system assist in biomass retention and reduce the reactor volume requirements. Even non-biodegradable matter in the system may get attached to the carrier media and consequently settle out with the flocs. Using synthetic molasses wastes at organic loading of 3.9 kg COD $m^{-3}d^{-1}$ and HRT of 2.4 days, total COD reduction of upto 90% were reported (Stronach et. al., 1986).

2.7.3.7 Expanded Bed Reactor

The reactor is a cylindrical structure packed with inert supportive particles to about 10% of its volume. The media particles are covered in the biofilm matrix and expanded by a vertical fluid velocity generated by a high degree of recycle. The expansion is such that each particle retains its position relative to every other particle within the bed. The major advantage in expanding the anaerobic reactor bed is the minimization of clogging problems while simultaneously accumulating significant quantities of microorganisms on the surface of the media. Study carried out by Schraa and Jewell showed that both methanogenic and non-methanogenic bacteria were present in the attached and the entrapped biomass. The effectiveness of the expanded bed process may be accredited to the large surface area to volume ratio. This is made possible by the use of small carrier media, the thin nature of the biofilm minimizing diffusion difficulties and the large mass of attached bacteria that can be maintained within the bed at high fluid velocities. COD removal of upto 85% was reported at loading rates of the order of 6.0 kg $CODm^{-3}d^{-1}$(Stronach et. al., 1986).

2.7.3.8 Fluidised Bed Reactor

The microorganisms in anaerobic fluidized bed (AFB) system attach to small diameter media. The high vertical velocity of the wastestream to be treated expands the bed to a point beyond which the net gravitational force is equaled by the frictional drag. Single carrier grains do not have a fixed position within the bed. The reaction zone expands to accommodate increasing microorganism growth. Bacterial activity in fluidized beds, unlike that in other fixed-film reactors has been shown to be greatest for both acetogenic and methanogenic bacteria in the central region of the bed (Stronach et.al. 1986). The fixed film nature of the fluidized bed process permits the maintenance of extended mean cell residence times at low HRT without the requirement for biomass settling and recycles. Organic loading and bacteria growth are the only two parameters controlling the mean cell residence time (Cooper et. al., 1981). Investigated by comparison of four reactor configurations, predicated the superiority of a single pass fluidized bed, in that the plug-flow aided the even distribution of biofilm throughout the reactor. COD removal efficiencies of between 79% and 93% with 81-84% methane content in the gas have been recorded. (Stronach, et. al. 1986).

2.8 Environmental Factors Requirements

Microorganisms function effectively within certain environmental ranges. Several environmental factors can affect the process, either by enhancing or inhibiting parameters such as specific growth rate, decay rate, gas production, substrate utilization, start-up and response to changes in input (Stronach et. al 1986). Anaerobic digestion being a two phase process is characterized by two types of microorganisms namely the acid formers which are fast growing and pH tolerant, while the methane formers are slow growing and very sensitive to pH variation. Generally the two groups of microorganisms are very different in terms of nutritional requirements, growth kinetics and response to environmental changes. The purpose of environmental factor control is to maintain a dynamic equilibrium between the two types of microorganisms in the same bioreactor. Due to the sensitive nature of the methanogens, the design and operation of anaerobic bioreactor will be dictated by the environmental requirements of the methane formers. The environmental factors affecting the proper functioning of methanogens include: -

a) Anaerobic conditions
b) pH, alkalinity and volatile acid concentration
c) Nutrients
d) Inhibition/Toxicity
e) Temperature

2.8.1 Anaerobic Conditions

Methanogens are a very distinct group of microorganisms in terms of their physiological and ecological environment. They are strictly anaerobic and therefore can only thrive in such conditions. Even low concentration of dissolved oxygen has a major drawback on the methane formers, and therefore must be avoided. Acid formers are more tolerant in that they are either obligate or facultative (Wanjau, 1986).

2.8.2 pH Alkalinity and Volatile Acid Concentration

Most microorganisms exhibit a pH value at which growth is maximal. Thus control of pH is fundamental to the maintenance of optimal bacterial growth and/or conversion processes in anaerobic microbial systems. Most of the microorganisms operate optimally at pH close to 7. The ideal pH range for growth and production of methane is between 6.8 and 7.2, but may vary among the known species (Desouza, 1986). The pH in anaerobic systems is controlled by the interaction of the carbon dioxide/bicarbonate buffer system and a strong base which is the summation of all strong acids and bases including volatile fatty acids and ammonia (Stuckey et.al, 1981). Acidity or alkalinity of the anaerobic reactor contents is the result of acid base system interactions. These systems can be weak or strong and the acidic and basic components may be present in the influent wastestream, or may be the result of reactions occurring throughout the degradation process. When digesters become unbalanced, the volatile acid concentration increases, destroying the bicarbonate alkalinity, resulting in pH decrease. In such cases the pH can be maintained in the optimum range by the addition of a base.

Methane conversion rate inhibition by the volatile acids at acidic pH values can be attributed to the existence of unionized VFAs in significant quantities in the system. These unionized acids are present in amounts dependant upon the total concentration of volatile acids in solution. The undissociated nature of these acids allow them to penetrate the bacterial cell membrane more efficiently than their ionized counterparts, and once assimilated, induce an intracellular decrease in pH and hence a decrease in the metabolic rate of the microorganisms (Wanjau, 1986). Acetate has been described as the least toxic of the volatile acids, whilst propionate has often been implicated as a major source of digester failure. Methanogens are inhibited at propionate concentrations in excess of 3000 mg/l although this effect could be overcome by acclimatization. It has been observed that methanogens tolerated both acetate and butyrate at concentrations of upto 10,000 mg/l and 5000 mg/l (Stronach et al, 1986).

In general a high volatile acid concentration is the result of unbalanced treatment and not the cause as is sometimes believed. Thus a high acid concentration in itself is not harmful, but indicates that some other factors are affecting the methane bacteria. A bicarbonate alkalinity in the more desirable range of 2500 – 5000 mg/l provides much buffer capacity so that a much larger increase in acid can be handled with a minimum drop in pH than that of 1000 mg/l (McCarty, 1964).

2.8.3 Nutrients

Efficient digestion processes require that the medium in which the microorganisms grow and multiply contains energy sources, sources of nitrogen and carbon for the biosynthesis of new cells, and trace elements, sulfur and other ions necessary for bacterial metabolism. Phosphorous, which is necessary for nucleic acid synthesis and as a component of many other cellular constituents, is required in low amounts as phosphorous (Stronach et al, 1986). Due to the low synthesis yields of anaerobes, nutrient requirements are relatively low. Stuckey (1981) suggested a C.N.P. ratio of 150:15:1 for optimal digestion, and these nutrients can be added in the form of ammonium phosphate and ammonium chloride. Micronutrients needed include magnesium, potassium, cobalt, zinc, manganese, calcium, and iron and copper (Stuckey et al, 1981). These nutrients must be present in an available form, in slight excess of their optimum since if they are not they can markedly decrease the rate of anaerobic degradation. Often industrial wastes are deficient in some nutrients, and close attention should be paid to nutrient requirements in initial feasibility studies.

The COD: N ratio is frequently utilized to describe nutrient requirement. Stronach et al (1986) reported that for these anaerobic processes at high loading 0.8 –1.2 kgCOD/kgVSS/d a COD: N ratio of around 400:7 has been estimated whereas at lower loading (<0.5 kgCOD/kgVSS/d) values of 1000:7 or more are necessary. The N/P ratio has been reported to be approximately 7. Other forms of trace elements are required in small quantities since they are toxic beyond certain concentration levels.

2.8.4 Temperature

There are three temperature ranges in which anaerobic microorganisms exist; Psychrophilic (below 20^0C), mesophilic ($20-45^0C$) and thermophilic ($50-65^0C$). The optimum temperature for mesophiles appears to be around 35^0C, while for thermophiles it is 55^0C (Stronach et al, 1986).

Until recently, temperature of operation was an important parameter in the design of anaerobic processes since it had to be kept close to the optimum to ensure maximum growth rates, and hence minimum detention times. To maintain optimum temperatures a large fraction of the methane produced often had to be burned to preheat the influent waste, resulting in low or negative energy yields. Recently with innovations in design, it has been possible to operate at temperatures lower than the optimum without significantly decreasing the efficiency of the process. With industrial wastes in developing countries two factors usually arise which tend to mitigate this problem. Firstly, most industrial wastewater tend to be warm due to the nature of the production processes, hence they usually require little or no heat before treatment. Secondly, average ambient temperatures tend to be warmer in comparison with developed countries, and hence heat losses are less. Activation energies for microbial growth are often in the range 10 to 20 Kcal/gmol or about 40 to 80 KJ/g/mol (Erickson et. al., 1988). The effect of temperature on growth may depend on the concentrations of other chemicals in the fermentation broth (Erickson et. al., 1988). Such solvents as ethanol or butanol have an effect on membrane transport that depends on temperature e.g. the optimum temperature for growth decreases as ethanol concentration is increased. Temperature affects the product formation kinetics. It has been observed that the maintenance coefficient of non-growth associated product formation coefficient increased with temperatures and also with ethanol concentration for Zymomenas Mobilis (Erickson et. al., 1988).

2.8.5 Inhibition and Toxicity

Toxins tend to inhibit the growth of anaerobes leading to a stressed situation and eventual process failure. Their effect appears to be more on the last two steps of anaerobic digestion rather than the fermentative bacteria, although heavy metals appear to affect all three (Stuckey et al, 1981). Toxins tend to fall into two categories, organic and inorganic. The organic, which cause toxicity at low concentrations, include the methane analogs; tetrachloromethane, chloroform, azides, amines, hydrozines, ethylene dichloride and vinylchloride. Other organic such as propionic acid and long chain fatty acids are toxic at high levels (Stuckey et al, 1981).

Many inorganic are not toxic except at high levels, relative to organic compounds except a few like cyanide and hydrogen ions, which are toxic at very low levels (Stuckey et al 1981). Inorganic toxic at high levels includes sulphide, salt cations, ammonia, calcium, magnesium, sodium, potassium and heavy metals. However, due to antagonism, synergism and acclimatization it is often very hard to determine the toxicity threshold of a specific substance. Antagonism is a reduction of the toxic effect of one substance by the presence of another, while synergism is an increase in the apparent toxicity of one substance caused by the presence of a second substance in the environment. Toxicity can be controlled by either;

- removal of toxic material from wastewater
- dilution below toxic threshold
- formation of insoluble complex or precipitate
- Addition of an antagonistic material to decrease the toxicity of another material e.g. sodium or potassium for wastes with calcium or magnesium.

2.9 Start-Up of Anaerobic Digester

Research has shown that a considerable time lapse is needed in the initial stages of anaerobic reactor systems before stability (steady state) is achieved. The time lapse is referred to as start up and is characterized by very erratic parameters. The major difficulties are the development of the most suitable microbial culture for the particular wastewater introduced in the system. Once the necessary biomass has been established the operation of the digester becomes stable (Stronach, et al., 1986). The efficiency of a start-up procedure is evaluated by the number of days after which full load could be introduced without causing any digester upsets or the time to achieve steady state conditions. The start-up procedure should involve waste analysis, inoculation, loading varied from minimum to maximum and monitoring of the digester during the loading period to avoid failure. (Kiama, 1992).

2.9.1 Waste Analysis

Waste analysis is essential in accessing the biodegradability, nutrient requirements and the presence of toxic substances. BOD_5: COD ratio indicates the biodegradability of the waste while either COD: N: P or BOD_5: N: P ratio are the indicators of nutrients requirement.

2.9.2 Inoculation

Methanogenic bacteria exhibit a growth rate much slower than those of aerobes, thus the need for an active biomass to permit a rapid start-up of the anaerobic digester has to be emphasized (Wanjau, 1986). In essence, therefore seeding of reactors at start-up is very significant in terms of start-up time reduction. The amount of seed required depends on the availability of the inoculation for a given digester size but in general a seed inoculum of 30 to 50% of the digester volume reduces the start-up time required considerably (Stronach et.al 1986). Seeding can be done by use of sludge from an identical process, domestic sewage treatment plant or seed grown on complex waste. In the use of seed from an operational identical digester, microorganisms required for degradation are already present and acclimatized to the waste. With the municipal sludge, the relevant microorganism for the particular waste have to be selected from the heterogeneous biomass and they need time to acclimatize to the wastestream before effective digestion can occur. Where the seed sludge had been grown up on a complex substrate, the presence of heterogeneous microbial population ensures rapid selection of relevant microorganisms upon introduction into the digester system (Stronach et.al 1986).

A pH control start-up procedure is yet another alternative that assumes that the raw seed have biomass in small amount to act as the inoculum. The digester is filled with raw seed and full hydraulic load is established in a stepwise operation. The pH is controlled by addition of a base until stable condition are attained (Kiama, 1992). Unfortunately time to attain fully-grown biomass may be too long.

2.9.3 Loading Procedure

An appraisal of the start-up of anaerobic fluidized bed made by Bull et. al (1983) using continuously loading and step-loading during start-up showed that the most efficient start-up regime was stepped-loading process (Stronach et.al., 1986). The absence of operational difficulties using this system indicated that markedly greater COD loading could be applied, with resultant rapid start-up and continued reactor efficiency. According to Stronach et.al (1986) loading rate in the initial phase of start-up of the reactor must be low. Loading increase should be halted immediately any sign of imbalance is observed (Kiama, 1992).

2.9.4 Monitoring of the Digester

The most common indicator of digester failure is the imbalance between production and consumption of volatile acids. These acids which serve as the substrate are also inhibitory to the methane producers. In the inhibitory range, a substrate increase causes a decrease in methanogen growth, which in turn decreases the total acid consumption rate, resulting in a further increase in acid concentration. The simplest way of detecting the imbalance is by monitoring of pH in that an increase in acidity lowers the pH.

For the purposes of monitoring the general behavior of the digesters the influent and effluent, COD, SS,BOD_5, MLSS, mixed liquor pH and daily gas production are usually measured (Gashaw, 1984).

2.10 Digester Failure

Several factors can be responsible for imbalance such as poor mixing, low residence time, high solids concentration in the seed, toxic substances, nutrient imbalance and temperature shock. The intermediate products of anaerobic fermentation, such as volatile organic acids, may be toxic to the methane forming bacteria, thus upsetting the whole process. Equally waste may not contain sufficient electron acceptors to permit complete oxidation, hence may not result in stable products (McGhee, 1991). Mixing avoids grit and scam accumulations, which reduces the actual volume of the digester and also provides uniform substrate and biomass concentrations and hence prevent localized formation of acid spots or dead regions. Good mixing is necessary for satisfactory digester performance. Depending on the design there is a maximum allowable feed solids concentration beyond which adequate mixing is not possible. A decrease in mean cell residence time can decrease the biomass concentration of methane formers with respect to acid formers, due to the lower specific growth rate of the methane formers. If the inhibitory range is reached, the digester becomes unstable because of acid accumulation, and methanogens are washed out.

According to Erickson et. al. (1988) the drops in pH, alkalinity, gas production, rises in volatile acids and the acid/alkalinity ratio although evident near failure are not very reliable as good indicators of an imminent digester failure since they can vary significantly even under normal conditions. In their study, Erickson et. al. (1988) concluded that a more reliable indicator seems to be the distribution of organic acids, with large relative increase towards butyric and higher acids occurring near failure (Erickson et. al., 1988). For control purposes the most commonly employed parameter is the control of pH by additions of a base to increase alkalinity (Stronach et. al., 1986).

3 PROCESS MODIFICATION

3.1 Theoretical Model

Despite the development of several anaerobic treatment systems, use of some of them still remains low, especially in the treatment of industrial wastewaters. Usually the fear is based on the process lack of stability, low loading rates, slow recovery after failure and other specific requirements (Van den Berg et. al., 1983). The continuously stirred tank reactor has no specific means of biomass retention, thus the SRT must be sufficiently high to permit effective microbial growth in the reactor. This can only be achieved by allowing long HRT. Therefore, reactor volume must be sufficiently large to accommodate that long HRT. Based on literature data, the minimum HRT for a fully mixed digester is determined by the growth rate of the acetate-converting methanogenic microorganisms. The HRT is dependent on the organic loading rate and varies between 10 and 60 days for heated digester and between 90 and 200 days for cold digester (Stronach et. al., 1986). Industrial wastewaters contain organic matter largely in solution, and are characterized by low microorganism population. Consequently, their treatment by CSTR system is limited by the extended HRT necessary to develop and maintain an active microbial mass.

Furthermore, there is a limit to the organic load that can be applied to the CSTR system due to the relatively low level of microorganisms present in industrial wastewater. Kiama (1992), gave typical organic loading rate for conventional treatment process in the range of 0.25 to 3.0 kg COD m^{-3} d^{-1}. Unfortunately, most industrial wastewaters exhibit very high COD levels, such that maintaining the organic loading rate in this range would require very large reactors or very low flow rates, which may not be economically viable.

Aerobic process has been improved by the concept of activated sludge process in which the solid retention time is controlled independent of the hydraulic residence time, by way of recycling sludge rich in acclimatized microorganisms. Similarly industrial wastewater can be treated anaerobically at low hydraulic retention time by incorporating microorganism concentration by either recycle or retention, analogous to activated sludge process. Biomass can be retained either as suspended or attached growth. In principle loading potentials of anaerobic treatment systems are dictated by:

- the amount of viable biomass which can be retained under the loading conditions;
- the contact between the viable sludge and the wastewater to be treated;
- the rate of the biological conversion processes (Pol et. al., 1986).

The advanced reactors differ in the way the biomass is retained and the way the contact is achieved (Van den Berg et. al., 1983). In terms of viable biomass retention, the difference is fairly marginal, but sufficient contact between the retained biomass and the influent wastewater is significant. In this respect the attached biomass systems are superior over the suspended biomass systems (Pol et. al., 1986). Unfortunately, the latter depend more or less on the packed bed and suffer from severe clogging (Pol 1986).

The specific interest was the contact of the sludge and the wastewater in the suspended growth systems with emphasis on recycled biomass as a way of improving the contact efficiency. In most laboratory studies the flow is intermittent with respect to both influent wastewater and recycled biomass (Curds et.al., 1983). This way, the residence time for both the wastewater and the biomass is the same, hence a high degree of contact is anticipated. However in field situation, the incoming flow is usually continuous and this is thought to have its unique effects, hence a study with a continuous wastewater flow would approximate more closely to the field conditions.

In a fixed volume reactor the relationship of the specific growth rates for recycle and non-recycle reactors can be obtained by solving equation 2.17 (for recycle) and comparing it with equation 2.10.

$$\mu = \frac{\mu_m S}{K_s + S} = \frac{Q_w X_u}{VX} + k_e$$

But $$\frac{Q_w X_u}{VX} = \frac{1}{\theta_c}$$

$$\mu = \frac{1}{\theta_c} + k_e \tag{3.1}$$

By comparing equations 2.10 and 3.1 it can be concluded that for a given residence time the specific growth rate is decreased by introducing recycle since θ_c is normally much high than θ. Consequently a given specific growth rate can be attained at a lower residence time when biomass recycle is employed. This can be better illustrated by plotting specific growth rate against residence time and taking θ_c as factors of θ and assuming a value of k_e as in Figure 3.1.

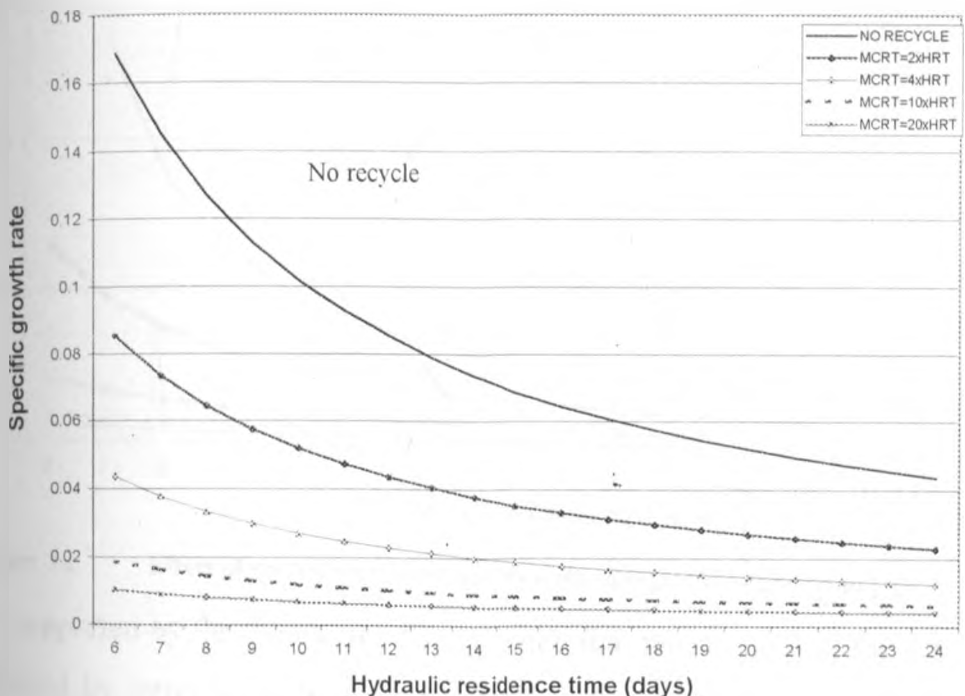


Figure 3.1 Effect of biomass recycle on specific growth rate

Figure 3.1 shows that the higher the θ_c the lower the specific growth rate implying that an increase in solid retention time has the effect of reducing the time required to achieve a particular microorganism population. Consequently, for the same quality of effluent a recycle system would require a shorter residence time.

To confirm this theory the effluent substrate concentration for both recycle and non-recycle systems are plotted against residence times as shown in Figure 3.2. This is done by taking various θ_c as factors of θ and assuming typical kinetic values and using equation 2.13 for no recycle and equation 2.24 for a recycle system.

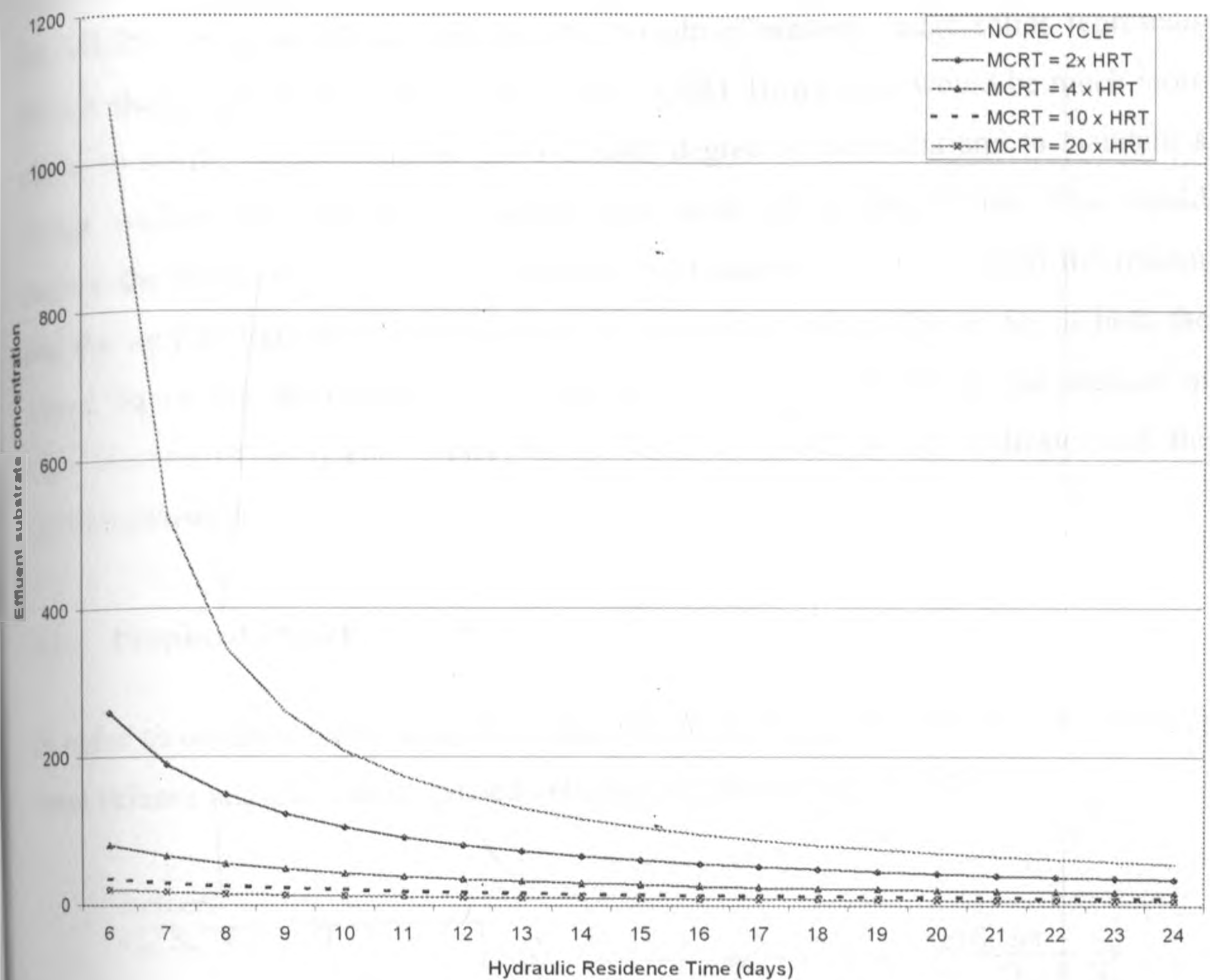


Figure 3.2 **Effect of recycle on effluent quality with changing residence times**

As supported by the theory, it can been noted that the strength of the effluent is greatly reduced by introducing biomass recycle. Furthermore, the higher the solid retention time, the higher the degree of waste purification.

The amount of return sludge needed depends on the MLSS or MLVSS required in the reactor. In activated sludge treatment, upto 100% of the inflow can be reached for the return sludge rate (Gashaw, 1984). Based on this, the required recycle rate can be calculated for any reactor. Daily sludge wasting is an important aspect in the maintenance of steady state (Gashaw, 1984). According to literature of activated sludge process wasting of sludge can be done: -

- directly from the reactor
- from the delivery pipe between the reactor and the clarifier
- from the recycle line

Normally the sludge is wasted from the recycle line. If by sludge wasting operation, the MLSS is maintained constant then the weight of wasted sludge solids represents the net sludge growth in the system (Gashaw, 1984). However it would be much more easier to set the MCRT required for a desired degree of treatment and to maintain a sludge wastage rate that would result in this mean cell residence time. This would require the determination of the concentration of microorganisms in both the reactor and the recycle line, which can be done by measuring either VSS or SS of both the mixed liquor and the biomass. According to Peavy et al., (1985), in the absence of high fraction of inorganic, either SS or VSS are good enough indicators of the microorganism levels.

3.2 Proposed Model

In order to obtain a relationship between influent flow, Q_o, and the recycle flow, Q_r, mass balance analysis can be carried out along the dotted line of Figure 3.3.

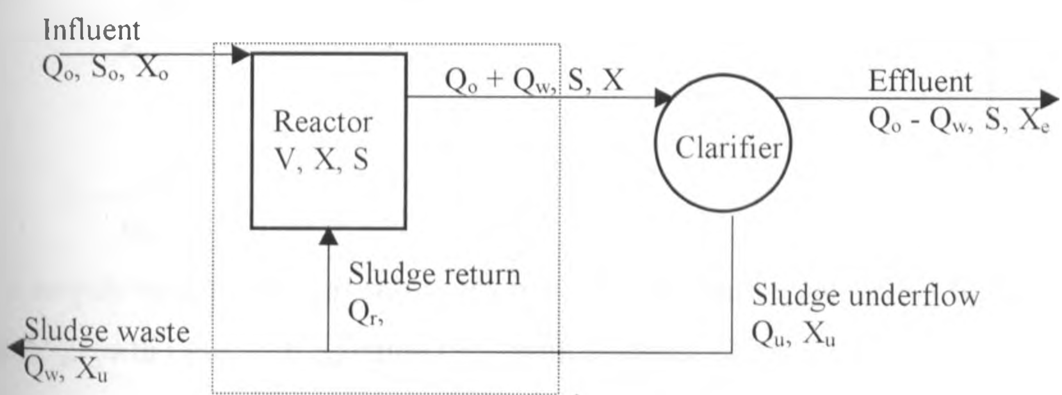


Figure:3.3 Completely mixed flow reactor with recycle

Biomass balance

$$Q_o X_o + Q_r X_u + V(\mu X - k_e X) = (Q_o + Q_r)X + V\frac{dX}{dt}$$

$$\frac{Q_r}{V}X_u + \mu X - k_e X = (\theta + \frac{Q_r}{V})X$$

$$\frac{\alpha}{\theta}X_u + \mu X - k_e X = (\frac{1+\alpha}{\theta})X \qquad \alpha = \frac{Q_r}{Q_o} \quad = \text{Recycle ratio}$$

$$\mu X = \frac{1}{\theta}[(1+\alpha)X - \alpha X_u] + k_e X$$

$$\mu = \frac{1}{\theta}\left[1 + \alpha(1 - \frac{X_u}{X}\right] + k_e \tag{3.2}$$

When equation 3.2 is compared with equation 2.10 (no recycle reactor) it can be deduced that for a given residence time the specific growth rate is decreased by a factor $\alpha(1-X_u/X)$ since X_u is always higher than X

By use of the Monod function (Equation 2.2) the effluent substrate concentration can be expressed in terms of specific growth rate, μ

$$\mu = \frac{\mu_m S}{K_s + S}$$

$$S = \frac{\mu K_s}{\mu_m - \mu} \tag{3.3}$$

For a recycle system effluent substrate concentration can be calculated by substituting specific growth rate, μ, in equation (3.3) with equation (3.2).

$$S_r = \frac{\frac{K_s}{\theta}\left[1 + \alpha\left(1 - \frac{X_u}{X}\right)\right] + k_e}{\mu_m - \frac{1}{\theta}\left[1 + \alpha\left(1 - \frac{X_u}{X}\right)\right] + k_e} \tag{3.4}$$

For a non recycle system the specific growth rare is as in equation (2.10) and can be used to express the effluent substrate concentration by substituting in equation (3.3)

$$\mu = \frac{1}{\theta} + k_e$$

$$S = \frac{K_s(1 + k_e\theta)}{\theta(\mu_m - k_e) - 1} \tag{3.5}$$

By setting specific values of recycle ratio, X_u, X and taking various values of hydraulic residence time and assuming typical kinetic values it is possible to demonstrate that biomass recycle system would be expected to display a better effluent quality (lower concentration) than a conventional system. This can be illustrated graphically as in Figure 3.4 by calculate the effluent concentration using equation (3.4) for a recycle process and equation (3.5) for a non-recycle process.

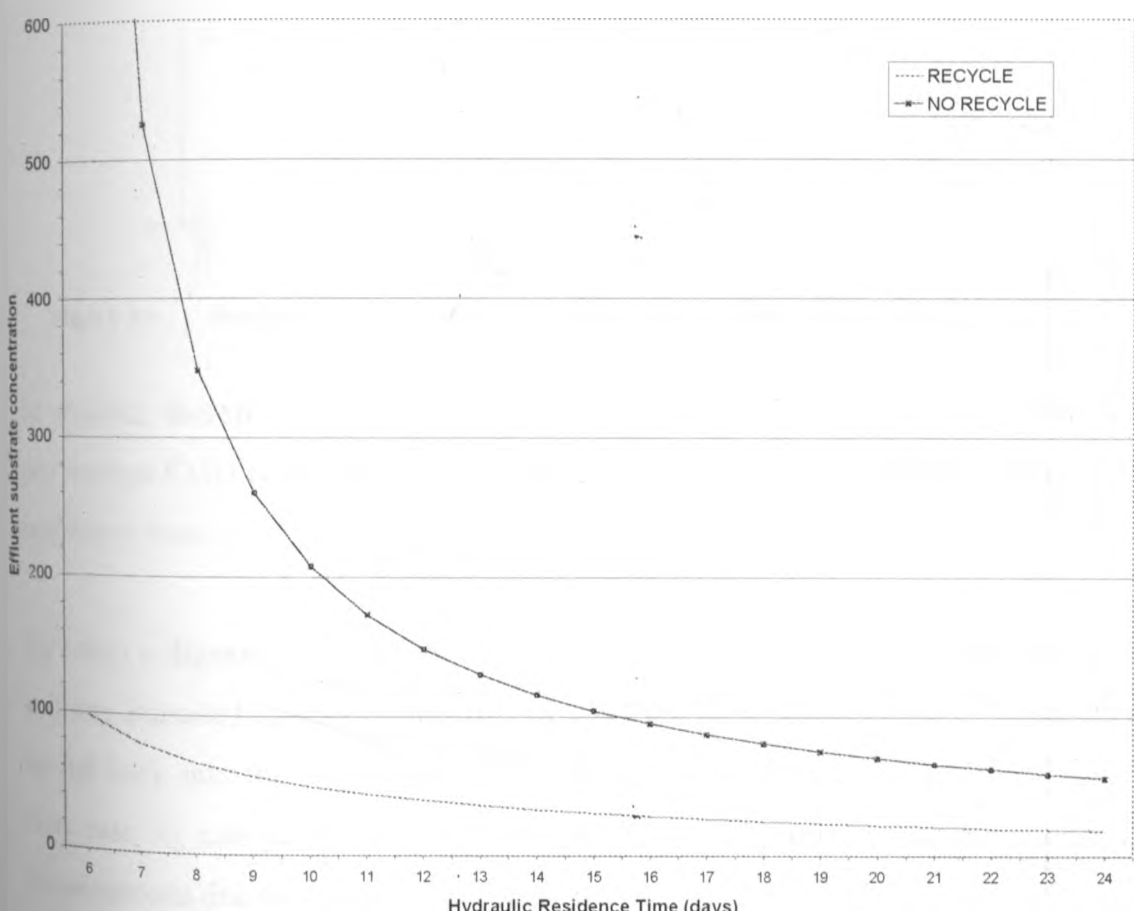


Figure 3.4 Predicted trend of effluent quality against HRT

It is equally possible to predict the relationship between loading rate and COD removal by using the proposed model. This can be achieved by calculating θ for preset influent concentration and loading rates and assuming typical kinetic values and again using the above equations. Figure 3.5 show the model prediction of percentage COD removal against loading rate achieved by use of imaginary values for illustration purposes.

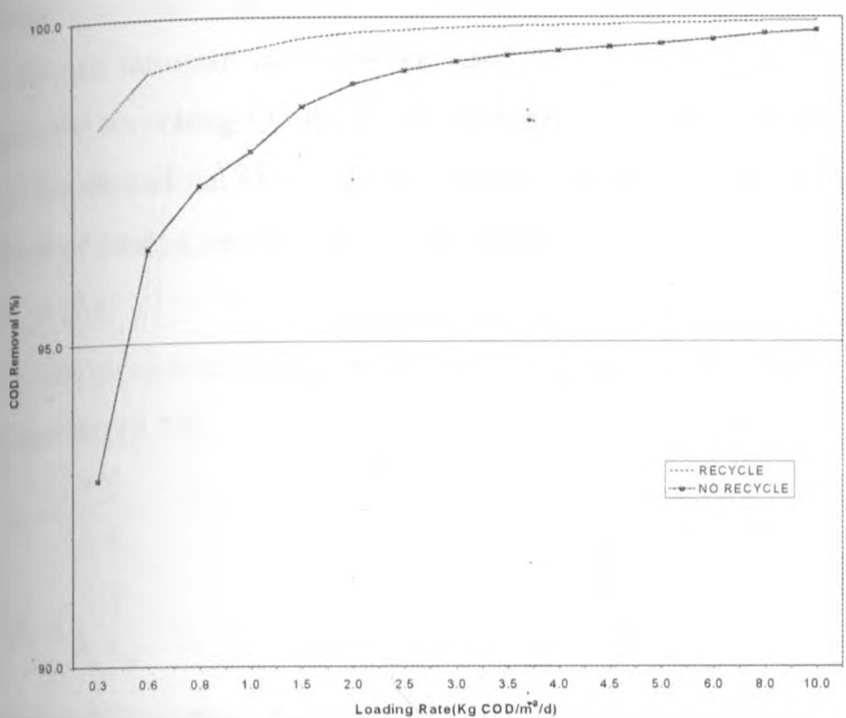


Figure 3.5 Predicted trend of percentage COD removal against loading rate

In essence therefore biomass recycle digester would be expected to exhibit a higher percentage COD removal relative to the conventional digester for any given hydraulic residence time.

By using a digester of fixed volume, V, the flow rate, Q_o can be varied accordingly to suit any intended hydraulic retention time. A predetermined volume, V_r, of sludge can be fed back into the reactor after a given time interval, t. Therefore the sludge return flow rate, Q_r can be taken as V_r/t for simplicity. The mixing can be assumed to be instantaneous due to complete mix regime.

$$\theta = \frac{V}{Q_o + Q_r} \qquad (3.6)$$

For a fixed digester volume and a set HRT the combined flow rate ($Q_o + Q_r$) can be obtained by dividing the volume by the HRT. The recycle ratio, Q_r/Q_o can be predetermined on the basis of the activated sludge process. Generally in the activated sludge process a sludge volume of 20-50% of the flow through the plant is drawn off from the settling tank and between 50-90% of this is recycled. If insufficient sludge is returned mixed liquor suspended solids (MLSS) will be low and poor stabilization will result, while the return of excessive amount of sludge will result in very high MLSS which may not settle down well (Tebbutt, 1991). Analysis from the above indicates that the recycle ratio can vary between 10-45%.

Consequently on setting Q_o the return flow rate, Q_r can easily be calculated. Having obtained the theoretical Q_r the sludge volume, V_r, which had to be introduced after a set interval of time, t, can be obtained as below.

$$V_r = Q_r t \tag{3.7}$$

By fixing the mean cell residence time, the waste sludge flow rate can be calculated by use of equation (2.21).

$$\theta_c = \frac{VX}{Q_w X_u}$$

$$Q_w = \frac{VX}{\theta_c X_u} \tag{3.8}$$

The actual solid retention time, θ_c, is in the region of 10-20days (Tebbutt, 1991). At steady state MLSS can be measured to represent biomass concentration in the reactor, X, and the sludge suspended solids as biomass concentration in the underflow, X_u.

The parameters θ, X, X_u and α can be determined as shown above and applied directly in equation 3.2.

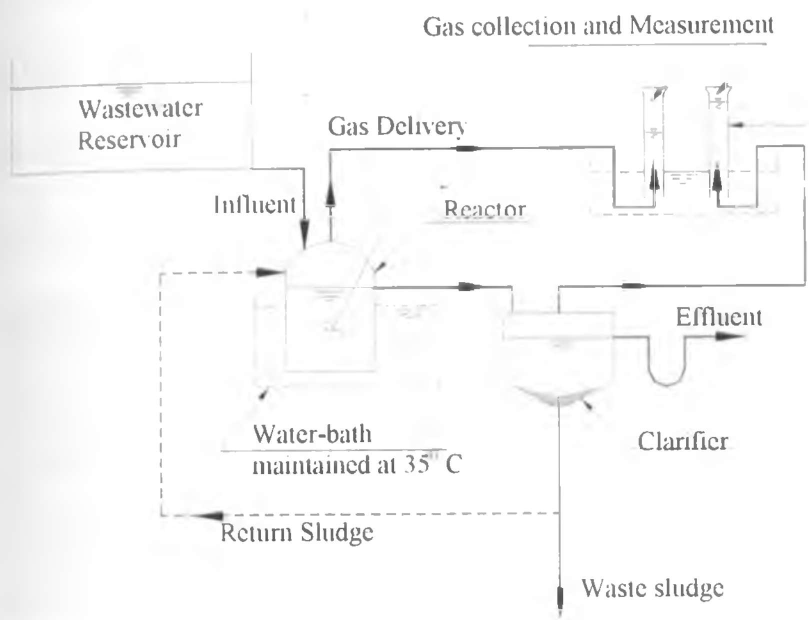
4 EXPERIMENTAL STUDIES

4.1 Apparatus Set-Up

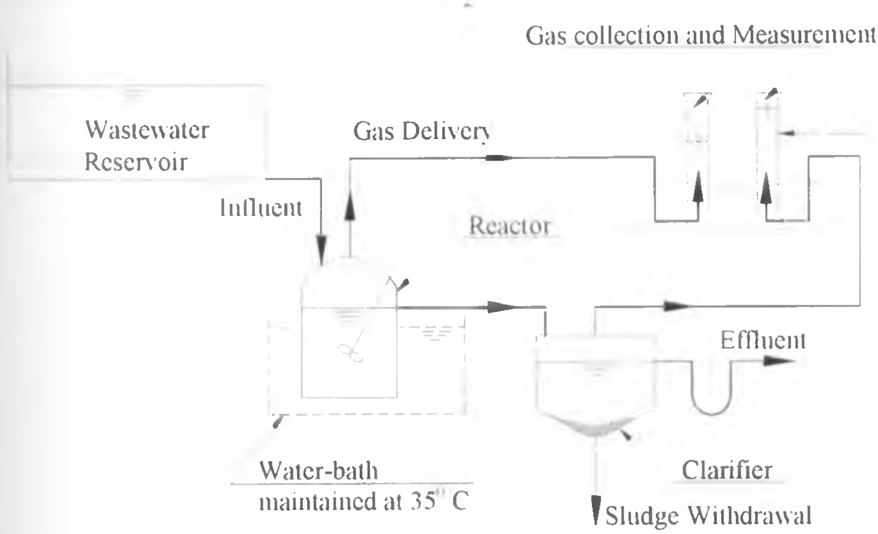
The experimental set-up (Plate 1.0) consists of a 40-litres overhead reservoir, reactors (similar circular containers of a total volume of 4-litres and an effective volume of 3.5 litres each) and a clarifier together with gas collection facilities. Both the reactor and the clarifier were sealed to ensure airtight conditions.

Plate 1.0 Assembled experimental model

The reactors of the recycled system shown in Figure 4.1 (a) had four openings, while that of the conventional model shown in Figure 4.1 (b) had three. The first opening in both was located at the liquid meniscus level served as the effluent outlet pipe and was connected to the clarifier by a small delivery tube. The other openings were at the top of the reactors. The second opening had an inlet glass pipe penetrating the digester to a depth of 30mm from the bottom of the reactor and was used as a feed inlet.



(a) **Recycled Anaerobic Model**



(b) **Conventional Anaerobic Set-up**

Figure 4.1 Schematic diagram of the experimental model

The third was connected to a rubber tube and directed into measuring cylinder partly immersed in water for gas collection and measurement by displacement method. The fourth opening had a glass pipe equally inserted to 30mm above the bottom of the reactor, and was the inlet for the recycled sludge from the clarifier. The pipe was clipped at the top to prevent any aeration into the reactor.

The wastewater was fed into the reactors from an overhead reservoir (Plate 2.0), with a big enough surface area to minimise change in height before additional of more wastewater. The flow in the system from the reservoir to the effluent outlet in the settling tank was all by gravity.

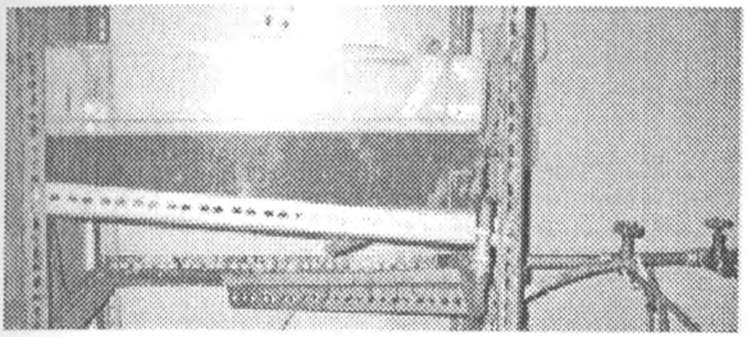


Plate 2.0 Overhead wastewater storage reservoir

The system was provided with regulation valves in order to be able to regulate the flow rates accordingly. All the reactors were immersed in a water bath (Plate 3.0) maintained at a temperature of 35^0c by a thermostat-controlled heater.

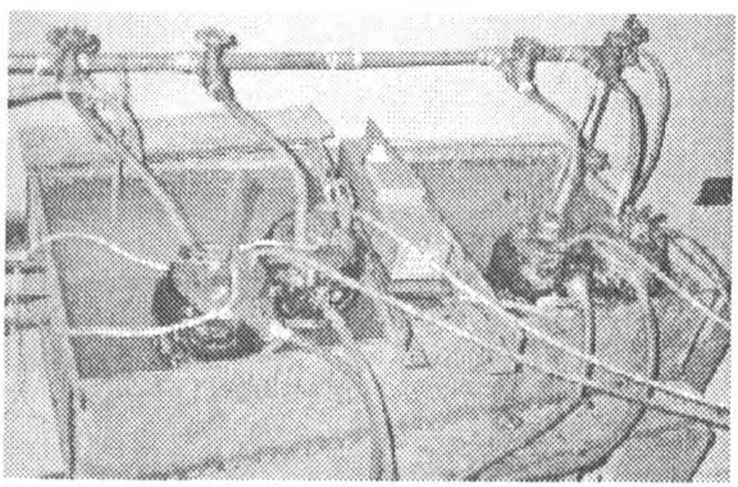
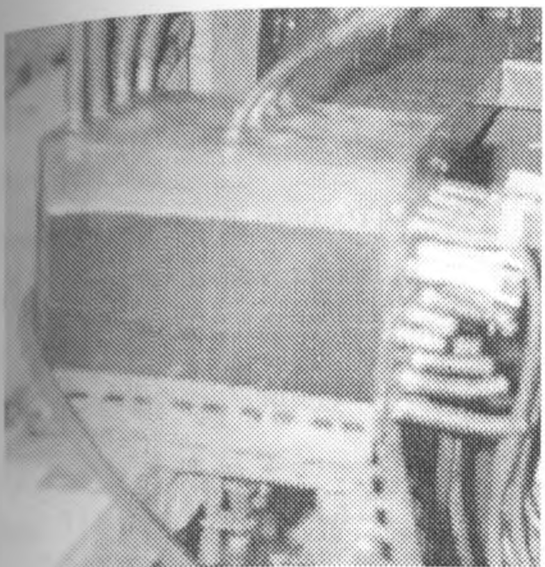
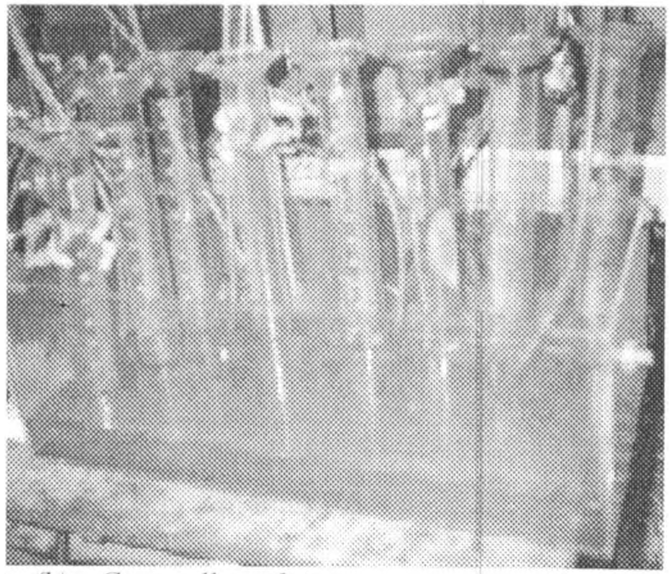


Plate 3.0 Reactors inside a water-bath maintained at 35^0C

The clarifier shown in Plate 4.0 (a) was an airtight container with an inlet at the top and an effluent outlet at the liquid meniscus at the extreme end. The effluent pipe was connected to a U-tube to ensure air seal. The sludge outlet was fitted at the bottom of the clarifier. The gas from each unit was collected by water displacement method as shown in Plate 4.0 (b).



(a) Container with partitions to separate clarifiers



(b) Gas collected into measuring cylinders by displacement methods

Plate 4.0 Clarifier and the Gas cylinders

The required daily volume of return sludge was being drawn using a syringe and returned to the reactor.

4.2 Experimental Plan

In order to investigate the behaviour of the process in a wide range of wastewater polluting load, the COD of the wastewater was varied by either addition of water to lower its strength or by addition of pure beer to increase it strength. After the start-up stage the process ran reasonably well in the experimented volumetric loading range of 0.29 to 10 kg COD $m^{-3}d^{-1}$, except for minor experimental problems such as clogging of delivery tubes and thermostat malfunction, which were rectified well in good time. The experimental study involved the following

- Analysis of the characteristics of the Thika Brewery wastewater.
- Inoculation and start-up of the digesters.
- Digester feeding.
- Determination of recycle and waste sludge volumes.
- Monitoring of digester performance at various HRT and loading rates.

4.2.1 Analysis of The Wastewater Characteristics

The main wastestreams of the Thika brewery are the brewhouse, packaging, domestic sewage, cleaning and lubrication all directed to an existing balancing tank. Only screening is carried out, before pumping to the municipal wastewater treatment works. As can be observed from Appendix A wastewater exhibited a wide variation at any single moment due to the nature of operation of the plant. The wastewater samples were analyzed for biodegradability using BOD_5/COD ratio and for the nutrients requirement by evaluating COD nitrogen and phosphorus ratios. The ratio BOD_5/COD ranged from 0.48 to 0.63, showing that the wastewater was within the biodegradable range. The result of the BOD_5/COD analysis is shown in Appendix B.

At low COD the nutrients (nitrogen and phosphorous) levels were sufficient. However, at high COD especially on addition of the pure beer the nitrogen levels had to be supplemented by addition of ammonium carbonate. The phosphorus content remained high. The high nutrient levels can be attributed to the addition of domestic wastewater, cleaning and bottle washing liquor at the balancing tank.

4.2.2 Inoculation and Start-up

To avoid a very long start-up time all the digesters were seeded with domestic wastewater sludge from an active conventional anaerobic treatment plant (Kariobangi sewage works - Nairobi). Initially the reactors were 50% filled with the seed sludge and placed in the water-bath all at room temperature. In order to minimize thermal shocks, the temperature was gradually raised from 21°C (room temperature) to 35°C in a period of eight hours by heating the water bath gradually. 25% of the wastewater that had equally been heated at the same rate was added into the reactor and the content maintained at 35°C for 24 hours before addition of the remaining 25% of the wastewater that had been kept under similar conditions. The digesters were kept undisturbed for four days to allow some time for acclimatization after which regular feeding programme was started.

4.2.3 Digester Feeding

A hydraulic retention time (HRT) of 20 days and a volumetric loading rate of 0.29kg COD $m^{-3}d^{-1}$ were maintained during start-up. Using the effective volume of 3.5 litres for the reactor, the required flow for a given HRT was calculated. The regulation valves on the delivery pipe from the overhead reservoir were adjusted accordingly to attained the required flow. This flow was maintained until the steady state conditions were obtained. The steady state conditions were assumed when effluent COD remained constant. In order to investigate the effect of HRT variation at a fixed loading rate the flow was increased to gradually reduce the HRT from 20 days to 1 day, during which the loading rate was maintained constant by dilution of the original wastewater with tap water. In order to investigate the effect of loading rate variation at a fixed HRT the strength of the wastewater was increased by addition of pure beer while maintaining the HRT at 10 days.

4.2.4 Recycle and Waste Sludge Volumes

A recycle ratio of 40% was used throughout the experiment. The daily flow rate, Q_o, was calculated from the HRT, and the return flow rate, Q_r, obtained using Equation 4.1

$$Q_r = 0.4Q_o \qquad (4.1)$$

Using Equation 3.7 and a time of one day, the daily volume of return sludge, was obtained. This volume was extracted from the underside of the clarifier using a syringe and re-introduced into the reactor of the recycle system.

To obtain the volume of the waste sludge, the MLSS (to represent biomass concentration in the reactor, X) and the sludge suspended solids (biomass concentration in the underflow, X_u) were measured to enable the use of Equation 3.8. The mean cell residence time, θ_c was fixed at 20 days and the daily waste sludge flow rate, Q_w, was calculated, hence the volume of waste sludge per day was obtained. Some values of the recycle and waste sludge volumes are shown in Table 4.1.

Table 4.1 Typical values of recycle and waste sludge volumes

HRT (days)	Daily Flow (ml)	Volume of Recycled Sludge (ml)	Volume of Wasted Sludge (ml)
20.0	175	70	70
17.5	200	80	72
15.0	233	93	73
12.5	280	112	74
10.0	350	140	74

4.2.5 Performance Assessment

The treatment performed at 35^0C was continuously monitored for any signs of imbalance. Imbalance in any anaerobic process can be indicated by the following parameters.

- Increase in volatile acid concentration.
- Decrease in gas production
- Decrease in pH of the mixed liquor
- Increase of percentage of CO_2 in the gas
- Decrease in the degree of waste purification

No single parameter would be fully reliable as an indicator of imbalance (Kiama, 1992). In this experiment a combination of pH, gas production and degree of purification were monitored on a daily basis. A decrease in pH was controlled by addition of a base (Sodium bicarbonate solution) to ensure it remained in the range 6.5 to 7.5. In the initial stages a daily analysis was carried out to determine the effluent COD, SS and total gas production for all the systems. The suspended solids (SS) for both the mixed liquor and the settled biomass were determined daily for the recycle system while those of the conventional system were measured three times a week. The MLSS and biomass SS were used as indicators of cell concentrations in the reactor, X, and in the underflow, X_u respectively. These parameters were needed daily for the determination of the waste sludge volume for the recycle system as described in section 4.2.4. Initially values of 4000 and 10000mg/l were assumed for MLSS and underflow respectively. Performance was assessed by analysis of effluent COD, SS gas production, pH, and MLSS for all the systems. The experimental data are given in Appendix D1 and D2.

All the laboratory analysis were carried out in accordance with the Standard Methods for the Examination of Water and Wastewater Analysis (17th Edition) as stipulated in Water and Wastewater Examination Manual (Adams, 1990).

5 RESULTS AND DISCUSSION

5.1 Start Up

In the first few days of the experiment it was observed that the effluent COD and SS were higher than the influent parameters. The high levels of effluent parameters decreased as expected with continued addition of the wastewater. In the start-up phase the percentage COD removal increased rapidly with time, eventually becoming fairly constant, but at different rates for the different reactors. It was observed that the recycled system attained steady states slightly earlier (23 days) than the conventional reactor (28 days).

The high levels of effluent COD and SS can only be attributed to the high rate of washout of the unsettleable suspended solids of the inoculum, given that the inoculum had higher COD and SS than the brewery wastewater in that it was introduced into the reactors without filtering. The high levels of effluent parameters would be expected to decrease in that the addition of brewery wastewater acted as a dilution to the inoculum. The poor performance observed initially can be explained in terms of the time needed by micro-organisms to acclimatize and the low level of microorganisms capable of degrading the specific substrate, hence the time required for the development of the predominant species for the substrate. During start-up the most suitable microbial culture for the specific substrate is developed and this is indicated by attainment of the steady state conditions. The difference in start-up time between the two reactors can be attributed to the high concentration of the microorganisms in the recycled system as a result of biomass recycle. This prediction is supported by the higher level of MLSS for the recycle process relative to conventional process as shown in Appendix D. Having been retained in the system for some time, the recycled microorganisms can be said to be slightly accustomed to the substrate and would therefore act much faster, the effect of which is a reduction in the lag time. The other possibility is that the recycle greatly minimizes microorganism's washout, while in the CSTR the biomass suffer a constant washout due to lack of effective solid retention.

5.2 COD Removal

The process efficiency of any treatment is best assessed by the effluent quality relative to the influent concentration. The COD removal is a good indicator of this efficiency and was used here as a measure of organic load reduction and process stability. From Appendix D and Figures 5.1 to 5.4, it was observed that both processes achieved a relatively high degree of wastewater purification.

The possible explanation to this is that the HRT adopted was too long such that the microorganisms digested the waste in less time than the residence time provided. The remaining COD can be described as that which has to remain since part of it is non-biodegradable and the biodegradable part left is too dispersed for the microorganism to effectively get into contact. This is an indication that a lower HRT would most likely achieve reasonable waste decomposition.

Figures 5.1 and 5.2 show that the biomass recycle process had a higher percentage COD removal than the conventional process for the various hydraulic residence time. For hydraulic residence time of between 1 and 20 days, the recycled process achieved an average percentage COD removal 90% while the conventional anaerobic process achieved 82%.

The mathematical model in section 3.2 predicted that the effluent substrate concentration would be lower for a biomass recycle system than for the conventional process. Consequently, the theoretical approach as delivered in Equation 3.2 and illustrated in Figure 3.4 supports the experimental results. However, at steady state conditions as illustrated in Figure 5.1 the effluent substrate concentration is independent of the hydraulic retention time (HRT) and influent substrate concentration at constant mean cell residence time (MCRT) when operating at organic loading rate. This is as would be expected since it is in agreement with the theory as represented by Equation 2.24.

Table 5.1 **Comparison of COD removal**

Influent COD	HRT	LOADING RATE	Effluent COD				Gas yield per cod removed at 35^0 C			
			Recycle		Conventional		Recycle		Conventional	
(mg/l)	(days)	(Kg COD/ m3/d.)	Mean (mg/l)	σ	Mean (mg/l)	σ	Mean (ml/d)	σ	Mean (ml/d)	σ
5840	20	0.3	15400		15400					
5840	20	0.3	13547	1393	14147	969	912	255	978	339
5840	20	0.3	7777	1721	9957	3005	1038	314	803	264
5840	20	0.3	4973	804	5333	752	968	97	988	83
5840	20	0.3	2145	881	2623	913	734	219	533	216
5840	20	0.3	818	95	1190	211	456	23	432	26
5840	20	0.3	610	18	967	9	480	8	473	12
5110	18	0.3	657	50	908	52	458	48	453	10
4380	15	0.3	483	57	825	91	466	22	436	6
3650	13	0.3	400	46	745	149	463	14	423	14
2920	10	0.3	320	24	560	49	476	12	418	16
1460	5	0.3	165	10	275	18	500	53	402	22
290	1	0.3	33	5	64	12	472	8	427	5
9000	20	0.5	860	42	1680	200	696	33	615	38
11680	20	0.6	965	136	2055	119	908	34	803	25
5840	10	0.6	480	24	1055	54	910	18	818	18
8000	10	0.8	640	99	1407	81	1217	55	978	127
10000	10	1.0	665	33	1740	86	1541	53	1276	114
15000	10	1.5	990	77	2523	97	2365	50	2130	39
20000	10	2.0	1225	89	3250	77	3234	91	2821	33
25000	10	2.5	1450	124	4135	48	3990	63	3589	77
30000	10	3.0	1620	68	5098	71	4795	82	4225	86
35000	10	3.5	1880	133	6950	100	5599	85	4879	72
40000	10	4.0	2220	133	8643	116	6391	129	5608	131
45000	10	4.5	2795	91	10890	443	7341	274	5738	116
50000	10	5.0	3253	105	12685	232	7890	138	6156	123
60000	10	6.0	5745	194	16360	640	9180	218	7125	186
80000	10	8.0	9530	103	25750	899	12415	645	8463	817
100000	10	10.0	14700	640	35550	1299	14365	504	10410	417

Considering that the first five rows in Table 5.1 represent the start up period where the conditions were not steady, it can be observed that there is a significant variation between the two processes in terms of both effluent stabilization and gas production. Consequently, it can be predicted that the recycle process would result in better effluent quality than the conventional process.

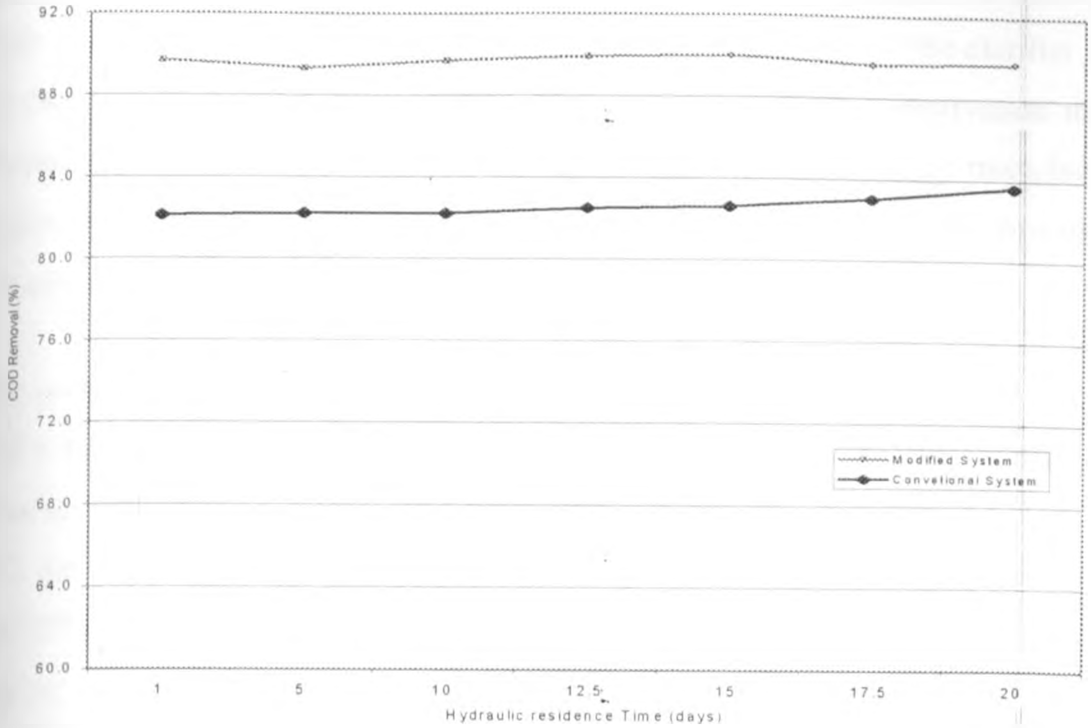


Figure 5.1 **Variation of effluent COD with HRT at constant loading and MCRT**

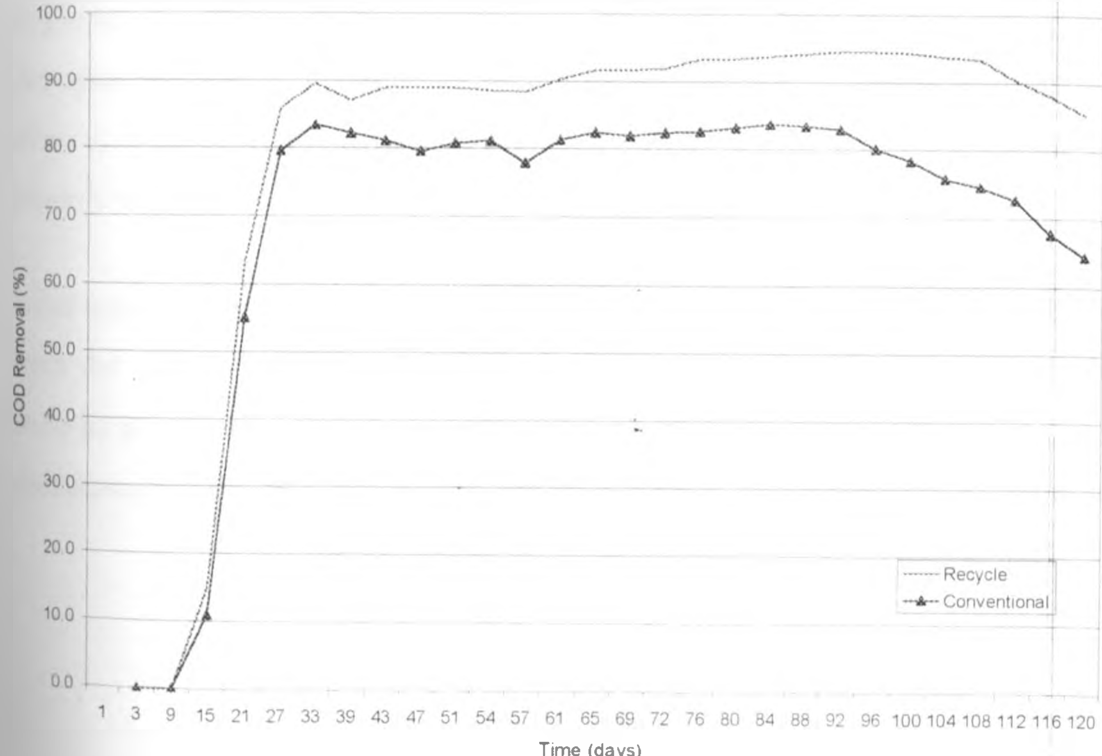


Figure 5.2 **Average COD removal with time**

As illustrated in Figure 5.2 it was observed that there was a slight improvement in the degree of purification after the initial start-up stages as the organic loading rate increased. This is thought to be due to variation in the residual COD. Anaerobic processes perform much better at high COD. Wastewater purification at low influent COD is limited, and may be governed more by the performance of the clarifier than by the biological processes (Curi, 1980). This is in line with the observation made by Harremoes in his study of advanced treatment by manipulation of microbiological processes (Curi, 1980). The above observation indicates that anaerobic processes are not cost effect at low COD levels.

The results as represented in Figures 5.3 and 5.4 show that the biomass recycle process had a higher COD reduction than the conventional process for the various loading rates at constant HRT. For the organic loading rate of between 0.29 and 10 kg COD $m^{-3}d^{-1}$, the recycled process achieved a percentage COD removal ranging between 86% and 95% while the conventional anaerobic process achieved between 66% and 84%. It can be noted also that at a constant HRT an increase in volumetric loading rate resulted in improvement to the degree of purification up to a maximum, after which any further increase in loading resulted in a decrease in the degree of purification. The implication is that for both systems there is an optimum loading rate. From the results the optimum organic loading rate for the recycle process was about 3.5 kg COD $m^{-3}d^{-1}$ when a 95% COD removal was achieved, while that of the conventional anaerobic process was 2.0 kg COD $m^{-3}d^{-1}$ with 84% removal.

After any change in loading rate some degree of instability were developed, as noticed from the effluent quality for any particular loading rate. This gradually decreases to more or less constant level after about three to four days. The fluctuations were more pronounced in the conventional system than the recycled system.

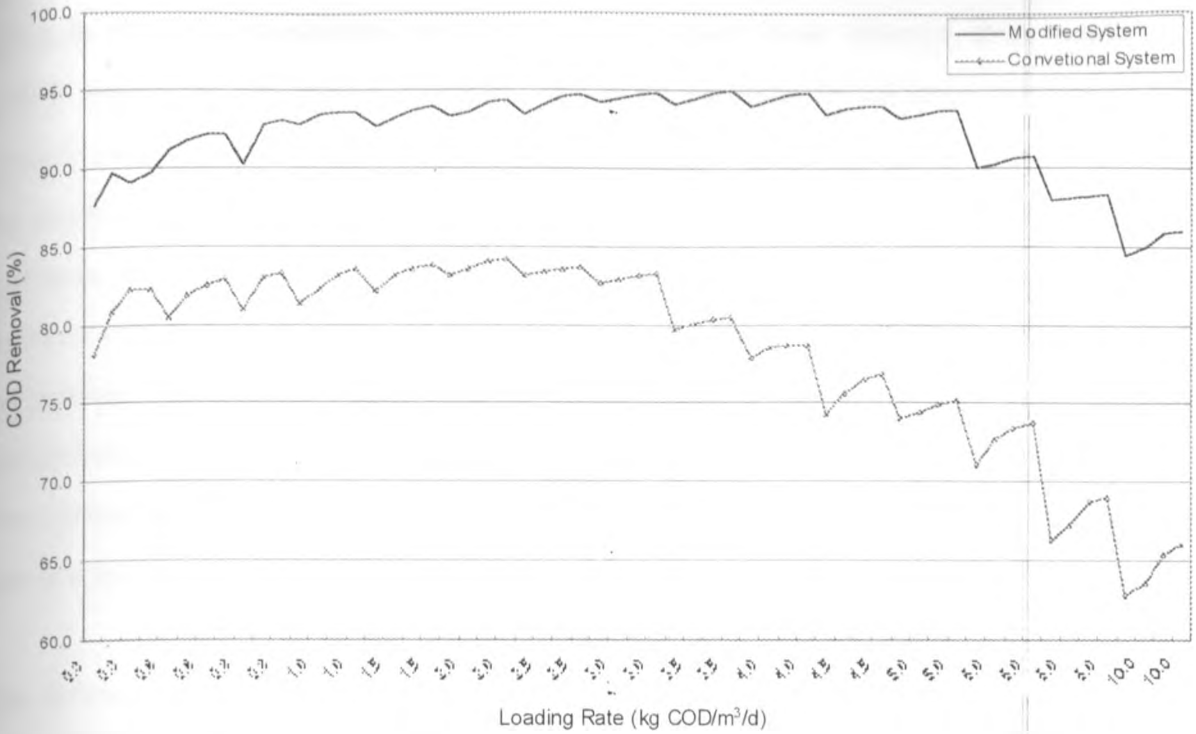


Figure 5.3 COD removal as a function of loading rate for a constant HRT of 10 days

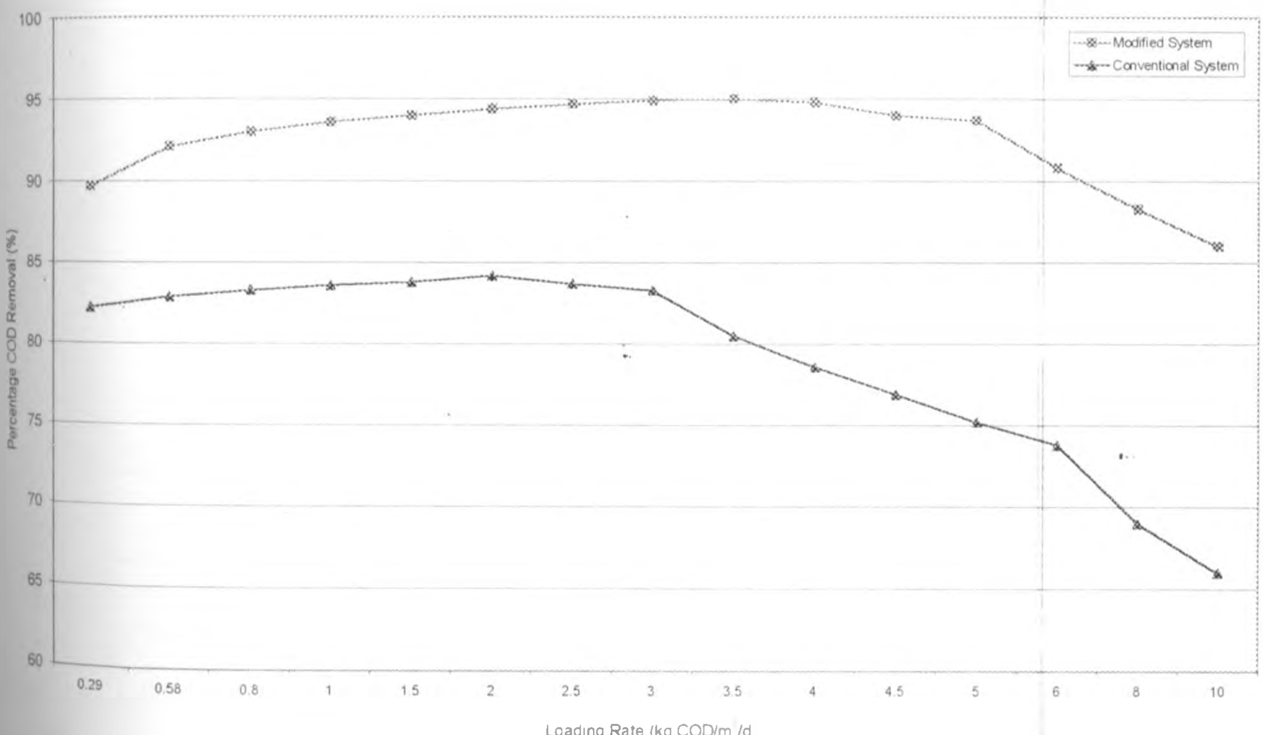


Figure 5.4 COD removal as a function of loading rate at steady state for a constant HRT of 10 days

The performance of the digesters in relationship to the loading rates agrees with the prediction in the proposed model as demonstrated in Figure 3.5 of section 3.2. The gradual increase to a maximum can be explained in that from a certain loading rate upwards the microorganisms are fully fed and they have attained their maximum growth rate level. At these conditions any extra increase in substrate concentration, tends to make the microorganisms selective, and part of the excess feed passes through the reactor without undergoing any digestion. The observation indicates that there is an optimum load at which microorganisms perform best. The noticeable difference between the theoretical curve (Figure 3.5) and the above is thought to be because of the arbitrary parameters which were assumed in theory and the low level of influent concentration assumed in which case the optimum load may not have been attained. The optimum load is the one aimed at in design, hence the conception that the loading rate is a limiting design criterion.

The difference in the degree of instability on changing the loading rate is due to the fact that the population of the acclimatized microorganisms in the recycled system is higher than in the conventional system. It is for the same reason that the biomass recycle digester had a better response to changes in loading rates.

5.3 Gas Production

In anaerobic treatment gas yield is of prime importance since it can be used as a source of energy. Figure 5.5 show the trend of daily gas production with time. In the start-up phase the amount of daily gas production was relatively higher compared to the days immediately after start up, but decreased gradually before stabilizing as the start-up period ended. After the start-up period the gas production increased with increase in influent substrate concentration.

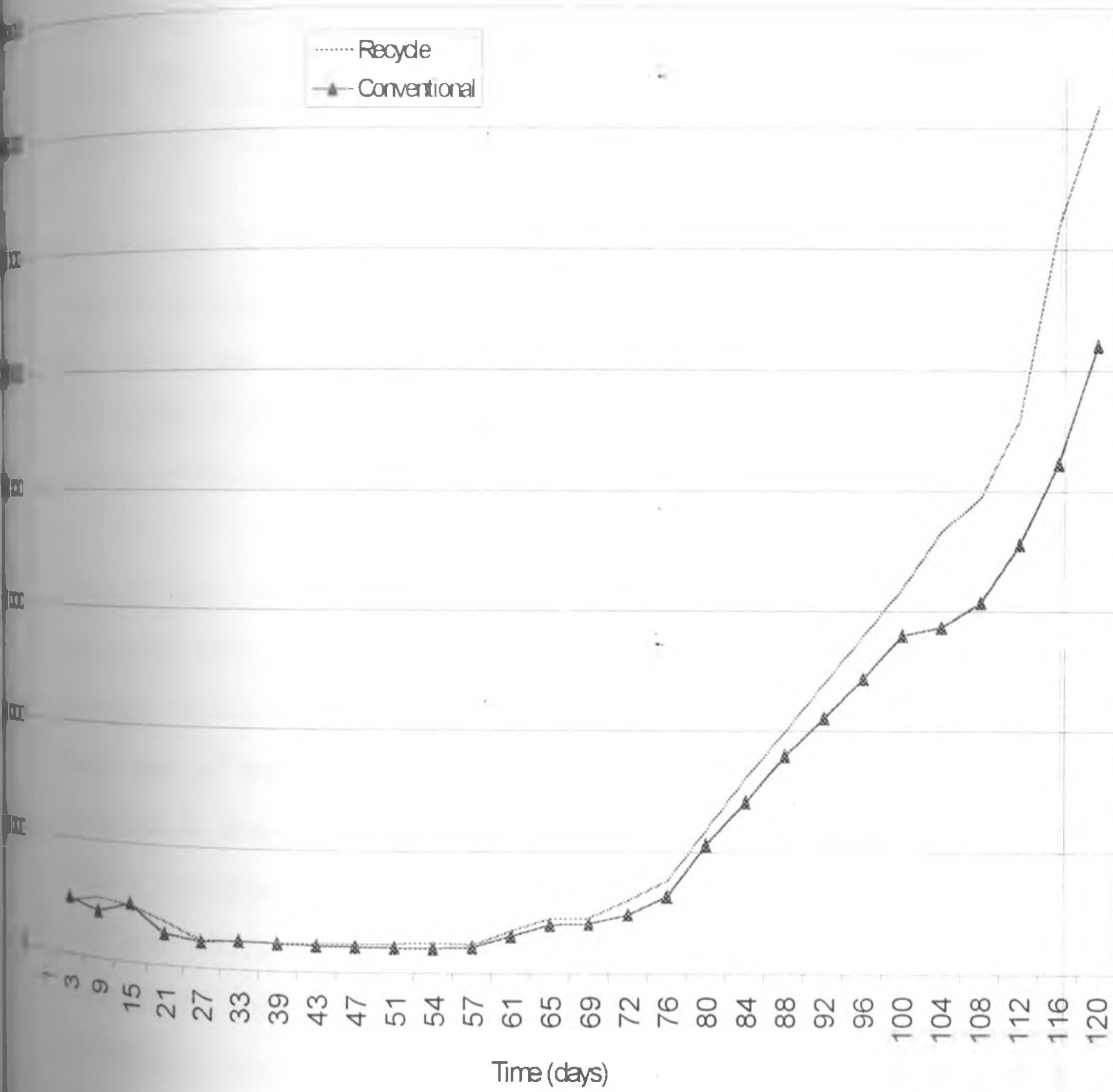


Figure 5.5 **Daily gas production**

The high gas production in the start-up stage can be attributed to: -

- Existence of obligate aerobes microorganisms due to the presence of air initially in the freeboard of the reactor. This could have added to the volume of CO_2 due to the aerobic digestion.

- Effects of endogenous respiration - it is expected that as oxygen is depleted in the reactor, the aerobes continued to die off and this could have resulted in higher gas production.

As the anaerobic conditions continued to pre-dominate the gas production stabilized, and as expected, increased with influent substrate concentration, in that at higher substrate concentration more COD would be removed as long as there is no system failure. Since gas production is a function of the COD removed, the higher the COD removed the higher the gas produced.

As shown in Table 5.1 the total volume of gas production at standard temperature ranged between 0.43 and 0.55 m^3/kg COD removed. The average methane content for the recycle process was about 60% of the total gas, therefore, its yield was between 0.25 and 0.32 m^3/kg COD removed. The conventional process had an average methane content of 58% and yielded between 0.19 and 0.30 m^3/kg COD removed

Theoretically a methane yield of 0.35 m^3/kg COD removed is expected at steady state (Desouza, 1986). This is assuming that no part of the original COD is synthesized to biomass. However, the two end products of anaerobic process are gas and sludge, hence part of the COD is always converted to biomass. Normally some of the gas produced is dissolved and eventually lost with the effluent (Gunnerson, 1986). In essence therefore, the practical methane yield is lower than the theoretical value (McCarty, 1964). According to Desouza (1986) a methane yield of 0.3 m^3/kg COD removed has been reported. Comparing the results of the experiment and the theoretical values, it can be observed that most of the COD removed is converted to methane, hence a low volume of sludge. According to Holder et al. (1978), anaerobic decomposition are slow processes with low energy requirements, which results in less cell synthesis.

Table 5.2 Gas yield and methane yield at steady state

Loading Rate (kgCOD/m^3/d)	Gas Yield (m^3/kgCOD removed)		Methane Yield (m^3/kgCOD removed)	
	Modified	Conventional	Modified	Conventional
0.29	0.50	0.49	0.30	0.28
0.58	0.46	0.44	0.28	0.26
0.8	0.46	0.32	0.28	0.19
1	0.42	0.44	0.25	0.25
1.5	0.47	0.47	0.28	0.27
2	0.48	0.46	0.29	0.27
2.5	0.47	0.48	0.28	0.28
3	0.47	0.47	0.28	0.27
3.5	0.47	0.48	0.28	0.28
4	0.47	0.51	0.28	0.30
4.5	0.49	0.46	0.30	0.27
5	0.47	0.45	0.28	0.26
6	0.48	0.45	0.29	0.26
8	0.55	0.46	0.33	0.26
10	0.48	0.45	0.29	0.26

Daily gas production was found to increase with the increase in organic loading rate. This could be as a result of increase in the amount of COD removed. As the influent substrate concentration increases the absolute value of the COD removed is bound to be higher irrespective of an increase or decrease in percentage removal, consequently the actual volume of methane produced was higher.

5.4 Processes Comparison

5.4.1 Performance

Although washout of active microbial mass is common phenomenon in both suspended and attached systems, there is a marked difference between the various systems. The start-up times for the two digesters were in the range given by Kiama (1992), ranging between 20 and 56 days. However, at the start up stage the recycled system attained stability earlier than the non recycle (CSTR) system implying that it had a short start-up time. The significance of the above is that biomass recycle can play a major role in terms of lag time reduction.

The suitability of any anaerobic biological systems can be determined by the highest possible loading rate, smallest possible reactor and highest volume of gas yield relative to the degree of wastewater purification. The performance of the recycled system relative to a conventional anaerobic process can be observed from Figures 5.1 to 5.5 above. For the organic loading rate of between 0.29 and 10 kg COD $m^{-3}d^{-1}$, the results showed the recycled process achieved a percentage COD removal ranging between 86% and 95% while the conventional anaerobic process achieved between 66% and 84%. The highest percentage COD removal for the recycled system was 95% at an organic loading rate of 3.5kg COD $m^{-3}d^{-1}$, during which the conventional system achieved 80%.

At a loading rate of 10kg COD $m^{-3}d^{-1}$ where the influent COD was 100,000mg/l, the recycled system achieved an 86% reduction to an effluent COD of 14,000mg/l. For the same loading rate, the conventional achieved an effluent COD of 34,000mg/l, which was only 66% reduction. Therefore, the recycled system showed about 2.5 times better effluent quality than the conventional process at the high loading rate. For the whole range of experimental loading rates, the recycled system was superior in COD reduction.

Gas production was higher in the recycled process than in the conventional process. The percentage of methane in the gas was equally slightly higher at an average of 60% for the recycled process relative to the conventional process with an average of 58%. The methane yield at standard temperature (20°C) ranged between 0.25 and 0.32 m^3/kg COD removed for the recycled process while it was between 0.19 and 0.30 m^3/kg COD removed for the conventional process. Based on the theoretical production, the methane conversion efficiency was as high as 91% for the recycled system and 86% for the conventional system. Comparing the experimental results and the theoretical value, most of the COD removed was converted to methane as opposed to biomass synthesis. This also resulted in less sludge production for the recycled process than for the conventional process.

5.4.2 Design

With an influent substrate COD of 100,000mg/l the effluent COD were 14,000 and 34,000mg/l for the recycled and the conventional processes respectively. By assuming typical kinetic values ($Y = 0.5kg/kg$, $k_e = 0.05d^{-1}$) and an average MLSS of 4,000mg/l a design for both reactor was undertaken aimed at an effluent COD of 14,000mg/l.

By using a flow of 1,200 m^3/d which were typical of Thika brewery wastewater, it was noted that the volume of the conventional reactor would have to be about 1.8 times bigger than that of the recycled reactor.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following can be concluded based on this study:

1. Brewery wastewater can be treated anaerobically at the mesophilic temperature, since both processes achieved quite high COD removal. However the very high degree of purification shows that a lower HRT can be used and still achieve satisfactory results.

2. The start-up time of about 23 and 27 days for the recycled and the conventional systems respectively was noted to be relatively short. This shows that a low loading rate during start-up is very significant in achieving faster steady state. It was equally noted that the recycled system responded much better to variation in both hydraulic and organic loading rates. It can therefore be concluded that biomass recycle improves the start-up process.

3. The organic loading rate varied between 0.29 to 10 kg COD $m^{-3}d^{-1}$, but there was a specific loading level at which each process performed best. The experimental results showed the recycled process achieved a percentage COD removal of between 86% and 95% while the conventional anaerobic process achieved between 66% and 84.2% for the same range of loading rates. Both reactors could reach the loading rate of 10kg COD$m^{-3}d^{-1}$, but the degree of effluent purification improved to a maximum before starting to decrease with increased loading rate. The best performance for the recycled system was 95% at a loading rate of 3.5kg COD$m^{-3}d^{-1}$, whereas the conventional system achieved only 80% at the same loading rate. At higher loading rate the efficiency of the conventional process is greatly reduced and the recycled process resulted in an effluent quality which was more than twice as good. Consequently,

the recycled process was relatively better than the conventional process in terms of organic matter decomposition.

4. Gas production was higher in the recycled process than in the conventional process. The methane yield at standard temperature (20°C) ranged between 0.25 and 0.32 m^3/kg COD removed for the recycled process while it was between 0.19 and 0.30 m^3/kg COD removed for the conventional process. Based on the theoretical production of 0.35m^3/kg COD removed, the methane conversion efficiency was found to be as high as 91% for the recycled system and 86% for the conventional system. With methane yield as high as 0.32 m^3 per kg COD removal the brewery wastewater has potentials in terms of resource recovery.

5. Monitoring and controlling pH can be effective enough in maintaining process stability without necessarily measuring volatile fatty acid levels, however daily gas production must be closely observed.

6. A digester where the flow is batch with respect to biomass and continuous with respect to wastewater, is effective enough in improving contact efficiency in a recycle system. The process can be applied at high COD strength of up to 100,000 mg/l and still achieve a high removal rate of over 80% at a loading rate of up to 10 kg COD m^3d^{-1}.

7. Domestic sewage sludge is a suitable inoculum for this process in the treatment of industrial effluent such as brewery wastewater.

8. The results of the study show that anaerobic process with biomass recycle holds potential for treatment of high-strength industrial wastewaters like brewery effluent. However, a pilot plant study would be necessary in order to obtain operational and design parameters for a full-scale operation.

6.2 Recommendations

The following are the recommendations for further work.

1. A study on the process performance at a lower HRT may be necessary in order to take full advantage of the microorganisms in the system.

2. Cost of continuous pumping as opposed to the batch recycle of biomass used in the system may be investigated to determine if there are any benefits that would justify continuous pumping of recycle sludge.

3. Investigation should be carried out on the effects of filtered inoculum in order to establish the best form of seeding.

4. A study may be necessary to investigate the behaviour of the process with variation in recycle ratio.

5. Further study may be necessary to observe the process performance with variation in mean cell residence time, in order to determine an optimum MCRT.

6. A pilot plant study would be necessary in order to obtain operational and design parameters for a full-scale operation.

REFERENCES

1 Adams, D V , 1990. Water and Wastewater Examination Manual. Lewis Publisher Inc.

2 Barnes, D. and Wilson, F., 1983. Chemistry and Unit Operations in Water Treatment. Applied Science Publishers Ltd.

3 Barnes, D., Foster, C. F. and Hrudey, S. E., 1984. Survey in Industrial Wastewater Treatment Vol 1 Pitman Advanced Publishing Program.

4 Bruce, A. M., Kouzeli, – K and Newman, P. J., 1986. Anaerobic Digestion of Sewage Sludge and Organic Agricultural wastes. Proc. Of a Seminar organized by Commission of European Communities, Greece. Elsevier Applied Science Publishers Ltd.

5 Bunyagidj, C. and Greason, D., 1996. Industry and Environment Vol 19 No. 3. Proceedings of the Fourth High Level Seminar. UNEP-I E

6 Cooper, P F and Atkinson, B., 1981. Biological Fluidised Bed Treatment of Water and Wastewater. Ellis Horwood Limited.

7 Curds, C. R and Hawkes, H A., 1975. Ecological Aspects of Used-water Treatment. Vol 1 Academic Press.

8 Curds, C. R and Hawkes, H A., 1983. Ecological Aspects of Used-water Treatment. Vol. 3 Academic Press.

9 Curi, K., 1980. Treatment and Disposal of Liquid and Solid Industrial Wastes. Pergamon Press

10 Dart, R K and Strelton, R J., 1980. Microbiological Aspects of Pollution Control. Elsevier Scientific Publishing Company

11 Desouza, M. E., 1986. Anaerobic Treatment in Tropical Countries (Water Science & Technology Vol 18) Pergamon Press

12 Erickson, L. E and Yee-Chakfung, D, 1988 Handbook on Anaerobic Fermentations. Marcel Dekker Inc.

13 Ferranti, M P, Ferrero, G L and L'Hermite, P 1987 Anaerobic Digestion Results of Research and Demonstration Projects. Elsevier Applied Science Publishers Ltd.

14 Ferrero, G. L., Ferranti, M P and Naveau, H., 1987 Anaerobic Digestion and Carbohydrates Hydrolysis of Waste. Elsevier Applied Science Publishers Ltd.

15 Gashaw, Y., 1984 Combined Treatment of Domestic and Industrial Wastewater MSc. Thesis Tampere University of Technology.

16 Gray, N. F., 1989. Biology of Wastewater Treatment. Oxford University Press

17 Gunnerson, C G , 1986 Anaerobic Digestion Principle and Practices for Biogas Systems. Washington D C – The World Bank Technical Paper No. 49.

18 Holder, G. A.; Sewards, G J and Scott, P. H., 1978. Studies of an Anaerobic/Aerobic Treatment Process for a Strong Organic Waste. Inter. Conf. On Water Pollution Control in Developing Countries, Thailand

19 Isaac, P. G. C. and Alan, M., 1980. Nature and Disposal of Effluent from Malting Brewing and Distilling Proc. Of a Symposium on Food Industry Wastes organised by The Association of Consulting Scientists. Norwich U. K

20 Kakabadse, G., 1978. Chemistry of Effluent Treatment. Applied Science Publishers Ltd

21 Kiama, G. W., 1992. A Study of Start-up Process and Operation of Anaerobic Digestion with Coffee Pulping Wastewater MSc. Thesis, University of Nairobi

22 Kilani, J S., Gecaga, J. and Nzainga, J. M , 1989 Characteristics of Selected Industrial Wastes in Kenya Research Paper, University of Nairobi

23 Koziorowski, B and Kucharski, J , 1972 Industrial Waste Disposal Pergamon Press.

24 Lettinga, G., 1984 The Prospects of Anaerobic Wastewater Treatment – Proceedings of an Information Symposium Under the European Economic Commission Programme on Recycling of Urban and Industrial Wastes, Luxembourg. Elsevier Applied Science Publishers Ltd

25 McCarty, P L 1964 Anaerobic Waste Treatment Fundamentals Part 1-4 Stanford University.

26 McGhee, Terence J., 1991 Water Supply and Sewage McGraw-Hill.

27 Metcalf and Eddy, Inc., 1979. Wastewater Engineering Treatment Disposal Reuse. McGraw-Hill

28 Mosey, F. E 1977. Anaerobic Filtration – A Biological Process for Warm-Trade Wastewaters. Water Research Centre.

29 Newton, D., Keinath, H L., and Hillis, L S., 1962. Pilot Plant Studies for the Evaluation of Methods of Treating Brewery Wastes. Proc. 16th Industrial Waste Conference. Purdue Engineering Extension Series.

30 Novaes, R F V., 1986 Microbiology of Anaerobic Digestion. Water Science & Technology Vol. 18 No 12 Pergamon Press

31 Nzainga, J. M., 1989. Studies of the Characteristics and Treatment of Selected Industrial Effluent. MSc. Thesis, University of Nairobi.

32 Painter, H A., Hemens, J and Shrben, D G., 1960. Treatment of Malt Whisky Distillery Wastes by Anaerobic Digestion The Brewery's Guardian

33 Peavy, H S., Rowe, D R and Tchobanoglous, G., 1985 Environmental Engineering McGraw-Hill

34 Pettet, A. E., Tomlinson, T G and Hemens, J., 1959. The Treatment of Strong Organic Wastes by Anaerobic Digestion Journal of Institution of Public Health Engineers

35 Pol, L. H and Lettinga, G , 1986. New Technologies for Anaerobic Wastewater Treatment Water Science and Technology Vol 18 No 12. Pergamon Press.

36 Rintala, J , 1987 Start-up of an Upflow Anaerobic Sludge Blanket Reactor for Treating Thermomechanical Pulp Effluent Aqua Finnica

37 Stronach, S M, Rudd, T and Lester, J N., 1986 Anaerobic Digestion Process in Industrial Wastewater Treatment Springer – Verlag

38 Stuckey, D and Hamza, A., 1981. Management of Industrial Wastewater in Developing Nations. Pergamon Press.

39 Tebbutt T H Y , 1991 Principals of Water Quality Control Pergamon Press

40 Tomlinson, T G, 1976 Industrial Pollution Control YearBook Industrial Newspaper Limited.

41 UNEP IE, 1995 Industry and Environment Volume 18 No 1 UNEP Industry and Environment

42 Van den Berg and Kennedy, K J , 1983. Comparison of Advanced Anaerobic Reactors Proc 3rd International Symposium on Reactor Anaerobic Digestion-Boston

43 Walters, J K. and Wint, A., 1981 Industrial Effluent Treatment vol. 1 Applied Science Publishers.

44 Wanjau, D.M , 1986 Comparison of the Anaerobic Contact and Packed Bed Processes. MSc Thesis, University of Newcastle Upon Tyne.

APPENDIX

A CHARACTERISTICS OF THIKA BREWERY WASTEWATER

B BIODEGRADABILITY ANALYSIS

C INFLUENT COD FOR VARIOUS ORGANIC LOADING RATE

D EXPERIMENTAL RESULTS

D1 Recycled process

D2 Conventional Process

E COMPARISON OF COD REMOVAL

F VOLUMES OF RECYCLED AND WASTED SLUDGE

CHARACTERISTICS OF THIKA BREWERY WASTEWATER

PARAMETERS	BREWING HOUSE		PACKAGING & WASHING		DOMESTIC SEWAGE		COMBINED EFFLUENT	
	Range	Average	Range	Average	Range	Average	Range	Average
COD	280-13460	7840	80-8110	1260	240-1040	760	820-12900	5840
BOD_5	150-8680	4060	40-4240	630	120-680	400	510-7480	3440
SS	40-3640	2610	20-800	280	40-390	120	80-3120	2100
pH	3.9-8 4	5.7	6.0-12.3	9.8			5.1-11.0	7.8
Alkalinity	40-1600	840	140-2200	1320			60-980	820
Phosphorous	-	-	-	-	-	-	60-410	280
Total nitrogen	-	-	-	-	-	-	12-305	150

All parameters in mg/l except pH

BIODEGRADABILITY ANALYSIS

COD (mg/l)	BOD5 (mg/l)	BOD5/COD
5,840	3,440	0.59
5,110	3,120	0.61
4,380	2,510	0.57
3,650	2,120	0.58
2,920	1,720	0.59
1,460	800	0.55
290	170	0.59
9,000	5,220	0.58
11,680	6,670	0.57
8,000	4,640	0.58
10,000	6,120	0.61
15,000	8,250	0.55
20,000	11,020	0.55
25,000	13,620	0.54
30,000	16,200	0.54
35,000	18,900	0.54
40,000	21,100	0.53
45,000	24,160	0.54
50,000	26,260	0.53
60,000	30,740	0.51
80,000	40,800	0.51
100,000	48,790	0.49

APPENDIX C

INFLUENT COD AND ORGANIC LOADING RATES (10 DAYS)

ORGANIC LOADING RATE (Kg COD/m^3.d)	**INFLUENT COD (mg/l)**
0.29	2,920
0.58	5,840
0.80	8,000
1.00	10,000
1.50	15,000
2.00	20,000
2.50	25,000
3.00	30,000
3.50	35,000
4.00	40,000
4.50	45,000
5.00	50,000
6.00	60,000
8.00	80,000
10.00	100,000

REACTOR : R1 RECYCLED BIOMASS SYSTEM

DAY	INFLUENT		HRT	LOADING RATE	EFFLUENT				%REMOVA		DAILY GAS PRODUCTION			GAS YIELD PER COD REMOVED	MIXED LIQUOR				Base Added	SLUDGE		
	COD	SS (mg/l)	(days)	(Kg COD /m3/d.)	COD (mg/l)	SS (mg/l)	TS (mg/l)	VS (mg/l)	COD	SS	Reactor (ml)	Clarifie (ml)	Total Yield (ml)	(at 35°C) (m³/kgCOD r)	SS (mg/l)	TS (mg/l)	VS (mg/l)	pH	(mg)	SS (mg/l)	TS (mg/l)	VS (mg/l)
1	5840	2100	20	0.3	15400	12500	21900	14600			695		695		13600	22900	15600			13400	21500	14000
2	5840	2100	20	0.3	13200	11200	19040	12400			770		770		13000	20400	14200			13100	21480	14060
3	5840	2100	20	0.3	12040	10400	18100	11680			1270		1270		13000	19100	13600			13000	20040	12980
4	5840	2100	20	0.3	9600	9000	16600	10800			1020		1020		12600	18200	11400	8.30		13000	20100	12900
5	5840	2100	20	0.3	8440	8600	13800	9040			1170		1170		11800	16000	10100	8.30		12700	19760	12900
6	5840	2100	20	0.3	8000	8000	12000	7700			970		970		11200	15600	10100	8.04		12600	17400	11300
7	5840	2100	20	0.3	7840	7000	10800	7100			530		530		10500	14400	9200	8.00		12640	16640	10800
8	5840	2100	20	0.3	6800	7200	9300	6400			1120		1120		10200	13600	8800	8.00		12500	15800	10380
9	5840	2100	20	0.3	5980	6500	8300	6100			1420		1420		9000	12200	8000	7.50		12500	15500	11080
10	5840	2100	20	0.3	5800	1500	3200	2400	0.7	28.6	900		900		8600	11000	7200	7.34		12440	15200	9800
11	5840	2100	20	0.3	5000	1000	2800	2000	14.4	52.4	1100		1100		7800	10000	6740	7.31		12400	14800	9500
12	5840	2100	20	0.3	5300	600	2300	1700	9.2	71.4	1040		1040		7200	9900	6300	7.33		12100	14600	9300
13	5840	2100	20	0.3	5600	500	2200	1600	4.1	76.2	800		800		7000	9800	8000	7.26		11700	14100	9100
14	5840	2100	20	0.3	4800	700	2500	1800	17.8	66.7	1000		1000		7000	9600	6200	7.20		11000	13500	8700
15	5840	2100	20	0.3	3340	360	2100	1500	42.8	82.9	970		970		6100	7800	5000	7		10500	13000	8300

REACTOR : R1 RECYCLED BIOMASS SYSTEM

DAY	INFLUENT COD	INFLUENT SS (mg/l)	HRT (days)	LOADING RATE (Kg COD/m3/d)	EFFLUENT COD (mg/l)	EFFLUENT SS (mg/l)	EFFLUENT TS (mg/l)	EFFLUENT VS (mg/l)	%REMOVA COD	%REMOVA SS	DAILY GAS PRODUCTION Reactor (ml)	DAILY GAS PRODUCTION larifie (ml)	DAILY GAS PRODUCTION Total Yield (ml)	GAS YIELD PER COD REMOVED (at 35°C) (m^3/kgCOD r	MIXED LIQUOR SS (mg/l)	MIXED LIQUOR TS (mg/l)	MIXED LIQUOR VS (mg/l)	MIXED LIQUOR pH	Base Added (mg)	SLUDGE SS (mg/l)	SLUDGE TS (mg/l)	SLUDGE VS (mg/l)
16	5840	2100	20	0.3	3700	500	2000	1600	36.6	76.2	1120		1120		5400	7100	4600	6.99		9700	12200	7800
17	5840	2100	20	0.3	3010	440	2000	1400	48.5	79.0	900	50	950		5200	7000	4500	6.99		9400	11800	7600
18	5840	2100	20	0.3	1600	320	2000	1400	72.6	84.8	530	60	590	0.795	4500	5900	3800	7.05		8800	11200	7200
19	5840	2100	20	0.3	1540	240	1920	1440	73.6	88.6	500	75	575	0.764	4100	5400	3600	7.06		8700	11100	7200
20	5840	2100	20	0.3	1420	240	1920	1400	75.7	88.6	510	90	600	0.776	4000	5600	3800	6.91		8900	11300	7400
21	5840	2100	20	0.3	1600	320	2000	1600	72.6	84.8	490	80	570	0.768	3800	5200	3700	6.60		8800	11200	7200
22	5840	2100	20	0.3	1010	200	1920	1400	82.7	90.5	400	70	470	0.556	3800	5100	3500	6.42	1680	8700	11100	7200
23	5840	2100	20	0.3	840	160	1880	1280	85.6	92.4	420	60	480	0.549	3600	5000	3300	7.30		8800	11200	7300
24	5840	2100	20	0.3	820	160	1560	1160	86.0	92.4	340	70	410	0.467	3800	5200	3500	6.95		8700	11000	7200
25	5840	2100	20	0.3	760	120	1540	1120	87.0	94.3	390	65	455	0.512	3700	5200	3400	6.63		8600	11000	7200
26	5840	2100	20	0.3	760	100	1520	1120	87.0	95.2	400	70	470	0.529	3700	5000	3300	6.54	420	8700	11100	7200
27	5840	2100	20	0.3	720	120	1700	1220	87.7	94.3	400	50	450	0.502	3800	5300	3500	6.98		8700	11000	7200
28	5840	2100	20	0.3	650	100	1500	1080	88.9	95.2	420	60	480	0.528	3600	5100	3300	6.52	840	8800	11000	7300
29	5840	2100	20	0.3	600	100	1520	1080	89.7	95.2	415	55	470	0.513	3600	5000	3200	7.01		8800	11100	7200
30	5840	2100	20	0.3	600	120	1540	1080	89.7	94.3	425	60	485	0.529	3700	5000	3300	6.78		8800	11100	7200

REACTOR : R1 RECYCLED BIOMASS SYSTEM

DAY	INFLUENT COD	INFLUENT SS (mg/l)	HRT (days)	LOADING RATE (Kg COD/m3/d.)	EFFLUENT COD (mg/l)	EFFLUENT SS (mg/l)	EFFLUENT TS (mg/l)	EFFLUENT VS (mg/l)	%REMOVA COD	%REMOVA SS	DAILY GAS PRODUCTION Reactor (ml)	DAILY GAS PRODUCTION larifie (ml)	DAILY GAS PRODUCTION Total Yield (ml)	GAS YIELD PER COD REMOVED (at 35°C) (m³/kgCOD r)	MIXED LIQUOR SS (mg/l)	MIXED LIQUOR TS (mg/l)	MIXED LIQUOR VS (mg/l)	MIXED LIQUOR pH	Base Added (mg)	SLUDGE SS (mg/l)	SLUDGE TS (mg/l)	SLUDGE VS (mg/l)
31	5840	2100	20	0.3	610	100	1520	1080	89.6	95.2	410	60	470	0.514	3600	5000	3200	6.60		8600	11100	7200
32	5840	2100	20	0.3	600	100	1500	1080	89.7	95.2	425	65	490	0.534	3600	5000	3200	6.45	1260	8700	11100	7300
33	5840	2100	20	0.3	600	100	1500	1080	89.7	95.2	430	55	485	0.529	3600	5000	3200	7.10		8700	11100	7200
34	5110	1600	18	0.3	1180	160	1540	1080	76.9	90.0	300	60	360	0.458	3600	5100	3300	7.00		8700	11000	7400
35	5110	1600	18	0.3	600	100	1520	1080	88.3	93.8	400	40	440	0.488	3600	5000	3200	7.01		8700	11000	7200
36	5110	1600	18	0.3	560	80	1480	1040	89.0	95.0	420	60	480	0.527	3600	5100	3200	6.94		8700	11100	7300
37	5110	1600	18	0.3	540	120	1480	1040	89.4	92.5	430	65	495	0.542	3700	5000	3400	6.64		8700	11000	7200
38	5110	1600	18	0.3	530	80	1480	1040	89.6	95.0	430	65	495	0.540	3600	5000	3300	6.49	840	8700	11000	7400
39	5110	1600	18	0.3	530	80	1480	1040	89.6	95.0	420	60	480	0.524	3600	5000	3200	7.04		8600	11000	7200
40	4380	1200	15	0.3	580	80	1480	1080	86.8	93.3	370	60	430	0.485	3600	5000	3200	6.98		8600	11000	7200
41	4380	1200	15	0.3	460	100	1440	1040	89.5	91.7	420	50	470	0.514	3600	5000	3200	6.46	1260	8600	11000	7200
42	4380	1200	15	0.3	450	80	1440	1040	89.7	93.3	420	60	480	0.523	3600	5000	3300	7.21		8700	11000	7200
43	4380	1200	15	0.3	440	80	1440	1040	90.0	93.3	430	55	485	0.528	3600	5000	3200	6.98		8600	11000	7200
44	3650	900	13	0.3	480	100	1400	1040	86.8	88.9	390	50	440	0.496	3700	5100	3300	6.81		8800	11200	7400
45	3650	900	13	0.3	380	80	1400	1000	89.6	91.1	420	40	460	0.502	3600	5000	3200	6.69		8600	11100	7300

REACTOR : R1 RECYCLED BIOMASS SYSTEM

DAY	INFLUENT COD	INFLUENT SS (mg l)	HRT (days)	LOADING RATE (Kg COD m3/d)	EFFLUENT COD (mg l)	EFFLUENT SS (mg l)	EFFLUENT TS (mg l)	EFFLUENT VS (mg l)	%REMOVA COD	%REMOVA SS	DAILY GAS PRODUCTION Reactor (ml)	DAILY GAS PRODUCTION larifie (ml)	DAILY GAS PRODUCTION Total Yield (ml)	GAS YIELD PER COD REMOVED (at 35°C) (m^3 kgCOD r)	MIXED LIQUOR SS (mg l)	MIXED LIQUOR TS (mg l)	MIXED LIQUOR VS (mg l)	MIXED LIQUOR pH	Base Added (mg)	SLUDGE SS (mg l)	SLUDGE TS (mg l)	SLUDGE VS (mg l)
46	3650	900	13	0.3	370	40	1340	880	89.9	95.6	430	45	475	0.517	3600	5000	3200	6 53	840	8600	11000	7200
47	3650	900	13	0.3	370	40	1360	880	89.9	95.6	425	50	475	0.517	3600	5000	3300	6 77		8700	11100	7200
48	2920	800	10	0.3	360	40	1320	880	87.7	95.0	400	55	455	0.508	3500	5000	3200	6.50	840	8600	11100	7200
49	2920	800	10	0.3	300	40	1320	920	89.7	95.0	425	60	485	0.529	3600	5000	3200	6 67		8600	11200	7300
50	2920	800	10	0.3	320	40	1280	880	89.0	95.0	425	55	480	0.527	3600	5000	3200	6 52	840	8500	11000	7000
51	2920	800	10	0.3	300	40	1280	880	89.7	95.0	425	60	485	0.529	3600	5100	3200	7.05		8600	11000	7200
52	1460	300	5	0.3	180	40	700	480	87.7	86.7	420	40	460	0.513	3600	5000	3200	6 99		8500	11000	7000
53	1460	300	5	0.3	160	40	740	480	89.0	86.7	425	40	465	0.511	3700	5000	3200	6 58	420	8600	10900	7100
54	1460	300	5	0.3	156	40	700	480	89.3	86.7	525	50	575	0.630	3600	4900	3200	7 04		8600	11000	7000
55	290	120	1	0.3	40	40	240	160	86.2	66.7	410	50	460	0.526	3700	5000	3100	6.98		8500	11000	7000
56	290	120	1	0.3	30	40	240	160	89.7	66.7	420	55	475	0.522	3600	5000	3200	6 70		8600	11100	7200
57	290	120	1	0.3	30	40	240	160	89.7	66.7	420	60	480	0.527	3600	5100	3200	6.51	840	8600	11000	7200
58	9000	1200	20	0.5	900	80	1640	1160	90.0	93.3	600	40	640	0.451	3700	5100	3200	6 99		8600	11000	7200
59	9000	1200	20	0.5	900	60	1600	1160	90.0	95.0	660	50	710	0.501	3800	5100	3200	6 58	420	8600	10900	7100
60	9000	1200	20	0.5	800	60	1640	1160	91.1	95.0	670	55	725	0.505	3800	5200	3200	6 86		8700	11000	7300

REACTOR : R1 RECYCLED BIOMASS SYSTEM

DAY	INFLUENT COD	INFLUENT SS (mg l)	HRT (days)	LOADING RATE (Kg COD /m3/d.)	EFFLUENT COD (mg l)	EFFLUENT SS (mg l)	EFFLUENT TS (mg l)	EFFLUENT VS (mg l)	%REMOVA COD	%REMOVA SS	DAILY GAS PRODUCTION Reactor (ml)	DAILY GAS PRODUCTION Clarifie (ml)	DAILY GAS PRODUCTION Total Yield (ml)	GAS YIELD PER COD REMOVED (at 35°C) m^3/kgCOD r	MIXED LIQUOR SS (mg l)	MIXED LIQUOR TS (mg l)	MIXED LIQUOR VS (mg l)	MIXED LIQUOR pH	Base Added (mg)	SLUDGE SS (mg l)	SLUDGE TS (mg l)	SLUDGE VS (mg l)
61	9000	1200	20	0.5	840	60	1600	1160	90.7	95.0	660	50	710	0.497	3800	5200	3200	6.60		8600	11000	7200
62	11680	1800	20	0.6	1200	100	1640	1160	89.7	94.4	810	40	850	0.463	3800	5100	3200	6.52	840	8800	11100	7300
63	11680	1800	20	0.6	880	100	1640	1120	92.5	94.4	870	55	925	0.489	3900	5300	3300	7.02		8800	11200	7300
64	11680	1800	20	0.6	880	80	1640	1160	92.5	95.6	880	55	935	0.495	3800	5200	3200	6.62		8800	11200	7300
65	11680	1800	20	0.6	900	80	1640	1160	92.3	95.6	860	60	920	0.488	3900	5300	3200	6.52	840	8700	11300	7400
66	5840	800	10	0.6	520	40	1360	920	91.1	95.0	830	50	880	0.473	3800	5200	3200	6.99		8800	11300	7400
67	5840	800	10	0.6	480	40	1360	920	91.8	95.0	870	50	920	0.490	3800	5100	3200	6.72		8800	11300	7400
68	5840	800	10	0.6	460	40	1360	920	92.1	95.0	870	55	925	0.491	3800	5300	3200	6.55	420	8800	11200	7400
69	5840	800	10	0.6	460	40	1360	920	92.1	95.0	870	45	915	0.486	3800	5200	3200	6.75		8700	11200	7300
70	8000	900	10	0.8	780	80	1360	960	90.3	91.1	1100	40	1140	0.451	3800	5300	3300	6.57	420	8800	11300	7300
71	8000	900	10	0.8	580	80	1360	960	92.8	91.1	1200	45	1245	0.479	3800	5300	3200	6.70		8800	11300	7400
72	8000	900	10	0.8	560	80	1320	920	93.0	91.1	1210	55	1265	0.486	3800	5200	3200	6.55	420	8800	11200	7300
73	10000	900	10	1.0	720	80	1340	940	92.8	91.1	1400	50	1450	0.446	3900	5200	3100	6.63		8800	11300	7400
74	10000	900	10	1.0	660	80	1340	920	93.4	91.1	1520	50	1570	0.480	3800	5300	3200	6.53	840	8800	11300	7400
75	10000	900	10	1.0	640	80	1320	940	93.6	91.1	1520	55	1575	0.481	3800	5200	3200	6.99		8800	11300	7400

REACTOR : R1 RECYCLED BIOMASS SYSTEM

DAY	INFLUENT COD	INFLUENT SS (mg/l)	HRT (days)	LOADING RATE (Kg COD/m3/d)	EFFLUENT COD (mg/l)	EFFLUENT SS (mg/l)	EFFLUENT TS (mg/l)	EFFLUENT VS (mg/l)	%REMOVA COD	%REMOVA SS	DAILY GAS PRODUCTION Reactor (ml)	DAILY GAS PRODUCTION Clarifie (ml)	DAILY GAS PRODUCTION Total Yield (ml)	GAS YIELD PER COD REMOVED (at 35°C) (m³/kgCOD r)	MIXED LIQUOR SS (mg/l)	MIXED LIQUOR TS (mg/l)	MIXED LIQUOR VS (mg/l)	MIXED LIQUOR pH	Base Added (mg)	SLUDGE SS (mg/l)	SLUDGE TS (mg/l)	SLUDGE VS (mg/l)
76	10000	900	10	1.0	640	80	1320	920	93.6	91.1	1520	50	1570	0.479	3900	5300	3200	6.86		8800	11300	7400
77	15000	1100	10	1.5	1100				92.7		2240	50	2290	0.471				6.54	840			
78	15000	1100	10	1.5	1020				93.2		2300	50	2350	0.480				7.10				
79	15000	1100	10	1.5	940				93.7		2350	55	2405	0.489				7.03				
80	15000	1100	10	1.5	900	100	1140	800	94.0	90.9	2360	55	2415	0.489	3900	5200	3200	6.98		8900	11400	7400
81	20000	1200	10	2.0	1340				93.3		3060	50	3110	0.476				6.75				
82	20000	1200	10	2.0	1280				93.6		3150	55	3205	0.489				6.69				
83	20000	1200	10	2.0	1160				94.2		3200	60	3260	0.494				6.62				
84	20000	1200	10	2.0	1120	120	1200	860	94.4	90.0	3300	60	3360	0.508	4000	5400	3300	6.56	420	9100	11600	7600
85	25000	1200	10	2.5	1640				93.4		3850	55	3905	0.478				6.98				
86	25000	1200	10	2.5	1480				94.1		3900	55	3955	0.480				6.84				
87	25000	1200	10	2.5	1360				94.6		3990	55	4045	0.489				6.72				
88	25000	1200	10	2.5	1320	120	1220	860	94.7	90.0	4000	55	4055	0.489	4000	5300	3200	6.60		9000	11600	7500
89	30000	1400	10	3.0	1720				94.3		4630	50	4680	0.473				6.52	840			
90	30000	1400	10	3.0	1640				94.5		4700	55	4755	0.479				7.06				

REACTOR : R1 RECYCLED BIOMASS SYSTEM

DAY	INFLUENT COD	INFLUENT SS (mg/l)	HRT (days)	LOADING RATE (Kg COD/m3/d.)	EFFLUENT COD (mg/l)	EFFLUENT SS (mg/l)	EFFLUENT TS (mg/l)	EFFLUENT VS (mg/l)	%REMOVA COD	%REMOVA SS	DAILY GAS PRODUCTION Reactor (ml)	DAILY GAS PRODUCTION Clarifie (ml)	DAILY GAS PRODUCTION Total Yield (ml)	GAS YIELD PER COD REMOVED (at 35°C) (m^3/kgCOD r)	MIXED LIQUOR SS (mg/l)	MIXED LIQUOR TS (mg/l)	MIXED LIQUOR VS (mg/l)	MIXED LIQUOR pH	Base Added (mg)	SLUDGE SS (mg/l)	SLUDGE TS (mg/l)	SLUDGE VS (mg/l)
91	30000	1400	10	3.0	1580				94.7		4800	60	4860	0.489				7 02				
92	30000	1400	10	3.0	1540	160	1280	900	94.9	88.6	4820	65	4885	0.490	4100	5600	3400	6 95		9000	11500	7500
93	35000	1460	10	3.5	2080				94.1		5420	55	5475	0.475				6.82				
94	35000	1460	10	3.5	1920				94.5		5510	55	5565	0.481				6.76				
95	35000	1460	10	3.5	1780				94.9		5610	55	5665	0.487				6 72				
96	35000	1460	10	3.5	1740	160	1320	920	95.0	89.0	5630	60	5690	0.489	4100	5600	3400	6.53	840	9100	11600	7600
97	40000	1600	10	4.0	2420				94.0		6200	50	6250	0.475				7.00				
98	40000	1600	10	4.0	2260				94.4		6220	55	6275	0.475				6 95				
99	40000	1600	10	4.0	2120				94.7		6450	55	6505	0.491				6 92				
100	40000	1600	10	4.0	2080	160	1360	940	94.8	90.0	6480	55	6535	0.492	4200	5700	3500	6 83		9200	11800	7700
101	45000	1600	10	4.5	2940				93.5		6950	50	7000	0.476				6 69				
102	45000	1600	10	4.5	2800				93.8		7100	50	7150	0.484				6 60				
103	45000	1600	10	4.5	2740				93.9		7500	55	7555	0.511				6 57	420			
104	45000	1600	10	4.5	2700	160	1380	980	94.0	90.0	7600	60	7660	0.517	4200	5800	3500	6 98		9200	11700	7600
105	50000	1800	10	5.0	3420				93.2		7660	50	7710	0.473				6 85				

REACTOR : R1 RECYCLED BIOMASS SYSTEM

DAY	INFLUENT COD	INFLUENT SS (mg/l)	HRT (days)	LOADING RATE (Kg COD/m3/d.)	EFFLUENT COD (mg/l)	EFFLUENT SS (mg/l)	EFFLUENT TS (mg/l)	EFFLUENT VS (mg/l)	%REMOVA COD	%REMOVA SS	DAILY GAS PRODUCTION Reactor (ml)	DAILY GAS PRODUCTION Clarifie (ml)	DAILY GAS PRODUCTION Total Yield (ml)	GAS YIELD PER COD REMOVED (at 35°C) (m^3/kgCOD r)	MIXED LIQUOR SS (mg/l)	MIXED LIQUOR TS (mg/l)	MIXED LIQUOR VS (mg/l)	MIXED LIQUOR pH	Base Added (mg)	SLUDGE SS (mg/l)	SLUDGE TS (mg/l)	SLUDGE VS (mg/l)
106	50000	1800	10	5.0	3260				93.5		7750	55	7805	0.477				6.79				
107	50000	1800	10	5.0	3180				93.6		7940	60	8000	0.488				6.73				
108	50000	1800	10	5.0	3150	200	1440	1000	93.7	88.9	7980	65	8045	0.491	4300	6000	3700	6.58	420	9200	11800	7700
109	60000	1800	10	6.0	6000				90.0		8900	60	8960	0.474				7.01				
110	60000	1800	10	6.0	5860				90.2		8990	65	9055	0.478				6.96				
111	60000	1800	10	6.0	5600				90.7		9100	70	9170	0.482				6.92				
112	60000	1800	10	6.0	5520	200	1640	1120	90.8	88.9	9450	85	9535	0.500	4300	6000	3700	6.86		9300	11800	7700
113	80000	2100	10	8.0	9680				87.9		11500	80	11580	0.471				6.74				
114	80000	2100	10	8.0	9560				88.1		12000	90	12090	0.490				6.62				
115	80000	2100	10	8.0	9480				88.2		12600	90	12690	0.514				6.57	420			
116	80000	2100	10	8.0	9400	240	1960	1320	88.3	88.6	13200	100	13300	0.538	4400	6000	3800	6.99		9300	11800	7800
117	100000	2100	10	10.0	15600				84.4		13800	80	13880	0.470				6.90				
118	100000	2100	10	10.0	15000				85.0		14000	80	14080	0.473				6.84				
119	100000	2100	10	10.0	14200				85.8		14200	100	14300	0.476				6.75				
120	100000	2100	10	10.0	14000	240	2040	1400	86.0	88.6	15100	100	15200	0.505	4400	6200	3800	6.65		9400	12000	7800

REACTOR : R2 CONVENTIONAL ANAEROBIC PROCESS

DAY	INFLUENT COD	INFLUENT SS (mg l)	HRT (days)	LOADING RATE (Kg COD /m3/d)	EFFLUENT COD (mg l)	EFFLUENT SS (mg l)	EFFLUENT TS (mg l)	EFFLUENT VS (mg l)	%REMOVA COD	%REMOVA SS	DAILY GAS PRODUCTION Reactor (ml)	DAILY GAS PRODUCTION larifie (ml)	DAILY GAS PRODUCTION Total Yield (ml)	GAS YIELD PER COD REMOVED (at $35^{0}C$) (m^3/kgCOD r)	MIXED LIQUOR SS (mg l)	MIXED LIQUOR TS (mg l)	MIXED LIQUOR VS (mg l)	MIXED LIQUOR pH	Base Added (mg)
1	5840	2100	20	0.3	15400	11200	21900	14600			1055		1055		13000	21600	14200		
2	5840	2100	20	0.3	14000	10400	18200	11700			530		530		12700	20000	13840		
3	5840	2100	20	0.3	13040	10000	17040	11100			1350		1350		12720	18400	11300		
4	5840	2100	20	0.3	12000	9400	16800	10800			1130		1130		12400	17500	11100	7 80	
5	5840	2100	20	0.3	11240	8200	11600	7900			885		885		12080	15900	10200	7.56	
6	5840	2100	20	0.3	12000	7200	10400	6860			755		755		10500	15800	10000	7 50	
7	5840	2100	20	0.3	9060	7000	10500	6900			920		920		9800	13600	9060	7.63	
8	5840	2100	20	0.3	9200	6700	8780	6000			530		530		10000	13400	8600	7.52	
9	5840	2100	20	0.3	6240	6500	8300	6100			600		600		9200	12000	7200	7 43	
10	5840	2100	20	0.3	6600	1500	3200	2400		28.6	900		900		8700	11000	7200	7.40	
11	5840	2100	20	0.3	5400	1000	2800	2100	7.5	52.4	1000		1000		7700	10000	6700	7 35	
12	5840	2100	20	0.3	5700	620	2500	2000	2.4	70.5	1080		1080		7040	9700	5920	7 33	
13	5840	2100	20	0.3	5200	580	2300	1800	11.0	72.4	860		860		6500	8760	5560	7 28	
14	5840	2100	20	0.3	5000	560	2300	1800	14.4	73.3	1040	40	1080					7 26	
15	5840	2100	20	0.3	4100	520	2300	1800	29.8	75.2	980	30	1010					7.21	

REACTOR : R2 CONVENTIONAL ANAEROBIC PROCESS

DAY	INFLUENT COD	INFLUENT SS (mg/l)	HRT (days)	LOADING RATE (Kg COD /m3/d.)	EFFLUENT COD (mg/l)	EFFLUENT SS (mg/l)	EFFLUENT TS (mg/l)	EFFLUENT VS (mg/l)	%REMOVA COD	%REMOVA SS	DAILY GAS PRODUCTION Reactor (ml)	DAILY GAS PRODUCTION Clarifie (ml)	DAILY GAS PRODUCTION Total Yield (ml)	GAS YIELD PER COD REMOVED (at 35°C) (m^3/kgCOD r.)	MIXED LIQUOR SS (mg/l)	MIXED LIQUOR TS (mg/l)	MIXED LIQUOR VS (mg/l)	pH	Base Added (mg)
16	5840	2100	20	0.3	3600	480	2200	1600	38.4	77.1	870	40	910		3900	5600	3500	7.13	
17	5840	2100	20	0.3	4100	480	2200	1600	29.8	77.1	700	50	750					7.08	
18	5840	2100	20	0.3	2500	440	2100	1500	57.2	79.0	305	55	360	0.616	3700	5400	3400	7.06	
19	5840	2100	20	0.3	2000	400	2100	1560	65.8	81.0	310	60	370	0.551				7.05	
20	5840	2100	20	0.3	1740	360	2040	1480	70.2	82.9	340	65	405	0.564	3600	5400	3200	7.04	
21	5840	2100	20	0.3	1800	320	2000	1480	69.2	84.8	350	50	400	0.566				7.02	
22	5840	2100	20	0.3	1600	320	2000	1440	72.6	84.8	345	60	405	0.546				6.99	
23	5840	2100	20	0.3	1120	320	2000	1480	80.8	84.8	390		390	0.472	3300	5200	3000	7.00	
24	5840	2100	20	0.3	1260	280	1960	1440	78.4	86.7	385	50	435	0.543				6.95	
25	5840	2100	20	0.3	1000	280	1960	1440	82.9	86.7	400	60	460	0.543	3100	4600	2800	6.54	840
26	5840	2100	20	0.3	960	240	1920	1440	83.6	88.6	395	50	445	0.521				6.67	
27	5840	2100	20	0.3	1200	200	1920	1440	79.5	90.5	405	50	455	0.560	3000	4400	2700	6.55	420
28	5840	2100	20	0.3	980	240	1920	1400	83.2	88.6	420	55	475	0.558				6.62	
29	5840	2100	20	0.3	960	200	1920	1400	83.6	90.5	410	50	460	0.539				6.65	
30	5840	2100	20	0.3	980	200	1900	1360	83.2	90.5	440	55	495	0.582	3000	4300	2700	6.57	420

REACTOR : R2 CONVENTIONAL ANAEROBIC PROCESS

DAY	INFLUENT COD	INFLUENT SS (mg/l)	HRT (days)	LOADING RATE (Kg COD /m3/d.)	EFFLUENT COD (mg/l)	EFFLUENT SS (mg/l)	EFFLUENT TS (mg/l)	EFFLUENT VS (mg/l)	%REMOVA COD	%REMOVA SS	DAILY GAS PRODUCTION Reactor (ml)	DAILY GAS PRODUCTION Clarifie (ml)	DAILY GAS PRODUCTION Total Yield (ml)	GAS YIELD PER COD REMOVED (at 35^{0}C) (m^3/kgCOD r.)	MIXED LIQUOR SS (mg/l)	MIXED LIQUOR TS (mg/l)	MIXED LIQUOR VS (mg/l)	MIXED LIQUOR pH	Base Added (mg)
31	5840	2100	20	0.3	960	240	1920	1400	83.6	88.6	405	60	465	0.544				6.60	
32	5840	2100	20	0.3	960	200	1920	1400	83.6	90.5	420	60	480	0.562	3000	4400	2700	6.46	1260
33	5840	2100	20	0.3	960	200	1920	1400	83.6	90.5	415	50	465	0.544				7.21	
34	5110	1600	18	0.3	1000	240	1920	1360	80.4	85.0	385	60	445	0.541	3000	4400	2700	7.09	
35	5110	1600	18	0.3	960	200	1880	1320	81.2	87.5	405	40	445	0.536				6.97	
36	5110	1600	18	0.3	870	200	1920	1360	83.0	87.5	410	60	470	0.554				6.58	420
37	5110	1600	18	0.3	880	160	1880	1280	82.8	90.0	400	45	445	0.526	2900	4300	2600	6.71	
38	5110	1600	18	0.3	870	160	1880	1280	83.0	90.0	410	55	465	0.548				6.55	420
39	5110	1600	18	0.3	870	160	1880	1320	83.0	90.0	395	55	450	0.531	2900	4400	2800	7.05	
40	4380	1200	15	0.3	980	140	1880	1280	77.6	88.3	370	60	430	0.542				7.00	
41	4380	1200	15	0.3	800	160	1880	1280	81.7	86.7	390	40	430	0.515	2900	4300	2600	6.53	840
42	4380	1200	15	0.3	760	140	1880	1280	82.6	88.3	390	50	440	0.521				7.12	
43	4380	1200	15	0.3	760	140	1880	1280	82.6	88.3	395	50	445	0.527				7.01	
44	3650	900	13	0.3	1000	120	1820	1180	72.6	86.7	350	50	400	0.539	3000	4400	2600	6.86	
45	3650	900	13	0.3	700	100	1760	1120	80.8	88.9	365	60	425	0.515				6.54	840

REACTOR : R2 CONVENTIONAL ANAEROBIC PROCESS

DAY	INFLUENT COD	INFLUENT SS (mg/l)	HRT (days)	LOADING RATE (Kg COD m3/d.)	EFFLUENT COD (mg/l)	EFFLUENT SS (mg/l)	EFFLUENT TS (mg/l)	EFFLUENT VS (mg/l)	%REMOVA COD	%REMOVA SS	DAILY GAS PRODUCTION Reactor (ml)	DAILY GAS PRODUCTION larifie (ml)	DAILY GAS PRODUCTION Total Yield (ml)	GAS YIELD PER COD REMOVED (at 35°C) (m³/kgCOD r	MIXED LIQUOR SS (mg/l)	MIXED LIQUOR TS (mg/l)	MIXED LIQUOR VS (mg/l)	MIXED LIQUOR pH	Base Added (mg)
46	3650	900	13	0.3	640	120	1780	1120	82.5	86.7	390	50	440	0.522	2900	4300	2600	7 06	
47	3650	900	13	0.3	640	100	1760	1120	82.5	88.9	385	40	425	0.504				6 98	
48	2920	800	10	0.3	640	120	1760	1160	78.1	85.0	340	50	390	0.489	2800	4300	2400	6 60	
49	2920	800	10	0.3	560	100	1760	1120	80.8	87.5	370	60	430	0.521				6 46	1260
50	2920	800	10	0.3	520	100	1720	1100	82.2	87.5	370	50	420	0.500				7.30	
51	2920	800	10	0.3	520	100	1720	1100	82.2	87.5	380	50	430	0.512	2800		2400	7.02	
52	1460	300	5	0.3	300	40	1180	760	79.5	86.7	360	40	400	0.493				6 89	
53	1460	300	5	0.3	265	40	1160	760	81.8	86.7	330	45	375	0.448	2800	4300	2600	6 66	
54	1460	300	5	0.3	260	40	1160	740	82.2	86.7	380	50	430	0.512				6 62	
55	290	120	1	0.3	80	40	360	220	72.4	66.7	380	50	430	0.585	2700	4300	2600	6 57	420
56	290	120	1	0.3	60	40	360	240	79.3	66.7	370	50	420	0.522				6 63	
57	290	120	1	0.3	52	40	360	220	82.1	66.7	375	55	430	0.516				6 54	840
58	9000	1200	20	0.5	2000	160	2140	1380	77.8	86.7	500	50	550	0.449	2900	4400	2600	7 10	
59	9000	1200	20	0.5	1700	120	2000	1280	81.1	90.0	580	55	635	0.497				6 86	
60	9000	1200	20	0.5	1520	120	2000	1280	83.1	90.0	580	55	635	0 485	2900	4400	2600	6 60	

REACTOR : R2 CONVENTIONAL ANAEROBIC PROCESS

DAY	INFLUENT		HRT	LOADING RATE	EFFLUENT				%REMOVA		DAILY GAS PRODUCTION			GAS YIELD PER COD REMOVED (at 35°C)	MIXED LIQUOR				Base Added
	COD	SS (mg l)	(days)	(Kg COD /m3.d)	COD (mg l)	SS (mg l)	TS (mg l)	VS (mg l)	COD	SS	Reactor (ml)	Clarifie (ml)	Total Yield (ml)	(m^3/kgCOD r	SS (mg l)	TS (mg l)	VS (mg l)	pH	(mg)
61	9000	1200	20	0.5	1500	120	2040	1300	83.3	90.0	585	55	640	0.488				6 57	420
62	11680	1800	20	0.6	2240	240	2280	1520	80.8	86.7	720	40	760	0.460	2800	4500	2700	6 62	
63	11680	1800	20	0.6	2080	200	2240	1400	82.2	88.9	770	40	810	0.482				6 55	420
64	11680	1800	20	0.6	1960	200	2240	1440	83.2	88.9	780	45	825	0.485				6 60	
65	11680	1800	20	0.6	1940	200	2240	1440	83.4	88.9	770	45	815	0.478	3000	4500	2800	6 54	840
66	5840	800	10	0.6	1140	120	1920	1240	80.5	85.0	770	45	815	0.495				7 04	
67	5840	800	10	0.6	1060	80	1900	1240	81.8	90.0	780	50	830	0.496	3000	4500	2700	6 98	
68	5840	800	10	0.6	1020	80	1920	1240	82.5	90.0	790	45	835	0.495				6 91	
69	5840	800	10	0.6	1000	80	1920	1240	82.9	90.0	750	40	790	0.466	2900	4500	2700	6 80	
70	8000	900	10	0.8	1520	80	2040	1320	81.0	91.1	760	40	800	0.353				6 71	
71	8000	900	10	0.8	1360	100	2000	1320	83.0	88.9	1000	45	1045	0.450				6 62	
72	8000	900	10	0.8	1340	100	2040	1320	83.3	88.9	1040	50	1090	0.468	2900	4500	2800	6 56	420
73	10000	900	10	1.0	1860	100	2040	1320	81 4	88.9	1040	40	1080	0.379				6 96	
74	10000	900	10	1.0	1780	100	2040	1320	82.2	88.9	1280	45	1325	0.461	2800	4500	2700	6 76	
75	10000	900	10	1.0	1680	100	2040	1320	83.2	88.9	1300	50	1350	0.464				6 64	

REACTOR : R2 CONVENTIONAL ANAEROBIC PROCESS

DAY	INFLUENT COD	INFLUENT SS (mg/l)	HRT (days)	LOADING RATE (Kg COD/m3/d)	EFFLUENT COD (mg/l)	EFFLUENT SS (mg/l)	EFFLUENT TS (mg/l)	EFFLUENT VS (mg/l)	% REMOVAL COD	% REMOVAL SS	DAILY GAS PRODUCTION Reactor (ml)	DAILY GAS PRODUCTION Clarifier (ml)	DAILY GAS PRODUCTION Total Yield (ml)	GAS YIELD PER COD REMOVED (at 35°C) (m^3/kgCOD r)	MIXED LIQUOR SS (mg/l)	MIXED LIQUOR TS (mg/l)	MIXED LIQUOR VS (mg/l)	pH	Base Added (mg)
76	10000	900	10	1.0	1640	100	2040	1320	83.6	88.9	1300	50	1350	0.461	2900	4500	2700	6.57	420
77	15000	1100	10	1.5	2680				82.1		2040	50	2090	0.485				7.03	
78	15000	1100	10	1.5	2520				83.2		2040	55	2095	0.480				6.98	
79	15000	1100	10	1.5	2460				83.6		2100	55	2155	0.491				6.96	
80	15000	1100	10	1.5	2430	140	1920	1280	83.8	87.3	2120	60	2180	0.496	3000	4600	2800	6.83	
81	20000	1200	10	2.0	3360				83.2		2720	55	2775	0.476				6.71	
82	20000	1200	10	2.0	3280				83.6		2750	55	2805	0.479				6.67	
83	20000	1200	10	2.0	3200				84.0		2790	60	2850	0.485				6.60	
84	20000	1200	10	2.0	3160	160	1920	1320	84.2	86.7	2800	55	2855	0.484	3000	4600	2900	6.54	840
85	25000	1200	10	2.5	4200				83.2		3420	55	3475	0.477				7.15	
86	25000	1200	10	2.5	4160				83.4		3500	60	3560	0.488				7.04	
87	25000	1200	10	2.5	4100				83.6		3600	60	3660	0.500				6.99	
88	25000	1200	10	2.5	4080	160	1960	1320	83.7	86.7	3600	60	3660	0.500	3100	4800	2900	6.90	
89	30000	1400	10	3.0	5200				82.7		4080	50	4130	0.476				6.81	
90	30000	1400	10	3.0	5120				82.9		4100	50	4150	0.477				6.77	

REACTOR : R2 CONVENTIONAL ANAEROBIC PROCESS

DAY	INFLUENT COD	INFLUENT SS (mg/l)	HRT (days)	LOADING RATE (Kg COD /m3/d.)	EFFLUENT COD (mg/l)	EFFLUENT SS (mg/l)	EFFLUENT TS (mg/l)	EFFLUENT VS (mg/l)	%REMOVA COD	%REMOVA SS	DAILY GAS PRODUCTION Reactor (ml)	DAILY GAS PRODUCTION larifie (ml)	DAILY GAS PRODUCTION Total Yield (ml)	GAS YIELD PER COD REMOVED (at 35°C) (m³/kgCOD r	MIXED LIQUOR SS (mg/l)	MIXED LIQUOR TS (mg/l)	MIXED LIQUOR VS (mg/l)	pH	Base Added (mg)
91	30000	1400	10	3.0	5060				83.1		4240	55	4295	0.492				6.73	
92	30000	1400	10	3.0	5010	200	2040	1360	83.3	85.7	4260	65	4325	0.494	3200	4900	3000	6 62	
93	35000	1460	10	3.5	7100				79.7		4730	50	4780	0.490				6 56	420
94	35000	1460	10	3.5	6980				80.1		4790	50	4840	0.494				7.04	
95	35000	1460	10	3.5	6880				80.3		4880	55	4935	0.501				7 00	
96	35000	1460	10	3.5	6840	200	2120	1400	80.5	86.3	4900	60	4960	0.503	3300	5000	3000	6 97	
97	40000	1600	10	4.0	8840				77.9		5380	50	5430	0.498				6.90	
98	40000	1600	10	4.0	8610				78.5		5480	55	5535	0.504				6 87	
99	40000	1600	10	4.0	8560				78.6		5650	60	5710	0.519				6 85	
100	40000	1600	10	4.0	8560	240	2240	1480	78.6	85.0	5680	75	5755	0.523	3200	5000	3100	6 74	
101	45000	1600	10	4.5	11560				74.3		5500	70	5570	0.476				6 63	
102	45000	1600	10	4.5	11000				75.6		5620	70	5690	0.478				6.60	
103	45000	1600	10	4.5	10600				76.4		5750	80	5830	0.484				6 54	840
104	45000	1600	10	4.5	10400	240	2280	1480	76.9	85.0	5780	80	5860	0.484	3400	5200	3200	7 10	
105	50000	1800	10	5.0	13000				74.0		5920	75	5995	0.463				7 00	

REACTOR : R2 CONVENTIONAL ANAEROBIC PROCESS

DAY	INFLUENT COD	INFLUENT SS (mg l)	HRT (days)	LOADING RATE (Kg COD /m3/d)	EFFLUENT COD (mg l)	EFFLUENT SS (mg l)	EFFLUENT TS (mg l)	EFFLUENT VS (mg l)	%REMOVA COD	%REMOVA SS	DAILY GAS PRODUCTION Reactor (ml)	DAILY GAS PRODUCTION larifie (ml)	DAILY GAS PRODUCTION Total Yield (ml)	GAS YIELD PER COD REMOVED (at 35°C) (m³/kgCOD r)	MIXED LIQUOR SS (mg l)	MIXED LIQUOR TS (mg l)	MIXED LIQUOR VS (mg l)	pH	Base Added (mg)
106	50000	1800	10	5.0	12800				74.4		6000	80	6080	0.467				6.96	
107	50000	1800	10	5.0	12540				74.9		6180	80	6260	0.477				6 94	
108	50000	1800	10	5.0	12400	280	2280	1520	75.2	84.4	6200	90	6290	0.478	3600	5500	3400	6.88	
109	60000	1800	10	6.0	17400				71.0		6800	80	6880	0.461				6.79	
110	60000	1800	10	6.0	16340				72.8		6950	90	7040	0.461				6.73	
111	60000	1800	10	6.0	15980				73.4		7100	100	7200	0.467				6.67	
112	60000	1800	10	6.0	15720	290	2420	1600	73.8	83.9	7280	100	7380	0.476	3700	5800	3400	6 61	
113	80000	2100	10	8.0	27000				66.3		8490	100	8590	0.463				6 56	420
114	80000	2100	10	8.0	26200				67.3		8780	100	8880	0.472				6 99	
115	80000	2100	10	8.0	25000				68.8		7000	110	7110	0.369				6 85	
116	80000	2100	10	8.0	24800	360	3100	2060	69.0	82.9	9150	120	9270	0.480	3800	5800	3500	6.77	
117	100000	2100	10	10.0	37200				62.8		9800	110	9910	0.451				6 64	
118	100000	2100	10	10.0	36400				63.6		10000	100	10100	0.454				6 58	420
119	100000	2100	10	10.0	34600				65.4		10590	120	10710	0 468				7 00	
120	100000	2100	10	10.0	34000	360	3280	2180	66.0	82.9	10800	120	10920	0.473	3900	6100	3700	6 93	

COMPARISON OF COD REMOVAL

DAY	Influent COD	HRT	LOADING RATE	Effluent COD						% COD Removal						GAS YIELD PER COD REMOVED AT 35° C					
				Recycle			Conventional			Recycle			Conventional			Recycle			Conventional		
	(mg/l)	(days)	(Kg COD /m3/d.)	Actual (mg/l)	Mean (mg/l)	Standard Deviation	Actual (mg/l)	Mean (mg/l)	Standard Deviation	Actual	Mean	Standard Deviation	Actual	Mean	Standard Deviation	Actual (m³/kgCOD removed)	Mean (m³/kgCOD removed)	Standard Deviation	Actual (m³/kgCOD removed)	Mean (m³/kgCOD removed)	Standard Deviation
1	5840	20	0.3	15400			15400									695			1055		
2	5840	20	0.3	13200			14000									770			530		
3	5840	20	0.3	12040	13547	1393	13040	14147	969							1270	912	255	1350	978	339
4	5840	20	0.3	9600			12000									1020			1130		
5	5840	20	0.3	8440			11240									1170			885		
6	5840	20	0.3	8000			12000									970			755		
7	5840	20	0.3	7840			9060									530			920		
8	5840	20	0.3	6800			9200									1120			530		
9	5840	20	0.3	5980	7777	1721	6240	9957	3005							1420	1038	314	600	803	264
10	5840	20	0.3	5800			6600			0.7						900			900		
11	5840	20	0.3	5000			5400			14.4			7.5			1100			1000		
12	5840	20	0.3	5300			5700			9.2			2.4			1040			1080		
13	5840	20	0.3	5600			5200			4.1			11.0			800			860		
14	5840	20	0.3	4800			5000			17.8			14.4			1000			1080		
15	5840	20	0.3	3340	4973	804	4100	5333	752	42.8	14.8	13.8	29.8	10.8	9.8	970	968	97	1010	988	83

COMPARISON OF COD REMOVAL

DAY	Influent COD	HRT	LOADING RATE	Effluent COD						% COD Removal						GAS YIELD PER COD REMOVED AT 35° C					
				Recycle			Conventional			Recycle			Conventional			Recycle			Conventional		
	(mg/l)	(days)	(Kg COD /m3/d.)	Actual (mg/l)	Mean (mg/l)	Standard Deviation	Actual (mg/l)	Mean (mg/l)	Standard Deviation	Actual	Mean	Standard Deviation	Actual	Mean	Standard Deviation	Actual (m^3/kgCOD removed)	Mean	Standard Deviation	Actual (m^3/kgCOD removed)	Mean	Standard Deviation
16	5840	20	0.3	3700			3600			36.6			38.4			1120			910		
17	5840	20	0.3	3010			4100			48.5			29.8			950			750		
18	5840	20	0.3	1600			2500			72.6			57.2			590			360		
19	5840	20	0.3	1540			2000			73.6			65.8			575			370		
20	5840	20	0.3	1420			1740			75.7			70.2			600			405		
21	5840	20	0.3	1600	2145	881	1800	2623	913	72.6	63.3	15.1	69.2	55.1	15.6	570	734	219	400	533	216
22	5840	20	0.3	1010			1600			82.7			72.6			470			405		
23	5840	20	0.3	840			1120			85.6			80.8			480			390		
24	5840	20	0.3	820			1260			86.0			78.4			410			435		
25	5840	20	0.3	760			1000			87.0			82.9			455			460		
26	5840	20	0.3	760			960			87.0			83.6			470			445		
27	5840	20	0.3	720	818	95	1200	1190	211	87.7	86.0	1.6	79.5	79.6	3.6	450	456	23	455	432	26
28	5840	20	0.3	650			980			88.9			83.2			480			475		
29	5840	20	0.3	600			960			89.7			83.6			470			460		
30	5840	20	0.3	600			980			89.7			83.2			485			495		

COMPARISON OF COD REMOVAL

DAY	Influent COD (mg/l)	HRT (days)	LOADING RATE (Kg COD/m3.d.)	Effluent COD						% COD Removal						GAS YIELD PER COD REMOVED AT 35^{0} C					
				Recycle			Conventional			Recycle			Conventional			Recycle			Conventional		
				Actual (mg/l)	Mean (mg/l)	Standard Deviation	Actual (mg/l)	Mean (mg/l)	Standard Deviation	Actual	Mean	Standard Deviation	Actual	Mean	Standard Deviation	Actual (m^3/kgCOD removed)	Mean (m^3/kgCOD removed)	Standard Deviation	Actual (m^3/kgCOD removed)	Mean (m^3/kgCOD removed)	Standard Deviation
31	5840	20	0.3	610			960			89.6			83.6			470			465		
32	5840	20	0.3	600			960			89.7			83.6			490			480		
33	5840	20	0.3	600	610	18	960	967	9	89.7	89.6	0.3	83.6	83.4	0.2	485	480	8	465	473	12
34	5110	18	0.3	1180			1000			76.9			80.4			360			445		
35	5110	18	0.3	600			960			88.3			81.2			440			445		
36	5110	18	0.3	560			870			89.0			83.0			480			470		
37	5110	18	0.3	540			880			89.4			82.8			495			445		
38	5110	18	0.3	530			870			89.6			83.0			495			465		
39	5110	18	0.3	530	657	235	870	908	52	89.6	87.1	4.6	83.0	82.2	1.0	480	458	48	450	453	10
40	4380	15	0.3	580			980			86.8			77.6			430			430		
41	4380	15	0.3	460			800			89.5			81.7			470			430		
42	4380	15	0.3	450			760			89.7			82.6			480			440		
43	4380	15	0.3	440	483	57	760	825	91	90.0	89.0	1.3	82.6	81.2	2.1	485	466	22	445	436	6
44	3650	13	0.3	480			1000			86.8			72.6			440			400		
45	3650	13	0.3	380			700			89.6			80.8			460			425		

COMPARISON OF COD REMOVAL

DAY	Influent COD (mg/l)	HRT (days)	LOADING RATE (Kg COD /m3/d.)	Effluent COD Recycle Actual (mg/l)	Effluent COD Recycle Mean (mg/l)	Effluent COD Recycle Standard Deviation	Effluent COD Conventional Actual (mg/l)	Effluent COD Conventional Mean (mg/l)	Effluent COD Conventional Standard Deviation	% COD Removal Recycle Actual	% COD Removal Recycle Mean	% COD Removal Recycle Standard Deviation	% COD Removal Conventional Actual	% COD Removal Conventional Mean	% COD Removal Conventional Standard Deviation	GAS YIELD PER COD REMOVED AT 35° C Recycle Actual (m^3/kgCOD removed)	GAS YIELD Recycle Mean (m^3/kgCOD removed)	GAS YIELD Recycle Standard Deviation	GAS YIELD Conventional Actual (m^3/kgCOD removed)	GAS YIELD Conventional Mean (m^3/kgCOD removed)	GAS YIELD Conventional Standard Deviation
46	3650	13	0.3	370			640			89.9			82.5			475			440		
47	3650	13	0.3	370	400	46	640	745	149	89.9	89.0	1.3	82.5	79.6	4.1	475	463	14	425	423	14
48	2920	10	0.3	360			640			87.7			78.1			455			390		
49	2920	10	0.3	300			560			89.7			80.8			485			430		
50	2920	10	0.3	320			520			89.0			82.2			480			420		
51	2920	10	0.3	300	320	24	520	560	49	89.7	89.0	0.8	82.2	80.8	1.7	485	476	12	430	418	16
52	1460	5	0.3	180			300			87.7			79.5			460			400		
53	1460	5	0.3	160			265			89.0			81.8			465			375		
54	1460	5	0.3	156	165	10	260	275	18	89.3	88.7	0.7	82.2	81.2	1.2	575	500	53	430	402	22
55	290	1	0.3	40			80			86.2			72.4			460			430		
56	290	1	0.3	30			60			89.7			79.3			475			420		
57	290	1	0.3	30	33	5	52	64	12	89.7	88.5	1.6	82.1	77.9	4.1	480	472	8	430	427	5
58	9000	20	0.5	900			2000			90.0			77.8			640			550		
59	9000	20	0.5	900			1700			90.0			81.1			710			635		
60	9000	20	0.5	800			1520			91.1			83.1			725			635		

COMPARISON OF COD REMOVAL

DAY	Influent COD (mg/l)	HRT (days)	LOADING RATE (Kg COD/m3/d)	Effluent COD – Recycle – Actual (mg/l)	Effluent COD – Recycle – Mean (mg/l)	Effluent COD – Recycle – Standard Deviation	Effluent COD – Conventional – Actual (mg/l)	Effluent COD – Conventional – Mean (mg/l)	Effluent COD – Conventional – Standard Deviation	% COD Removal – Recycle – Actual	% COD Removal – Recycle – Mean	% COD Removal – Recycle – Standard Deviation	% COD Removal – Conventional – Actual	% COD Removal – Conventional – Mean	% COD Removal – Conventional – Standard Deviation	GAS YIELD PER COD REMOVED AT 35° C – Recycle – Actual (m^3/kgCOD removed)	GAS YIELD PER COD REMOVED AT 35° C – Recycle – Mean (m^3/kgCOD removed)	GAS YIELD PER COD REMOVED AT 35° C – Recycle – Standard Deviation	GAS YIELD PER COD REMOVED AT 35° C – Conventional – Actual (m^3/kgCOD removed)	GAS YIELD PER COD REMOVED AT 35° C – Conventional – Mean (m^3/kgCOD removed)	GAS YIELD PER COD REMOVED AT 35° C – Conventional – Standard Deviation
61	9000	20	0.5	840	860	42	1500	1680	200	90.7	90.4	0.5	83.3	81.3	2.2	710	696	33	640	615	38
62	11680	20	0.6	1200			2240			89.7			80.8			850			760		
63	11680	20	0.6	880			2080			92.5			82.2			925			810		
64	11680	20	0.6	880			1960			92.5			83.2			935			825		
65	11680	20	0.6	900	965	136	1940	2055	119	92.3	91.7	1.2	83.4	82.4	1.0	920	908	34	815	803	25
66	5840	10	0.6	520			1140			91.1			80.5			880			815		
67	5840	10	0.6	480			1060			91.8			81.8			920			830		
68	5840	10	0.6	460			1020			92.1			82.5			925			835		
69	5840	10	0.6	460	480	24	1000	1055	54	92.1	91.8	0.4	82.9	81.9	0.9	915	910	18	790	818	18
70	8000	10	0.8	780			1520			90.3			81.0			1140			800		
71	8000	10	0.8	580			1360			92.8			83.0			1245			1045		
72	8000	10	0.8	560	640	99	1340	1407	81	93.0	92.0	1.2	83.3	82.4	1.0	1265	1217	55	1090	978	127
73	10000	10	1.0	720			1860			92.8			81.4			1450			1080		
74	10000	10	1.0	660			1780			93.4			82.2			1570			1325		
75	10000	10	1.0	640			1680			93.6			83.2			1575			1350		

COMPARISON OF COD REMOVAL

DAY	Influent COD (mg/l)	HRT (days)	LOADING RATE (Kg COD /m3/d.)	Effluent COD Recycle Actual (mg/l)	Effluent COD Recycle Mean (mg/l)	Effluent COD Recycle Standard Deviation	Effluent COD Conventional Actual (mg/l)	Effluent COD Conventional Mean (mg/l)	Effluent COD Conventional Standard Deviation	% COD Removal Recycle Actual	% COD Removal Recycle Mean	% COD Removal Recycle Standard Deviation	% COD Removal Conventional Actual	% COD Removal Conventional Mean	% COD Removal Conventional Standard Deviation	GAS YIELD PER COD REMOVED AT 35° C Recycle Actual (m^3/kgCOD removed)	Recycle Mean (m^3/kgCOD removed)	Recycle Standard Deviation	Conventional Actual (m^3/kgCOD removed)	Conventional Mean (m^3/kgCOD removed)	Conventional Standard Deviation
76	10000	10	1.0	640	665	33	1640	1740	86	93.6	93.4	0.3	83.6	82.6	0.9	1570	1541	53	1350	1276	114
77	15000	10	1.5	1100			2680			92.7			82.1			2290			2090		
78	15000	10	1.5	1020			2520			93.2			83.2			2350			2095		
79	15000	10	1.5	940			2460			93.7			83.6			2405			2155		
80	15000	10	1.5	900	990	77	2430	2523	97	94.0	93.4	0.5	83.8	83.2	0.6	2415	2365	50	2180	2130	39
81	20000	10	2.0	1340			3360			93.3			83.2			3110			2775		
82	20000	10	2.0	1280			3280			93.6			83.6			3205			2805		
83	20000	10	2.0	1160			3200			94.2			84.0			3260			2850		
84	20000	10	2.0	1120	1225	89	3160	3250	77	94.4	93.9	0.4	84.2	83.8	0.4	3360	3234	91	2855	2821	33
85	25000	10	2.5	1640			4200			93.4			83.2			3905			3475		
86	25000	10	2.5	1480			4160			94.1			83.4			3955			3560		
87	25000	10	2.5	1360			4100			94.6			83.6			4045			3660		
88	25000	10	2.5	1320	1450	124	4080	4135	48	94.7	94.2	0.5	83.7	83.5	0.2	4055	3990	63	3660	3589	77
89	30000	10	3.0	1720			5200			94.3			82.7			4680			4130		
90	30000	10	3.0	1640			5120			94.5			82.9			4755			4150		

COMPARISON OF COD REMOVAL

DAY	Influent COD (mg/l)	HRT (days)	LOADING RATE (Kg COD/m3/d.)	Effluent COD						% COD Removal						GAS YIELD PER COD REMOVED AT 35^0 C					
				Recycle			Conventional			Recycle			Conventional			Recycle			Conventional		
				Actual (mg/l)	Mean (mg/l)	Standard Deviation	Actual (mg/l)	Mean (mg/l)	Standard Deviation	Actual	Mean	Standard Deviation	Actual	Mean	Standard Deviation	Actual (m^3/kgCOD removed)	Mean	Standard Deviation	Actual (m^3/kgCOD removed)	Mean	Standard Deviation
91	30000	10	3.0	1580			5060			94.7			83.1			4860			4295		
92	30000	10	3.0	1540	1620	68	5010	5098	71	94.9	94.6	0.2	83.3	83.0	0.2	4885	4795	82	4325	4225	86
93	35000	10	3.5	2080			7100			94.1			79.7			5475			4780		
94	35000	10	3.5	1920			6980			94.5			80.1			5565			4840		
95	35000	10	3.5	1780			6880			94.9			80.3			5665			4935		
96	35000	10	3.5	1740	1880	133	6840	6950	100	95.0	94.6	0.4	80.5	80.1	0.3	5690	5599	85	4960	4879	72
97	40000	10	4.0	2420			8840			94.0			77.9			6250			5430		
98	40000	10	4.0	2260			8610			94.4			78.5			6275			5535		
99	40000	10	4.0	2120			8560			94.7			78.6			6505			5710		
100	40000	10	4.0	2080	2220	133	8560	8643	116	94.8	94.5	0.3	78.6	78.4	0.3	6535	6391	129	5755	5608	131
101	45000	10	4.5	2940			11560			93.5			74.3			7000			5570		
102	45000	10	4.5	2800			11000			93.8			75.6			7150			5690		
103	45000	10	4.5	2740			10600			93.9			76.4			7555			5830		
104	45000	10	4.5	2700	2795	91	10400	10890	443	94.0	93.8	0.2	76.9	75.8	1.0	7660	7341	274	5860	5738	116
105	50000	10	5.0	3420			13000			93.2			74.0			7710			5995		

COMPARISON OF COD REMOVAL

DAY	Influent COD	HRT	LOADING RATE	Effluent COD						% COD Removal						GAS YIELD PER COD REMOVED AT 35° C					
				Recycle			Conventional			Recycle			Conventional			Recycle			Conventional		
	(mg/l)	(days)	(Kg COD/m3/d)	Actual (mg/l)	Mean (mg/l)	Standard Deviation	Actual (mg/l)	Mean (mg/l)	Standard Deviation	Actual	Mean	Standard Deviation	Actual	Mean	Standard Deviation	Actual (m³/kgCOD removed)	Mean (m³/kgCOD removed)	Standard Deviation	Actual (m³/kgCOD removed)	Mean (m³/kgCOD removed)	Standard Deviation
106	50000	10	5.0	3260			12800			93.5			74.4			7805			6080		
107	50000	10	5.0	3180			12540			93.6			74.9			8000			6260		
108	50000	10	5.0	3150	3253	105	12400	12685	232	93.7	93.5	0.2	75.2	74.6	0.5	8045	7890	138	6290	6156	123
109	60000	10	6.0	6000			17400			90.0			71.0			8960			6880		
110	60000	10	6.0	5860			16340			90.2			72.8			9055			7040		
111	60000	10	6.0	5600			15980			90.7			73.4			9170			7200		
112	60000	10	6.0	5520	5745	194	15720	16360	640	90.8	90.4	0.3	73.8	72.7	1.1	9535	9180	218	7380	7125	186
113	80000	10	8.0	9680			27000			87.9			66.3			11580			8590		
114	80000	10	8.0	9560			26200			88.1			67.3			12090			8880		
115	80000	10	8.0	9480			25000			88.2			68.8			12690			7110		
116	80000	10	8.0	9400	9530	103	24800	25750	899	88.3	88.1	0.1	69.0	67.8	1.1	13300	12415	645	9270	8463	817
117	100000	10	10.0	15600			37200			84.4			62.8			13880			9910		
118	100000	10	10.0	15000			36400			85.0			63.6			14080			10100		
119	100000	10	10.0	14200			34600			85.8			65.4			14300			10710		
120	100000	10	10.0	14000	14700	640	34000	35550	1299	86.0	85.3	0.6	66.0	64.5	1.3	15200	14365	504	10920	10410	417

SLUDGE RECYCLE AND WASTAGE

Day	HRT (days)	Daily Flow (ml)	Sludge Recycle (ml)	X	X_u	X/X_u	Waste Sludge (ml)	% of Waste Sludge to Daily Flow
1	20	175	70	4000	10000	0.40	70	40
2	20	175	70	4000	10000	0.40	70	40
3	20	175	70	4000	10000	0.40	70	40
4	20	175	70	4000	10000	0.40	70	40
5	20	175	70	4000	10000	0.40	70	40
6	20	175	70	4000	10000	0.40	70	40
7	20	175	70	4000	10000	0.40	70	40
8	20	175	70	4000	10000	0.40	70	40
9	20	175	70	4000	10000	0.40	70	40
10	20	175	70	4000	10000	0.40	70	40
11	20	175	70	4000	10000	0.40	70	40
12	20	175	70	4000	10000	0.40	70	40
13	20	175	70	4000	10000	0.40	70	40
14	20	175	70	4000	10000	0.40	70	40
15	20	175	70	4000	10000	0.40	70	40
16	20	175	70	5400	9700	0.56	97	56
17	20	175	70	5200	9400	0.55	97	55
18	20	175	70	4500	8800	0.51	89	51
19	20	175	70	4100	8700	0.47	82	47
20	20	175	70	4000	8900	0.45	79	45
21	20	175	70	3800	8800	0.43	76	43
22	20	175	70	3800	8700	0.44	76	44
23	20	175	70	3600	8800	0.41	72	41
24	20	175	70	3800	8700	0.44	76	44
25	20	175	70	3700	8600	0.43	75	43
26	20	175	70	3700	8700	0.43	74	43
27	20	175	70	3800	8700	0.44	76	44
28	20	175	70	3600	8800	0.41	72	41
29	20	175	70	3600	8800	0.41	72	41
30	20	175	70	3700	8800	0.42	74	42

Day	HRT (days)	Daily Flow (ml)	Sludge Recycle (ml)	X	X_u	X/X_u	Waste Sludge (ml)	% of Waste Sludge to Daily Flow
31	20	175	**70**	3600	8600	0.42	**73**	**42**
32	20	175	**70**	3600	8700	0.41	**72**	**41**
33	20	175	**70**	3600	8700	0.41	**72**	**41**
34	17.5	200	**80**	3600	8700	0.41	**72**	**36**
35	17.5	200	**80**	3600	8700	0.41	**72**	**36**
36	17.5	200	**80**	3600	8700	0.41	**72**	**36**
37	17.5	200	**80**	3700	8700	0.43	**74**	**37**
38	17.5	200	**80**	3600	8700	0.41	**72**	**36**
39	17.5	200	**80**	3600	8600	0.42	**73**	**37**
40	15	233	**93**	3600	8600	0.42	**73**	**31**
41	15	233	**93**	3600	8600	0.42	**73**	**31**
42	15	233	**93**	3600	8700	0.41	**72**	**31**
43	15	233	**93**	3600	8600	0.42	**73**	**31**
44	12.5	280	**112**	3700	8800	0.42	**74**	**26**
45	12.5	280	**112**	3600	8600	0.42	**73**	**26**
46	12.5	280	**112**	3600	8600	0.42	**73**	**26**
47	12.5	280	**112**	3600	8700	0.41	**72**	**26**
48	10	350	**140**	3500	8600	0.41	**71**	**20**
49	10	350	**140**	3600	8600	0.42	**73**	**21**
50	10	350	**140**	3600	8500	0.42	**74**	**21**
51	10	350	**140**	3600	8600	0.42	**73**	**21**
52	5	700	**280**	3600	8500	0.42	**74**	**11**
53	5	700	**280**	3700	8600	0.43	**75**	**11**
54	5	700	**280**	3600	8600	0.42	**73**	**10**
55	1	3500	**350**	3700	8500	0.44	**76**	**2**
56	1	3500	**350**	3600	8600	0.42	**73**	**2**
57	1	3500	**350**	3600	8600	0.42	**73**	**2**
58	20	175	**70**	3700	8600	0.43	**75**	**43**
59	20	175	**70**	3800	8600	0.44	**77**	**44**
60	20	175	**70**	3800	8700	0.44	**76**	**44**

Day	HRT (days)	Daily Flow (ml)	Sludge Recycle (ml)	X	X_u	X/X_u	Waste Sludge (ml)	% of Waste Sludge to Daily Flow
61	20	175	**70**	3800	8600	0.44	77	44
62	20	175	**70**	3800	8800	0.43	76	43
63	20	175	**70**	3900	8800	0.44	78	44
64	20	175	**70**	3800	8800	0.43	76	43
65	20	175	**70**	3900	8700	0.45	78	45
66	10	350	**140**	3800	8800	0.43	76	22
67	10	350	**140**	3800	8800	0.43	76	22
68	10	350	**140**	3800	8800	0.43	76	22
69	10	350	**140**	3800	8700	0.44	76	22
70	10	350	**140**	3800	8800	0.43	76	22
71	10	350	**140**	3800	8800	0.43	76	22
72	10	350	**140**	3800	8800	0.43	76	22
73	10	350	**140**	3900	8800	0.44	78	22
74	10	350	**140**	3800	8800	0.43	76	22
75	10	350	**140**	3800	8800	0.43	76	22
76	10	350	**140**	3900	8800	0.44	78	22
77	10	350	**140**	3900	8800	0.44	78	22
78	10	350	**140**	3900	8800	0.44	78	22
79	10	350	**140**	3900	8800	0.44	78	22
80	10	350	**140**	3900	8900	0.44	77	22
81	10	350	**140**	3900	8900	0.44	77	22
82	10	350	**140**	3900	8900	0.44	77	22
83	10	350	**140**	3900	8900	0.44	77	22
84	10	350	**140**	4000	9100	0.44	77	22
85	10	350	**140**	4000	9100	0.44	77	22
86	10	350	**140**	4000	9100	0.44	77	22
87	10	350	**140**	4000	9100	0.44	77	22
88	10	350	**140**	4000	9000	0.44	78	22
89	10	350	**140**	4000	9000	0.44	78	22
90	10	350	**140**	4000	9000	0.44	78	22

Day	HRT (days)	Daily Flow (ml)	Sludge Recycle (ml)	X	X_u	X/X_u	Waste Sludge (ml)	% of Waste Sludge to Daily Flow
91	10	350	**140**	4000	9000	0.44	**78**	**22**
92	10	350	**140**	4100	9000	0.46	**80**	**23**
93	10	350	**140**	4100	9000	0.46	**80**	**23**
94	10	350	**140**	4100	9000	0.46	**80**	**23**
95	10	350	**140**	4100	9000	0.46	**80**	**23**
96	10	350	**140**	4100	9100	0.45	**79**	**23**
97	10	350	**140**	4100	9100	0.45	**79**	**23**
98	10	350	**140**	4100	9100	0.45	**79**	**23**
99	10	350	**140**	4100	9100	0.45	**79**	**23**
100	10	350	**140**	4200	9200	0.46	**80**	**23**
101	10	350	**140**	4200	9200	0.46	**80**	**23**
102	10	350	**140**	4200	9200	0.46	**80**	**23**
103	10	350	**140**	4200	9200	0.46	**80**	**23**
104	10	350	**140**	4200	9200	0.46	**80**	**23**
105	10	350	**140**	4200	9200	0.46	**80**	**23**
106	10	350	**140**	4200	9200	0.46	**80**	**23**
107	10	350	**140**	4200	9200	0.46	**80**	**23**
108	10	350	**140**	4300	9200	0.47	**82**	**23**
109	10	350	**140**	4300	9200	0.47	**82**	**23**
110	10	350	**140**	4300	9200	0.47	**82**	**23**
111	10	350	**140**	4300	9200	0.47	**82**	**23**
112	10	350	**140**	4300	9300	0.46	**81**	**23**
113	10	350	**140**	4300	9300	0.46	**81**	**23**
114	10	350	**140**	4300	9300	0.46	**81**	**23**
115	10	350	**140**	4300	9300	0.46	**81**	**23**
116	10	350	**140**	4400	9300	0.47	**83**	**24**
117	10	350	**140**	4400	9300	0.47	**83**	**24**
118	10	350	**140**	4400	9300	0.47	**83**	**24**
119	10	350	**140**	4400	9300	0.47	**83**	**24**
120	10	350	**140**	4400	9400	0.47	**82**	**23**