

Anaerobic Pre-Treatment of Strong Sewage A proper solution for Jordan

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Maha M. Halalsheh
August, 2002

ABSTRACT

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The main objective of this research was to assess the feasibility of applying low cost anaerobic technology for the treatment of relatively high strength sewage of Jordan using two-stage and one-stage UASB reactors operated at ambient temperatures. The wastewater produced in Jordan is characterised by a high concentration of COD_{tot} with averages higher than 1200 mg/l and with a large fraction in the suspended form (65-70%). The average wastewater temperature fluctuates between 18 and 25°C for winter and summer respectively.

The sludge bed in the UASB reactors was first simulated using CSTR systems. The objective was to study the digestion process as a function of temperature and SRT. Of particular interest was the assessment of the sludge potential to form a scum layer in relation to the degree of sludge digestion. The results revealed that methanogenesis starts only at an SRT between 30-50 days for reactors operated at 15°C, while it starts at an SRT between 5-15 days for reactors operated at 25°C. Both SRT and temperature affect the extent of scum formation. The degree of digestion has a clear effect on the concentration of lipids. Latter compounds tend to adsorb on sludge particles and have a strong tendency for floatation. However, it was found that sludge with a high scum forming potential only will produce scum in the presence of gas production. Based on these results scum formation in UASB systems could be prevented either by attempting to achieve a 'complete' conversion of lipids (one stage conventional UASB reactor with long SRT) or by preventing the evolution of gas production. The later could be achieved by designing a two stage UASB reactor, where the first stage mainly aims at the entrapment and partial hydrolysis of solids, while the second stage could act as a methanogenic reactor for the final conversion of the hydrolysed materials from the first stage.

A 96-m³ two-stage UASB reactor was built at the location of Khirbit As-Samra treatment plant, which treats wastewater produced by 2.2 million inhabitants –almost half of the population of Jordan-. Operating the reactor for a year at 8+6 hrs HRTs for the first and the second stages respectively resulted in average COD_{tot} and COD_{ss} removal efficiencies of 51% and 60% respectively for the first stage with no significant effect of temperature. The second stage had a poor performance and most of the treatment was attributed to the first stage. Biogas was produced in the first stage and resulted in heavy scum formation and sludge washout from the first to the second reactor, which affected the performance of the latter. Moreover, sludge produced in the first stage needs further stabilisation, particularly during wintertime.

The performance of the first stage could be improved by enhancing solids removal using an AF reactor instead of an UASB reactor. An AF reactor was operated at an HRT of 4.6 hrs at 25°C. The media in the filter are reticulated polyurethane foam sheets, which were vertically oriented in the reactor. Sludge was discharged regularly from the reactor. The results showed an average COD_{ss} removal efficiency of 71%.

The discharged sludge needs further stabilisation. Combining an AF with an UASB reactor operated at 4+8 hrs respectively is expected to have an average total COD removal efficiency between 70 and 82% during both summer and wintertime.

Operating the first stage reactor (60 m³) as a conventional UASB reactor at an HRT of 24 hr showed an average removal efficiency of 62% for COD_{tot} during summer. The removal efficiency dropped to 51% during wintertime. However, the effluent suspended solids were stabilised with a VSS/TSS ratio around 0.50 all over the year. Moreover, the sludge developing in the one stage reactor is well stabilised and exerts an excellent settlability. Regular sludge discharge from the one stage UASB reactor had no significant effect on the performance in terms of COD_{tot} removal efficiency; however, sludge discharge most likely resulted in a more stable performance of the system, as wash out of scum layer sludge would remain low. The removal of the stabilised solids from the effluent of the UASB reactor will provide an average total COD removal efficiency between 87-93%.

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Chapter 1

Introduction

1. Introduction

Anaerobic wastewater treatment is one of the oldest methods used for the treatment of sewage. It is increasingly recognized as a core method for a sustainable and non-vulnerable environmental protection concept (Lettinga, 1996; Lettinga, 2001). A unique characteristic of anaerobic treatment by methane fermentation is that no electron acceptor like oxygen or nitrate is needed for the process to work. Moreover, because oxygen mass transfer limitations are not involved, and energy requirements for mixing are greatly reduced, organic loading rates applied to anaerobic reactors can be much higher than to aerobic reactors, resulting in smaller volumes (McCarty, 2001). The energy produced during anaerobic treatment could act as a renewable energy source while the biosolids produced can be used as soil conditioners. Consequently, anaerobic treatment of domestic sewage could be an attractive sustainable option – especially in developing countries- compared to conventional activated sludge systems. Major benefits of anaerobic treatment are listed in Table 1.

Table (1): Main benefits of anaerobic wastewater pre-treatment

-
- Very low cost treatment technology compared to aerobic conventional systems.
 - Energy is produced in the form of biogas. No electricity or other fuel minerals are needed.
 - The technology is very flexible and could be applied at any scale.
 - The space loading rates applied to the systems are much higher compared to conventional treatment technologies.
 - The volume of sludge produced under anaerobic conditions is significantly lower compared to sludge production under aerobic conditions.
 - The sludge produced is well stabilized.
-

2. Existing situation of sewage treatment in Jordan

Jordan can be classified as a semi-desert country. The total population is 4.9 million for the year 1999. Table (2) shows the available water resources and the projected values for the years 2010 and 2020 (WAJ, 1999a). Due to the very limited water resources, all treated wastewater is used in irrigation. The wastewater discharged from the existing treatment plants therefore can be considered as an important water resource, especially in the future as the amount of wastewater is predicted to increase from 75 MCM in the year 2000 to 265 MCM in the year 2020 contributing to 20% of the available water.

Historically the first treatment plant in Jordan was built in 1969 to serve 500,000 inhabitant of the capital Amman. The plant consists of an activated sludge system with a capacity of 60,000 m³/d. The plant became biologically overloaded due to the high influent BOD₅ concentration with an average value around 600 mg/l, which is double the design value. In the 1980's, the government built a major wastewater stabilization pond system for Greater Amman area and other treatment facilities in big cities and towns in Jordan with a total of 17 treatment plants treating 60% of the

produced sewage. By 1999, about 50% of the plants (equivalent to 89% of the wastewater being treated) were overloaded (Table 3), including the largest treatment stabilization pond system of Khirbit As-Samra. Table 3 also shows that most of the wastewater collected is treated in stabilization ponds. The total cost of treatment ranges from 0.014 US\$/m³ for large stabilization ponds of Khirbit As-Samra to 0.34 US\$/m³ for the small activated sludge plant of Tafilah (WAJ, 1999b). Although stabilization ponds are quite simple and considered as a low cost technology, some serious drawbacks can be easily seen especially when agricultural reuse is considered (Lier, 2002). High evaporation rate –especially during summer causes an increase in the effluent salinity as compared to the influent. Moreover, it causes a significant loss of valuable water. Due to these limitations, upgrading the ponds should be done in an appropriate way that meets desired criteria for future technology, that is, sustainability. New high rate anaerobic systems could be an attractive simple alternative and should be considered during evaluating the most suitable option available for domestic sewage treatment in Jordan. In the following sections, the steps taking place during anaerobic conversion of organic matter is first introduced followed by description of the available high rate anaerobic treatment technologies with emphasis on the up flow anaerobic sludge blanket reactor.

Table (2): Projected available water supply (MCM/ year)

<i>Source</i>	1990	2000	2010	2020
Surface water	324	375	505	505
Renew. Ground water	434	407	325	285
Fossil Ground water	63	61	143	143
Reclaimed Wastewater	35	74.6	177.8	265.3
Brackish Water	0		15	50
Peace Treaty water	0	30	50	50
Lower Jordan water	0	0	30	30

3. Conversion of wastewater organic matter during anaerobic treatment

Anaerobic digestion of organic wastes can be described as a multi-step of sequential and parallel reactions (Gujer and Zehnder, 1983, Novaes, 1986). Hydrolysis is the first step in the anaerobic digestion where the suspended and colloidal matter are converted by hydrolytic enzymes into their monomeric or dimeric components, such as simple sugars, amino acids, and long chain fatty acids. This step is known to be complex and likely to be as diverse as the particles and organisms that are involved in the process (Morgenroth *et al.*, 2001). 145 extracellular hydrolytic enzymes have been identified and show wide temperature and pH ranges, and many have low specificity, which makes them versatile for cells scavenging various substrates. The second step in the digestion process is acidogenesis in which products of hydrolysis are fermented or anaerobically oxidised to short chain fatty acids, alcohols, carbon dioxides, hydrogen and ammonia. The short chain fatty acids (other than acetate) are then

Table (3): Biologically and Hydraulically overloaded treatment plants (1999)

Plant	Treatment method	Design flow rate (m ³ /d)	Existing flow rate (m ³ /d)	Design BOD ₅ (mg/l)	Existing BOD ₅ (mg/l)	Biologically overloaded	Hydraulically overloaded	Accomplishing Design specifications	Biological efficiency % ((BOD _{5m} -BOD _{5cm})/BOD _{5m})*100
As-Samra	Stabilization Pond	68,000	166,844	526	760	•	•		84
Aqaba	Stabilization Pond	9000	8774	900	353				69
Ramtha	Stabilization Pond	1920	2174	820	1194	•	•		80
Mafraq	Stabilization Pond	1800	1933	825	566		•		68
Madaba	Stabilization Pond	2000	3609	850	1332	•	•		80
Ma'an	Stabilization Pond	1600	1738	970	549		•		79
Irbid	Activated Sludge and T.F.	11,000	4612	800	1179	•			96
Jerash	Activated Sludge	3500	1603	119	1119			•	97
Kufranja	Trickling Filters	1900	1734	850	1331	•			95
Abu-Nusier	Activated Sludge and RBC	4000	1411	1100	634			•	97
Salt	Activated Sludge	7700	3166	1090	845			•	99
Baq'a	Trickling Filters	6000	10,284	900	1434	•	•		94
Karak	Trickling Filters	785	1146	1080	729		•		94
Tafilah	Activated Sludge	1600	851	1050	942				96
Wadi Essir	Aerated Lagoon	4000	914	780	622				92
Fuhais	Activated Sludge	2400	1019	995	677			•	98
Wadi Arab	Activated Sludge	22,000	5993	995	811			•	99

converted in the acetogenesis step to acetate, hydrogen gas and carbon dioxide. The last step is the methanogenesis in which carbon dioxide -reduced by hydrogen- and acetate are both converted into methane. The main parameter affecting the degree of conversion of the organic matter is the sludge residence time (SRT) (Haandel and Lettinga 1994; Zeeman *et al.*, 1999; Miron *et al.*, 2000). It is the key parameter affecting the biochemical and probably physical properties of the sludge. As in wastewater aerobic treatment, knowledge of kinetics of anaerobic digestion allows for optimisation of performance, a more stable operation, and better control of the process. Kinetic description in anaerobic digestion relies upon the –so called- rate-limiting step, which is defined as the slowest step in a sequence of reactions. The rate-limiting step in the digestion process depends on the type of waste being treated (soluble, particulate, or its chemical composition) (Speece, 1983; Pavlostathis and Giraldo-Gomez, 1991), process configuration, temperature, and loading rate (Speece, 1983). Several authors reported that hydrolysis of particulate matter is the rate-limiting step in the whole digestion process (Eastman and Ferguson, 1981; Ghosh, 1981; Sayed *et al.*, 1984; Valentini *et al.*, 1997; Zeeman *et al.*, 1997; Sanders, 2001). Heukelekian and Mueller, (1958), O' Rourke, (1968), and Novak and Carlson, (1970) reported that degradation of long chain fatty acids was the rate-limiting step during acid phase anaerobic digestion. Miron *et al.*, (2000), found in the anaerobic digestion of primary sludge that 20% and 60% of the particulate biopolymers are hydrolyzed under acidogenic and methanogenic conditions, respectively. Under acidogenic conditions, hydrolysis was found to be the rate-limiting step in the digestion of carbohydrates, acidification was the rate-limiting step in the degradation of lipids, while both hydrolysis and acidification were the rate-limiting steps in the conversion of proteins. Under methanogenic conditions, hydrolysis was the rate-limiting step in the whole digestion process.

The hydrolysis –as rate limiting step- was described in literature using different mathematical relationships (Valentini *et al.*, 1997). The most popular models used are either the first order kinetic relation (Eastman and Ferguson, 1981), or the surface based kinetic relation (Hobson, 1987; Vavilin; 1996). The first order kinetic model is an empirical relation, which assumes that the hydrolysis rate is a linear function of the available biodegradable substrate at a certain pH and temperature. Although this relation is simple and considered as most popular (McCarty and Mosey, 1991), it has the disadvantage that even if the reactor conditions and the substrate type are kept constant, different K_h values could be obtained because of the different particle size distribution of the substrate (Hills and Nakano, 1984). The surface area based hydrolysis kinetic model is a mechanistic model, which assumes that hydrolytic enzymes are present in excess during the digestion of particulate matter and that the hydrolysis rate depends upon the surface available for those enzymes to perform the depolymerization process (Sanders, 2001). In this relation, the hydrolysis is not affected by the particle size of the substrate, and it clearly showed that the amount of surface available for hydrolysis is the most important factor determining the hydrolysis rate, while all other factors are of minor importance. However, the main disadvantage of the model is the need for determination of the surface area of the substrate available for hydrolysis, which is practically very difficult for a complex substrate. Moreover, the model is only valid when dealing with substrate that is not susceptible to breaking up during the digestion.

In general, the surface based kinetic model cannot replace the first order kinetic model for the design of anaerobic digester. Sanders, (2001) evaluated the first order kinetic model based on available literature and concluded that the model can be used successfully for the description of hydrolysis when the wastewater is consisting mainly of proteins and carbohydrates. However, for wastewater containing high concentrations of lipids and treated under acidogenic conditions, first order kinetic model cannot be used since the lipids tend to coagulate. Under methanogenic conditions, the model could be used for the description of hydrolysis when batch experiments are used. However, for CSTRs, no first order kinetic could be established for the lipids, probably because of problems related to accurate sampling and scum layer formation. Selecting hydrolysis rates values from literature is not an easy task and requires a detailed knowledge about the substrate and the process conditions. Sanders (2001) reported that hydrolysis constants that are recorded in literature could be corrected for temperature of the digestion process following the Arrhenius equation, while corrections accounting for pH differences are difficult. Because of the difficulties present in selecting a suitable design value, it looks that assessment of the hydrolysis rate of each substrate still needs separate consideration.

4. High rate anaerobic systems

Modern anaerobic wastewater treatment systems are very flexible systems, feasible for treating many different kinds of wastewater and at different environmental conditions, (Lettinga, 2001). Several high rate anaerobic reactors were developed during the past decades, like the anaerobic filter reactor (AF) (Young and McCarty, 1969), the upflow anaerobic sludge blanket reactor (UASB) (Lettinga, 1979), anaerobic fluidized bed reactor (AFB) (Switzenbaum and Jewell, 1980), anaerobic hybrid reactor (AH) (Girotto and Berg, 1984) and baffled reactor (Bachmann *et al.*, 1985). The common feature between these reactors is that they operated at long sludge residence time, under conditions of short hydraulic retention times. This means that high treatment efficiency can be provided at relatively short time. Among high rate anaerobic treatment systems, the UASB reactor is the most widely and successfully used technology (Hulshoff Pol *et al.*, 1983; Singh *et al.*, 1996) since Lettinga and his co-workers developed the system in the seventies for the treatment of industrial wastewater. The system was described in details at several occasions (Lettinga *et al.*, 1980; Lettinga and Hulshoff Pol, 1986). An important observation made in studies carried out with the UASB reactor is the presence of anaerobic granular sludge (Hulshoff Pol *et al.*, 1982, 1983), which has the advantage of possessing very high settling properties. Experiments aiming at optimising the contact between the wastewater and the sludge in the UASB reactor led to the development of more advanced reactor design, viz. the expanded granular sludge bed reactor, into which higher up flow velocities in the range of 4-10 m/hr are applied (Rebac, 1998). The UASB reactor was researched for the treatment of different kinds of wastewater such as sugarbeets (Lettinga *et al.*, 1976, 1977), milk fat wastewater (Petruy and Lettinga, 1997), slaughterhouse (Sayed *et al.*, 1987, 1988), potato starch (Field *et al.*, 1987), and pulp and paper wastes (Lettinga *et al.*, 1991). The application of the system was found to be feasible for the treatment of domestic sewage as well (Lettinga *et al.*, 1983; Vieira and Souza, 1986; Last and Lettinga, 1992; Bogte *et al.*, 1993; Chernicharo and Machado, 1998). The presence of relatively high

concentrations of suspended solids in the influent hinders the formation of granular sludge, and the sludge developed is of flocculent nature. However, it still has better settling characteristics compared to the sludge developed in activated sludge systems. Actually, one may prefer a reactor with a flocculent sludge bed when treating domestic sewage, because the filtration of suspended solids (SS) by flocculent sludge might be better than that of granular sludge (Kalogo and Verstraete, 2001).

4.1. Conventional UASB reactors for sewage treatment

UASB reactors have been successfully used as the first unit of systems designed for domestic sewage treatment at ambient temperatures (20°C or higher). Schellinkhout and Collazos (1992) reported that applying a UASB reactor as a primary treatment step would reduce the total hydraulic retention time by a factor of 4 to 5 in comparison with ponds system, while a better effluent quality could be obtained as well. Catunda and Haandel (1996) reported that the size of the anaerobic ponds could be reduced by a factor of 20 to 30 times using UASB reactor for achieving the same removal efficiency as the ponds system. Satisfactory COD removal efficiencies have been obtained at applied organic loading rates (OLR) usually lower than 3 kg/m³.d and HRT ranging from 6-10 hrs (Chernicharo and Nascimento 2001; Florencio and Morais, 2001; Rodruiguez *et al.*, 2001; Torres and Foresti, 2001). Table 4 and table 5 show some of the results obtained during the treatment of raw domestic sewage in lab scale and full-scale UASB reactors. Promising results were obtained from the lab scale reactors at temperatures in the range of 13-35°C with average COD_{tot} and SS removal efficiencies in the range 60-80% and 53-80% respectively. The sludge developed had very good settling characteristics with a SVI in the range 12-25 ml/gTSS. The degree of digestion (percentage conversion to methane) was calculated to be in the range of 7-42% depending on the temperature. At lower temperatures, accumulation of sludge in the reactor takes place, and if not discharged, will result in washout from the reactor. In tropical regions, full-scale UASB reactors (Table 5) were put into operation and showed COD_{tot} and SS removal efficiencies in the range of 50-80% and 50-76% respectively. Very limited data were available describing the degree of solids digestion. However, and based on the available information, methanogenesis in the range of 33-50% of the influent COD can be calculated for some reactors.

Based on the results listed in Table 5, it can be seen that conventional UASB reactors for the treatment of domestic sewage were operated at OLRs in the range of 0.79-2.24 kg/m³.d, up flow velocities in the range of 0.52-0.9 m/hr and at HRT mostly in the range of 5-10 hrs. However, data on the degree of sludge stabilization achieved in these reactors are limited, and complete judgement of the system cannot be made. Moreover, the ranges of the applied OLRs, up flow velocities, and HRTs in the full-scale UASB reactors are wide, resulting in double to triple reactors volumes, while the performance of the systems in terms of total and suspended COD removals cannot be directly related to these parameters. Influent composition, mixing conditions, intensity of inlet points per surface of the reactor, efficiency of the gas solids separator (GSS), and differences in fluctuations in flows and composition of the wastewater during the day are among factors governing the performance of the reactor. Especially at lower temperatures, full-scale applications should be followed in more details.

Table (4): Performance of the UASB reactors treating domestic sewage at lab-scale

Vol. (L)	Temp. (°C)	HRT (hrs)	OLR (kg/m ³ .d)	V _{up} (m/hr)	COD _{tot} (mg/l)	COD _{es} (mg/l) (TSS)	COD _{tot} rem. (%)	COD _{ss} rem. (%) (TSS)	CH ₄ prod. l/kg COD _{infl}	% M*	Sludge note	Reference
106	35	4	2.00 ¹	0.7	341 ²	(88) ²	65	(61)	88.5	25 ³	SVI=25ml/gTSS	Vieira and Souza (1986)
106	10-23	4	2.49 ¹	0.7	415	(190)	60-65	(69)	73-84.5	23 ³	---	Vieira and Souza (1986)
120	18-28	4	3.76 ¹	0.48	627	476	74	(72)	55.2	16	Granular sludge developed. SVI=12-17ml/gTSS	Barbosa and Sant'Anna JR (1989)
47.1	10-30	7	1.02 ¹	---	300	---	77 ⁴	---	24-111 ⁵	7-32 ³	---	Agrawal <i>et al.</i> , (1997)
155	25	6	1.57 ¹	---	393	215 ⁶	58	53	---	---	---	Machdar <i>et al.</i> , (2001)
21.5	13-25	4.7	1.6	0.43	312	187	69.4	80	59-147	17-42 ³	SRT= 110-117days	Uemura and Harada (2000)
416	tropical	4	3.13 ¹	1.4	521	401 ⁶	65-79	---	---	---	---	Chernicharo and Nascimento (2001)
150	21±2	6	2.28 ¹	---	569	326	71	79	---	---	---	Torres and Foresti (2001)

(*): Percentage methanogenesis based on influent total COD; (1) calculated based on available data; (2) presettled sewage; (3) calculated at standard pressure and temperature. The dissolved CH₄ fraction was not taken into account except in Uemura and Harada experiment; (4) only during summer; (5) depending on temperature; (6) calculated based on available data as (COD_{tot}-COD_{sol}).

Table (5): Anaerobic domestic sewage treatment in full-scale UASB reactors

Volume (m ³)	Temp. (°C)	HRT (hrs)	OLR (kg/m ³ .d)	V _{up} (m/hr)	COD _{tot,inf} (mg/l)	COD _{ss,inf} (mg/l) (TSS)	COD _{tot} rem. (%)	COD _{ss} rem. (%) (TSS)	CH ₄ prod. l/kg COD _{inf}	CH ₄ prod. l/kg COD _{rem.}	% M*	Sludge note	Reference
64	25	6	1.1	0.67	267	155	50-75	---	---	190	33-50	Ash 55-65%	Lettinga, (2001)
1200 ¹	20-30	6	2.24	0.75	560	(420)	74	75	---	50-100	---	Sludge production 0.4kgTSS/kg TSS _{inf}	Haskoning, (1996)
12000 ¹	24-30	6	0.75	0.75	---	---	54	(65)	---	---	---	---	Wiegant <i>et al.</i> , (2001a)
67.5 ²	16-23	7 ³	3.0 ⁴	1.25 ⁵	700-1100 ⁶	(450 ⁶)	60-80	---	---	---	---	---	Vieira <i>et al.</i> , (1994)
120	18-30	5-15	---	0.3-0.9	113-593	(44-512)	60	70	80-170	90-250	36	---	Vieira & Garcia (1992)
11,200	26-29	6	---	0.75	---	---	61	(51)	---	---	---	---	Wiegant <i>et al.</i> , (2001a)
2*3,350	24	5.2	1.9-2.0	0.77	330-450	(210-300)	45-50	---	158	---	45 ⁷	---	Schellinkhout, (1993)
4660	20-31	8 ⁸	1.10	0.61	400-450	(360)	49-65	(50-76)	---	---	---	SRT=35d	Starkenb. <i>et al.</i> , (2001)
35	---	5-19	---	---	---	---	66-72	70	---	---	---	---	Schellinkhout & Collazos (1992)
810	30	8.8-9.7	0.79-1.40	0.52-0.57	290-563	(139-204)	59-75	(51-61)	---	---	---	VS/TS ratio of 32% ⁹	Florencio <i>et al.</i> , (2001)

(*) percentage methanogenesis based on influent total COD; (1) wastewater containing sulphate (tannery); (2) The reactor is preceded by a grease interceptor; (3) the reactor receives sewage during six hours a day due to the presence of pumping tank; (4) calculated based on the available values; (5) maximum; (6) read from figure; (7) calculated based on available data at standard pressure and temperature; (8) Taken from Tare *et al.*, 1997; (9) accumulation of inert materials in the reactor.

Chapter 1

In addition, for complete insight about the system, effluent also should be monitored for items like VFA, the VS/TS ratio and biodegradability, which in most full-scale studies was not the case.

4.2. Two-stage UASB reactors for sewage treatment

4.2.1. Introduction of the two-phase / two-stage anaerobic systems

In general, there is confusion between the terms two phase and two stage anaerobic digestion systems. Phase separation is always referring to the separation between acidogenesis and methanogenesis in two different reactors, while staged separation is referring to all other substrate and microorganisms separation processes either in one reactor or separated reactors. The main reason behind phase or stage separation is subjecting the biomass to concentration gradients, which has the potential of enhancing process efficiency by optimising substrate utilization rate of the consortium of bacteria present in the reactor. In both cases, high F/M ratio is introduced at the high rate first phase/ stage reactor, while the second stage reactor is subjected to low F/M ratio. Azbar *et al.*, (2001), considered that phased systems refer to the presence of different biomass in separate reactors, while staged systems refer to the presence of the same biomass in various environmental conditions (pH, reactor type, concentration) in separate reactors, (Figure 1: A and D). Phase separation may affect the metabolic pathway by which the contaminant is biodegraded. Under acidogenic conditions, intermediate substrates that enhance methanogenesis could be produced. For example, Pipyn and Verstraete, (1981) noticed that the formation of ethanol and lactic acid in a two-phase system enhance methanogenesis since these intermediates provide greater free energy for methanogens. Bull *et al.*, (1984) noticed that ethanol was the primary intermediate in the first acidogenic reactor during the operation of a two-phase glucose fed reactor when operating at pH in the range 3-5. Phase separation could be achieved by applying different techniques such as kinetic control, leaching beds, membrane separation, and pH control (Fox and Pohland, 1994; Ince, 1998; Shin *et al.*, 2001). It was also shown that phase separation could be obtained using single reactor by applying partial circulation of the effluent to the UASB reactor as illustrated by Imai *et al.*, (2001), Figure, 1C. In their study, separation between acidogenic bacteria and methanogenic archaea was achieved with a stable performance compared to both conventional single UASB reactor and UASB reactor with complete circulation. Well-operated staged anaerobic systems could also enhance intermediate degradation (Rebac *et al.*, 1998; Lettinga *et al.*, 1999) while such a system approaches more plug flow conditions (Lettinga *et al.*, 1997; Lier *et al.*, 2001; Kalyuzhnyi, 2001). In the staged reactors, maximum conversion of substrates occurs in the first stages, while the final stages act as effluent polishing compartments. Integrated staged reactor concepts vary from vertically oriented 3 to 5 stage reactors, to horizontally oriented baffled reactors with up to 8 stages (Langenhoff *et al.*, 2000; Lier, 2001). Some of the techniques used for both phased and staged systems are shown in Figure 1.

A complete physical separation of different species involved in the anaerobic degradation process has been suggested by Pohland and Ghosh, (1971) for the treatment of soluble wastewater. They proposed a two phase anaerobic process using two separate reactors under mesophilic conditions. The first reactor for hydrolysis/

acidification and the second for acetogenesis/ methanogenesis. Since then, the two-phase anaerobic digestion has been extensively studied as reviewed by Seghezzi *et al.*, (1998). Available literature suggests that several practical benefits can be obtained by phase/stage separation like the reduction in the total reactor volume (Perot *et al.*, 1988; Perot and Amar, 1989; Jeyaseelan and Matsuo, 1995; Yeoh, 1997; Ince, 1998; Lier, 2001); the improved stability of the system (Massey and Pohland, 1978; Zoetemeyer *et al.*, 1982; Yeoh, 1997; Ince, 1998; O'Keefe and Chynoweth, 2000); and a higher retention of methanogenic population can be achieved in the second reactor as sludge discharge can take place from the acidogenic reactor (Cohen, 1982). According to Ince, (1998), and Yeoh, (1997), satisfactory results have been obtained in full scale applications of the two phase processes for brewery wastewater, insoluble wastes palm oil, dairy wastewater, soft drink wastewater, sewage sludge and manure, and alcohol stillage.

On the other hand, it was shown in some cases that lipids are not degraded under acidogenic conditions (Miron *et al.*, 2000; Sanders, 2001), and that phase separation may affect the lipid water interface in the first acidogenic reactor resulting in a higher sludge residence time in the second methanogenic reactor (Zeeman *et al.*, 2001). Palenzuela-Rollen, (1999) showed that acidogenic conditions may negatively affect protein hydrolysis as a result of the low pH. Miron *et al.*, (2000) showed that the hydrolysis of proteins and carbohydrates were not promoted by phase separation during the digestion of primary sludge under anaerobic conditions. Moreover, they showed that lipids were not degraded under acidogenic conditions.

4.2.2. Staged UASB/EGSB reactors for the treatment of different kinds of wastewaters

4.2.2.1 Treatment of soluble wastewater

Staged UASB and EGSB reactors have been shown to be effective in many cases. In the treatment of VFA mixtures consisting of acetate, propionate, and butyrate at psychrophilic conditions, a two-stage EGSB reactor provided higher treatment efficiency compared to the single stage reactor (Lier *et al.*, 1997a; Rebac *et al.*, 1998; Lettinga *et al.*, 1999; Lier *et al.*, 2001). The higher removal efficiency could be mainly attributed to the enhanced removal of propionate in the second stage. Low propionate K_m value was measured, which was attributed to high degree of mixing in the EGSB reactor, which made the treatment feasible at cold temperatures.

Kleerebezem *et al.*, (1999a), recommended a staged reactor system for anaerobic treatment of terephthalate. They found that due to the presence of both readily degradable acetate and benzoate in the wastewater, the anaerobic degradation of terephthalate (slowly biodegradable organic material) was strongly inhibited in well-mixed reactors (Kleerebezem *et al.*, 1999b). Only if the concentrations of acetate and benzoate are kept low, the degradation of terephthalate can take place. For mainly soluble wastewater containing emulsified lipids, like dairy wastewater, the lipid fraction of the substrate can be precipitated and concentrated in a sludge blanket by allowing acidogenesis and pH drop using an upflow acidogenic substrate precipitation reactor (UASP) concept (Zeeman *et al.*, 1997).

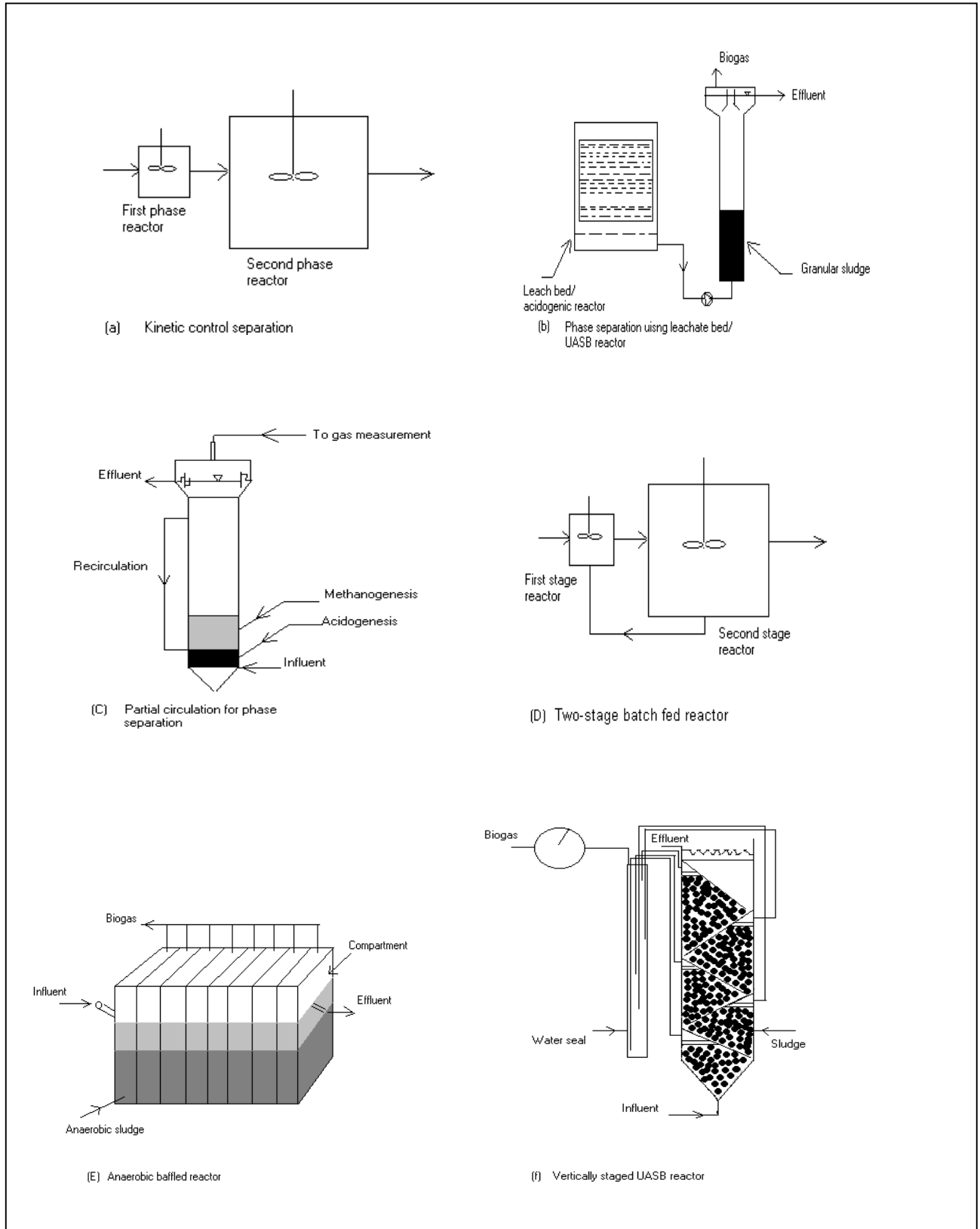


Figure (1): Examples on phase and stage separation technologies. (A), (B) and (C) are examples on phased reactors, while (D), (E) and (F) are examples on staged reactors.

In the treatment of partially unacidified wastewater under thermophilic conditions using conventional UASB reactors, a severe sludge washout and high concentrations of fatty acids in the effluent were observed (Wiegant and Lettinga, 1985; Lier *et al.*, 1992). Lier *et al.*, (1994) found that the application of vertically compartmented UASB reactor (called up flow staged sludge bed reactor USSB) for the treatment of sucrose-VFA mixture enhanced the development of specific sludge types in each compartment. The reactor showed a very stable performance with no sludge washout because of the low gas production at the final stages.

On the other hand, Lier *et al.*, (1997 b) observed in a two-stage EGSB/EGSB reactors for the treatment of partially unacidified wastewater, that the presence of suspended solids in the form of acidogenic bacteria coming from the first reactor could represent a serious limitation for the performance and the loading potentials of the EGSB methanogenic reactor. This is mainly due to the strong sludge flotation induced by acidogenic bacteria, resulting from possible presence of some components originating from lysis of suspended acidogens. These compounds might affect the granule surface characteristics in the EGSB (Alphenaar, 1994). Industrial applications also show that complete pre-acidification in the first stage reactor have adverse effects on the stability of anaerobic sludge bed systems (Lier, 2001).

4.2.2.2 Treatment of complex wastewater containing solids

O'Keefe and Chynoweth, (2000) operated Leachate Beds/ UASB hybrid reactor (filter material at the top of the reactor) with leachate recycle for the treatment of municipal solid waste and reported an improvement of performance in the leaching bed reactor compared to a combined phase treatment. The reason was attributed to removal of inhibitory fermentation products and buffering of acids in the leachate. Other researchers investigated semi- continuous two- stage UASB reactors for the removal of organic matter from coastal mud sediments (Takeno *et al.*, 2001). They circulated the culture broth between the acidogenic and methanogenic reactors and achieved a stable removal of organic matter and improvement in the performance compared to batch acidogenic fermentation followed by methanogenic UASB reactor.

Some disadvantages were also reported during phase separation. Burel and Trancart, (1985) reported negative effect on interspecies hydrogen transfer from acidogens to methanogens during anaerobic digestion. Rebac *et al.*, (1998) researched the treatment of malting wastewater where 25% of the influent COD was found in the suspended form using a two- stage EGSB reactor operated at 13°C and at variable OLR in the range of 4-24 kg/m³.d. They reported that significant acidification occurred in the first stage, which resulted in an extensive growth of acidogenic populations on the methanogenic sludge granules and ultimately washout of the granules.

4.2.2.3. Treatment of domestic wastewater in staged/ phased UASB reactors

Some researchers reported adverse effects of the suspended solids found in wastewater on the UASB reactors operated with granular sludge, such as the dilution of the active biomass. This will limit the applicable volumetric loading rates (Wang,

1994; Elmitwalli, 2000). Adsorption of biodegradable particles such as lipids and proteins on the surface of sludge granules or flocs may cause substrate limitation for the active biomass, especially when the degradation of these materials proceeds slowly. Possible formation of scum layer and washout of sludge particles may occur due to the low density of lipids (Zeeman *et al.*, 2001). The lipids may also hamper the gas release. Moreover, attachment of suspended methanogens to poorly settleable organic particles will cause washout of methanogenic archaea. Palenzuela-Rollen (1999) advised to remove lipids from wastewater prior to anaerobic treatment in order to achieve higher process stability. Wang, (1994), recommended phase separation by a combination of hydrolysis up flow sludge blanket (HUSB) reactor followed by an expanded sludge bed reactor (EGSB) for the treatment of domestic sewage at ambient temperatures. The system provided removal efficiencies of 51-71% of the total COD and 77-83% of the SS at 3 and 2 hrs HRT for the HUSB and the EGSB respectively. However, according to calculations of Zeeman *et al.*, (1997), only 0.7% of the influent COD was hydrolyzed in the previous system. The reactor, providing mainly physical removal of SS, was then referred to as up flow anaerobic solids removal (UASR) reactor. The sludge produced needs stabilization in a separate digester. Several full-scale installations of the 'HUSB' reactor have been built in China since 1992 (Kalogo and Verstraete, 1999). Berends (1996), focusing on the first step 'HUSB' reactor further studied the two-phase UASB reactor configuration. Two 'HUSB' reactors were operated at 15°C and 25°C and at HRT of 4 hrs. The average COD_{tot} removal efficiency obtained was 58% with no clear effect for the temperature. The reactors were operated at average OLR of 13 kg/m³.d. The amount of hydrolyzed materials based on the total COD accounted for 7% during winter and 9% during summer. Vogelaar (1997) further investigated the two-phase UASB reactors for the treatment of sewage (Table 6). The results obtained so far for phased reactors treating domestic sewage are summarized in Table 6. The results reported for the hydrolysis, acidification and methanogenesis in these reactors are summarized in Table 7. The table illustrates that the hydrolysis occurred in these systems were low, indicating that the first stage mainly served for the removal of solids. Elmitwalli (2000) recommended the application of an anaerobic filter reactor -instead of a high loaded UASB reactor- for the removal of suspended solids from the sewage prior to further treatment in anaerobic hybrid reactor. The system proposed removed 70% total COD at 13°C and at HRT of 4+8 hrs. The removal efficiency is similar to that achieved at tropical conditions. It was also reported that the removal of solids prior to anaerobic treatment will not only reduce the adverse effect of suspended solids, but also will promote the formation of granular sludge (Vieira *et al.*, 1986; Seghezzi *et al.*, 2001). Recently, Kalogo and Verstraete, (2000) proposed an integrated anaerobic treatment system for domestic sewage, which combines a UASB reactor and a conventional completely stirred tank reactor for the treatment of wastewater low in suspended solids and the sedimented primary sludge respectively. The system includes chemical enhanced primary sedimentation (CEPS) for the removal of suspended solids.

A two stage UASB system was also investigated by Sayed *et al.*, (1995) for the treatment of medium strength wastewater at ambient temperature (18-20°C). They used two compartments for the first stage, which were operated alternatively - two days each- to allow for an additional period for sludge stabilization. The results obtained showed that loading rates up to 2.0 kgCOD/m³.d could be applied to the first

Table (6): List of the researched two stage UASB reactors and the resulting removal efficiencies

Volume (m ³)	Temp. (°C)		OLR		HRT (hrs)		V _{in} (m/hr)		COD _{tot} g/l (in)		COD _{ss} g/l (in)		%rem. COD _{tot}		%rem. COD _{ss}		Rem. tot. COD _{tot}	Rem. tot. COD _{ss}	Reference
	1 st stage	2 nd stage	1 st stage	2 nd stage	1 st stage	2 nd stage	1 st stage	2 nd stage	1 st stage	2 nd stage	1 st stage	2 nd stage	1 st stage	2 nd stage					
170	13-31		4.75		2.5-5		1.6		0.495		0.316		41-48		75-84 ¹				Wang et al., (1994)
0.2	9-21		5.2		3		1.0		0.650		0.329		37-38	27-48	50-65	19-39	51-69	67-79	Wang et al., (1994)
0.042 ²	18-20		0.6-2.1	6.0	8				0.2-0.7		0.09-0.385		62	32-46	84	58	75		Sayed et al., (1995)
0.042 ²	18-20		1.2-4.2	6.0	4				0.2-0.7		0.09-0.385		66	32-46	70	54	84		Sayed et al., (1995)
0.085	15		10-14		4.0	6	0.68		1.7-2.8		1.3-2.4		56-70		71-83				Vogelaar (1997) ³
0.085	25		10-14		4.0	6	0.68	0.34	1.7-2.8		1.3-2.4		50-68		63-79				Vogelaar (1997) ³
4.3	9-26		1.1-1.5	1.0-1.7	6.1	4.0	0.6	0.9	0.47		0.25						40-60		Encina et al., (1998)
0.085	25		12.89	---	4.0	---	0.68	---	2.149		1.713		58	---	60±22	---	---		Berends ³ (1996)
0.085	15		12.89	---	4.0	---	0.68	---	2.149		1.713		58	---	55±23	---	---		Berends ³ (1996)
0.060	13		3.11	---	4.0	---	0.53	---	0.518		0.207		55	---	82	---	---	---	Elmitwalli (2000)

(1) SS removal efficiency; (2) They operated two reactors alternatively for the first stage, with a feed period of two days each to allow for sludge stabilisation; (3) the feed was a mixture of sewage and primary sludge.

Table (7): The percentage hydrolysis, acidification, and methanogenesis occurring in the first stage HUSB/UASR reactor and AF reactor

Reactor	Temp (°C)	SRT (d)	Hydrolysis (%)	Acidification (%)	Methanogenesis (%)
HUSB Wang, (1994)	19	34.5	0.7*	7	---
HUSB Berends, (1996)	15-25	7-8.7	7-9	---	0.03-0.4
UASR Vogelaar, (1997)	15-25	2.7-0.5	0.1-16 (15°C) no hydrolysis	---	negligible
Elmitwalli (2000)	13	43-49	12	21	23

(*): the gas production was not monitored and the hydrolysis could be underestimated.

stage with a maximum removal efficiency of 80% for the coarse materials. Tang *et al.*, (1995) treated domestic sewage in a two step UASB/AF system at a temperature of 20°C. Most of the COD removal was achieved in the first stage, viz. 70% of the 80%. Encina *et al.*, (1998), tested a two stage UASB reactor for the treatment of diluted domestic wastewater at a temperature range of 9-26°C. The applied organic loading rates were 1.1-1.5 and 1.0-1.7 kgCOD/m³.d for the first and the second stages respectively. The total removal efficiency of the COD for the system was 40-60% for the whole period of operation.

Based on the above discussion, it is clear that the composition of the substrate has a great effect on the anaerobic technology to be chosen. Although, two stage UASB and EGSB reactors were shown to be beneficial in some cases, the selection of the system should be done based on detailed assessment of the available literature on the treatment of specific substrate using staged reactors. For domestic sewage treatment both one stage and two stage systems were investigated. Staged systems were applied with higher loading rates compared to one stage UASB reactor, however, a digester should be combined to the system for sludge stabilization.

5. Design concept for the UASB reactors

The main design parameters for the UASB reactor are the upflow velocity, the solids retention time (SRT), and the biogas-loading rate. In fact, the concept of SRT, being the most central parameter for the design of biological plants, for both aerobic and anaerobic systems, has been recognized earlier by Lawrence and McCarty, (1970). For the purpose of UASB reactor design, loading rates (L) based on the three previous parameters can be estimated as described by Wiegant *et al.*, (2000). The *applicable design loading rate* will be the minimum value of the L_1 , L_2 , and L_3 presented below:

$$L_1 = \frac{V_{up} * C}{H_r} \quad \dots (1)$$

$$L_2 = \frac{TSS_{bed} * (H_R - H_S - H_D)}{Y_T * H_R * SRT} \quad \dots (2)$$

$$L_3 = \frac{B * P_G}{H_R * X * P_M} \quad \dots (3)$$

Where:

- L organic loading rate (kg/m³.d);
- V_{up} upflow velocity in the reactor (m/hr);
- C biodegradable COD: BCOD in the influent (kg COD/m³);
- H_r reactor's height;
- TSS_{bed} sludge concentration in the sludge bed (kgTSS/m³);
- H_S height of the settler;
- H_D free zone between the sludge bed and the bottom of the settler;
- Y_T sludge production per unit of biodegradable COD;
- SRT sludge residence time (d);
- B biogas loading rate (m³/m².d);
- P_G fraction of biogas consisting of methane;

X conversion factor from COD to methane ($0.35\text{m}^3/\text{kgBCOD}$ at 0°C);
 P_M fraction of COD converted into methane.

In equation (1), and for domestic wastewater, the height of a full-scale reactor is practically in the range of 4-5 m. However, an optimum design up flow velocity is not fully determined. Full scale reactors are generally designed at up flow velocities between 0.56-0.75 m/hr, while some results suggests that up flow velocities as high as 1.5 to 2.0 m/hr may still lead to acceptable COD treatment efficiencies (Wiegant, 2001b). Considering the height of the reactor, 4.5 m was used for weak and moderate strength sewage (Wiegant, 2001), however, this value may have to be increased during the treatment of strong sewage to allow for sufficient SRT needed for sludge stabilization. The (L) value in equation (2) can be selected based on the needed sludge stabilization, which strongly depends on the ambient temperature. Assuming that the solids removal efficiency in UASB reactors is around 85%-100% -effluent solids are mainly washed out sludge particles-, then it could be shown that solids retention time rather than hydraulic retention time -at a certain allowable up flow velocity- is the limiting criterion for the design of the UASB reactors after a certain influent concentration of TSS is reached, (equations 1 and 2). This is very important at lower temperatures when sludge stabilization is needed. Zeeman et al., (1991) and Zeeman and Lettinga, (1999) showed that at temperatures below 15°C , a minimum SRT of 100 days should be applied in order to retain sufficient methanogenic activity in an anaerobic reactor during the digestion of cow manure. In fact, incorporation of the SRT as an important design parameter of UASB reactors was introduced earlier by Zeeman and Lettinga (1999), who presented the following model for calculating the required hydraulic retention time (HRT) based on the degree of digestion needed:

$$HRT = \frac{C * SS}{X} * R * (1 - H) * SRT \quad \dots (4)$$

Where

SRT sludge retention time (days);
 R fraction of the CODss removed.
 H fraction of the removed solids, which is hydrolyzed; No distinction had been made between the fraction of the CODss that is removed but not hydrolyzed and the biomass yield;
 C COD concentration of the influent (gCOD/l);
 X sludge concentration in the reactor (gCOD/l); $1\text{gVSS}=1.4\text{gCOD}$;
 SS COD_{ss}/COD_{infl}

In equation (4), some assumptions has to be made for the values of H , R , and X , in order to be able to calculate the required HRT, based on data available in literature. This thesis also increases the knowledge in this field. Considering equation (3), very little information is available about the effect of the gas superficial velocity on the performance of UASB reactors. Unless detailed information are available, the use of the equation is believed to be not feasible.

6. Scope and outlines of the thesis

This thesis will describe the results of different experimental runs for testing the feasibility of anaerobic wastewater treatment for the strong sewage produced in Jordan under different temperature conditions. Chapter 2 describes the rate of

biodegradation of different polymers in sewage. The wastewater samples used were obtained from two different treatment plants: influent to Khirbit As-Samra stabilization ponds, which is the largest treatment plant in Jordan. It treats wastewater produced by Amman and Zarqa cities with a total population of around 2.5 million capita. The treatment plant receives also some illegal industrial discharges that may affect the anaerobic treatment efficiency. The other wastewater treatment plant treats completely domestic sewage produced by Abu-Nusier complex in the capital, Amman. In Chapter 3, the sludge bed in the UASB reactor was simulated using CSTRs. The aim was to increase the knowledge about the effect of SRT and temperature on the conversion of primary sludge with special emphasis on the effect of the degree of digestion on scum formation. Chapter 4 presents the results obtained during 2.5 years of operation of a 96 m³ UASB reactor installed and operated at the location of Khirbit As-Samra stabilization ponds for the treatment of strong domestic sewage under summer and winter conditions. During the first year, the reactor was operated as a two-phase UASB system aiming at the removal and partial hydrolysis of solids in the first stage, while the second stage aims at the removal of soluble fraction produced in the first stage. During the second year, the first compartment was operated as a full methanogenic UASB reactor aiming at the removal and digestion of solids. For the last three months of operation, regular sludge discharge was taking place from the reactor aiming at enhancing solids removal of the system. Chapter 5 introduces the results obtained during the operation of the upflow anaerobic filter reactor operated as a first step reactor aiming at improving the removal and hydrolysis of suspended solids prior to wastewater introduction to a second step methanogenic UASB reactor. The general discussion and conclusions of the thesis are presented in Chapter 6.

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Chapter 2

*Characteristics and anaerobic
biodegradation of sewage in Jordan*

CHARACTERISTICS AND ANAEROBIC BIODEGRADATION OF SEWAGE IN JORDAN

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ABSTRACT

A comparison was made between the influents of two treatment plants in Jordan in terms of their anaerobic biodegradability and the rate of biodegradation. General characteristics of the wastewater and the degradation of the different polymers were studied as a function of time at 25°C and 15°C representing summer and winter temperatures. The average total COD (COD_{tot}) was found to be in the range of 1500-1900 mg/l, with a relatively high percentage of suspended COD (COD_{ss}), between 65-70%. The results showed that 79% and 76% of the COD_{tot} in the influents to Khirbit As-Samra and Abu-Nusier treatment plants respectively were biodegradable under anaerobic conditions. The results also showed that 57% and 86% of the biodegradable fractions in the influents to Khirbit As-Samra and Abu-Nusier treatment plants respectively were converted into methane after 27 days of digestion at 25°C. However, only 26% and 42% of the biodegradable fractions in the influents of Khirbit As-samra and Abu-Nusier treatment plants respectively were degraded after 35 days of digestion at 15°C. The lower rate of biodegradation of the influent to Khirbit As-Samra was mainly attributed to the lower rate of proteins's degradation, viz. 0.025 d⁻¹ versus 0.08 d⁻¹ at 25°C for Abu-Nusier wastewater. Based on characteristics and biodegradability results, two different configurations for the UASB systems were proposed for anaerobic wastewater treatment of strong sewage at ambient temperatures in Jordan.

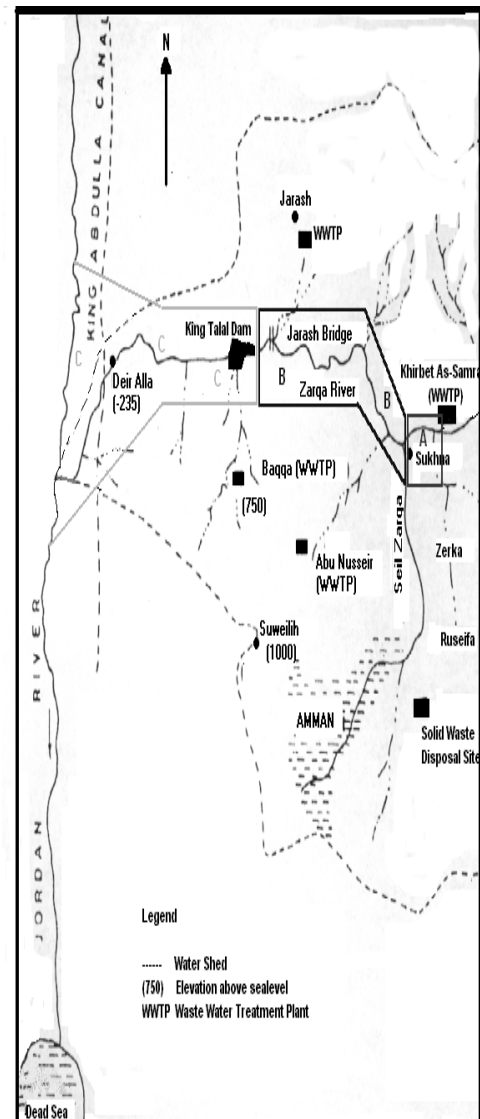
INTRODUCTION

Wastewater of around 2.2 million Jordanian inhabitants is treated in stabilization ponds, located 50 km to the northeast of the capital Amman. Khirbit As-Samra wastewater treatment plant was originally designed for the treatment of 68,000 m³/d; however, it is receiving now 168,000 m³/d (WAJ, 1999), and suffers from serious overloading problems. The treatment plant receives also some illegal industrial discharges and thickened sludge from some treatment plants in Amman and peripheries, which are discharging to the main sewer line leading to the ponds. The treatment plant is located above a fresh water aquifer, which is known to be polluted at some parts – area A, Figure 1- (Bannayan, 1990). The effluent is used for irrigating olive trees, forest, and fodder crops (Shreideh, 1999) in areas A, B, and C as shown in Figure 1. Area (A) only uses the effluent from the treatment plant. Area (B) utilizes mixed surface water from Seil Al- Zarqa with the effluent of the treatment plant. Area (C) receives the mixed water -as well as effluents of Abu-Nusier and Baq'a treatment plants- after a long sedimentation time in King Talal Reservoir. The existing situation of the Khirbit As-Samra treatment plant calls for an urgent upgrading of the system.

Anaerobic wastewater treatment could be an attractive option as described in chapter (1).

During the past 30 years, the popularity of anaerobic wastewater treatment increased due to the development of different attractive low cost technologies such as the UASB reactor. This system was developed in the seventies for the treatment of industrial wastewaters (Lettinga *et al.*, 1980). In UASB reactor, removal and anaerobic digestion of solids can take place providing an attractive compact system for wastewater treatment. The relatively new technology was applied successfully at full-scale for the treatment of domestic sewage in several tropical countries (Vieira, 1988; DHV Consultants, 1994; Haskoning, 1996; Monroy *et al.*, 2000; Chernicharo *et al.*, 2001; Wiegant 2001). However, higher COD concentration and fluctuating temperatures characterize the wastewater in Jordan and a modification of the conventional UASB reactor might be needed. The lower temperature during winter is known to limit the digestion of solids, especially the hydrolysis process (Zeeman *et al.*, 1997). For a proper design of the UASB reactor, the digestion process as a function of time and temperature should be first investigated for the wastewater. Moreover, the special nature of the influent of Khirbit As-Samra necessitates comparison with a 'pure' domestic sewage in terms of biodegradability and biodegradation rates of different polymers. For achieving this purpose, another treatment plant was chosen for the study. The treatment plant receives completely domestic wastewater from Abu-Nusier complex with a total population of 17,000 capita (Jamrah, 1999). Based on the comparison made, it can be decided whether special design parameters should be used for a proposed UASB reactor.

The specific goals of this study are firstly, to determine the general characteristics and the biodegradability of the wastewater of Khirbit As-Samra in comparison with the pure domestic sewage of Abu-Nusier. It should be mentioned that the biodegradability meant in this study is the



Figure(1): Locations of the wastewater treatment plants. Zone A shows the area irrigated with the effluent of Khirbit As-Samra; Zone B shows the area irrigated by the effluent of the ponds and fresh water from the Zarqa river; and zone C shows the area irrigated by the water stored in King Talal reservoir.

complete conversion of the organic compound into methane and carbon dioxide; Secondly, to determine the biodegradation rate of different polymers at summer and winter temperatures, and for both wastewaters. Proposed configurations for the UASB system are presented based on the results obtained.

MATERIALS AND METHODS

Influents to the treatment plants. The treatment plant of Khirbit As-Samra receives the wastewater from Amman, Ruseifa, Zarqa and Hashimiya areas. A main sewer line transfers the wastewater to the location. The average retention time in the sewer system is around 8 hrs (Royal scientific society (RSS), 2000). The wastewater produced in Amman is firstly introduced to preliminary treatment by a screen and a grit chamber before it is transferred to the stabilization ponds. Some illegal industrial discharges to the sewer system were also recorded. The treatment plant of Abu-Nusier is receiving wastewater from about 17,000 capita and is treating pure domestic wastewater from Abu-Nusier complex. The treatment plant is located 7 kms to the north of Amman. The temperatures of both wastewaters fluctuate during the year with 25°C and 18°C as averages for summer and winter respectively.

Multiple flasks set up for the determination of the biodegradation rate. The wastewater used in the experiment was based on 24 hrs-collected samples. Four series of batches were used for each wastewater to examine the biodegradation rate of each polymer at 25°C and 15°C with two extra bottles used as blanks for inoculated samples. The experiment was firstly conducted with the wastewater of Khirbit As-Samra, and 43 days later with wastewater of Abu-Nusier. The set up for each experiment is shown in Table 1. At each temperature two series were used for the examination of each wastewater. One series was inoculated with granular sludge, while the other series was kept without inoculation. Two reasons were behind this specific set up: firstly, the limited hydrolysis noticed for lipids under acidogenic conditions (Miron *et al.*, 2000; Sanders, 2001) made it important to use mehanogenic inoculum; and secondly, the concentrations of carbohydrates and proteins are high in granular sludge and may interfere with the lower concentrations found in the wastewater. In this case, it was important to measure the biodegradation rate of these polymers without the use of inoculum. Carbohydrates and proteins hydrolysis are not affected by the absence of methanogenesis (Miron *et al.*, 2000). Each series consists of 12 bottles acting as 6 pairs (duplicates). Another experiment using non-inoculated bottles was run a year later for both wastewaters with the same set up used for non-inoculated bottles described above at 25°C. The reason was to confirm the results obtained in the first experiment (Table 1). 24 hrs composite samples were also used for the purpose, and the experiment was ended after two weeks of measurements. Each 0.5l bottle -in all experiments- was filled with 470 ml of wastewater, 12 gram of granular sludge (only for the series aiming at lipids examination), 1 ml of trace elements, 1 ml of macronutrients, 0.1 g of yeast, and 10 ml of phosphate. The composition of the trace elements solution, the macronutrients and the buffer were as described by Lier, (1995). After closing the bottle, the headspace was flushed for 3 minutes with nitrogen gas in order to create anaerobic environment. After the preparation, the bottles were incubated using two water baths regulated at 25°C and

done in duplicates except for the lipids because of the limited amount of sample. Each bottle was analyzed for soluble COD (COD_{sol}), NH_4^+ , volatile fatty acids (VFA), and pH. The bottles with the inoculum were also tested for lipids, while the bottles without inoculum were tested for carbohydrates and proteins. Methane production was measured using the displacement method. The granular sludge used as inoculum was first reactivated since it was stored for more than one year at 4°C. The activation process was done using a solution containing 2:1:1 acetate, propionate, and butyrate on COD basis. The maximum measured activity for the sludge after the activation process was 0.14 gCOD/gVSS.d. The amount of inoculum used in each bottle was 12 gVSS, which should be enough for the degradation of the present VFA in the influent and the hydrolyzed suspended COD. The biodegradability of the wastewater was determined in triplicates using 0.5l serum flasks. Each flask was filled with 24 hrs composite wastewater sample. No inoculum was used in the test. The same macro and micronutrient, yeast, and buffer used above were also used for the biodegradability test. The bottles were incubated at 33°C until the gas production was finished.

Table (1): Experimental set up used for each wastewater

Temp (°C)	Use of blank	Flask Condition	No. of flasks
15	+	Flask with granular sludge as inoculum for measuring lipids degradation	6 pairs
15	--	Flask without inoculum for measuring proteins and carbohydrates degradation	6 pairs
25	+	Flask with granular sludge as inoculum for measuring lipids degradation	6 pairs
25	--	Flask without inoculum for measuring proteins and carbohydrates degradation	6 pairs
25*	--	Flask without inoculum for measuring the biodegradability after two weeks	6 pairs

(*) Experiment done a year later for each wastewater based on 24 hrs composite samples. (+) Blank is used. (-) Blank is not used.

Analytical methods. The COD was measured based on the standard methods (APHA, 1995). The paper filtered COD (COD_{pf}) was determined for a wastewater sample after filtration using paper filters (Whatmann No.40). The COD_{sol} was measured for the wastewater after filtration using 0.45-micrometer membrane filters (Orange Scientific). TS, VS, TSS, VSS, VFA (distillation method), total Kjeldahl nitrogen, and the lipids were analyzed according to the standard methods (APHA, 1995). For the lipids, the soxhlet extraction method by petroleum ether was used. However, diatomaceous earth solution (10 g/l) was used as an extra adsorption medium. 100 ml of this solution was filtered through paper filter (Whatmann 40). After the filtration, the earth material covered the whole paper filter and operated as an extra filter medium for the lipids. Carbohydrates were determined by the phenol-sulfuric acid method with glucose as a standard (Bardley *et al*, 1971). NH_4^+ -N was measured using the capillary Ion Analyser (CIA). The sample was membrane filtered using 0.45-micrometer filter paper (Orange Scientific) and 1 ml of the sample was transferred to a special vial in the CIA. The detector used is UV at 214nm and the voltage was 15-kilo volt.

Chapter 2

Conversions. 1g lipids=2.91gCOD (Sayed, 1987); 1g protein=0.16g Nkj=1.5gCOD (Miron et al., 2000); and 1g carbohydrates=1.07gCOD (Sayed, 1987).

Calculations.

$$1. H (\%) = \left(\frac{(CH_{4COD_{sample}} - CH_{4COD_{bl}}) + COD_{diseffl}}{COD_{tot\ inf}} \right) * 100$$

$$2. A(\%) = \left(\frac{(CH_{4COD_{sample}} - CH_{4COD_{bl}}) + COD_{VFAeffl}}{COD_{inf}} \right) * 100$$

$$3. M(\%) = \left(\frac{CH_{4COD_{sample}} - CH_{4COD_{bl}}}{COD_{infl}} \right) * 100$$

$$5. Lipids_{conv.} = \frac{lipids_{total_{t=0}} - lipids_{total_{t=t}}}{lipids_{total_{t=0}}} * 100$$

$$6. Carbohydrate_{conv.} = \frac{carbohydrates_{t=0} - carbohydrates_{t=t}}{carbohydrates_{t=0}} * 100$$

$$7. Protein_{converted} = Total_{converted} - (Lipids_{converted} + Carbohydrates_{converted} + VFA_{converted})$$

RESULTS AND DISCUSSION

General wastewater characteristics. Table 2 shows the average wastewater characteristics for the two influents during the period between 20th of March and 9th of August. Both influents are classified as strong wastewaters (Metcalf & Eddy, 1991) with high COD_{tot} and COD_{ss} concentrations. The average COD concentrations presented in the table are lower than those recorded for influents of some other treatment plants in Jordan. For example, Baqa'a treatment plant (Figure 1) receives an average COD_{tot} concentration of 3650 mg/l (Jamrah, 1999). The reason for the high COD concentration of sewage is the low consumption of water, which accounts for an average value of 85 l/C/d. The average water consumption is usually higher with values of 130 l/C/d for Syria and 275 l/C/d for Israel (Libiszewski, 1995). The COD_{ss} constitutes a high fraction of the COD_{tot} – around 70%- compared to values reported in literature for domestic sewage, which were found to be in the range of 45-55% (Kalogo and Verstraete, 1999; Elmitwalli, 1999). It can also be seen from the table that the colloidal COD (COD_{col}) presents less than 10% of the COD_{tot}, which is considered as a low value compared with a percentage of 25% reported by Elmitwalli, (1999) for domestic sewage. The average percentages of the different polymers in both wastewaters are shown in Table 3 and are similar to values reported in literature for domestic sewage (McInery, 1988; Elmitwalli, 2002). It seems that the industrial discharges to the sewer system did not affect the composition of the wastewater of Khirbit As-Samra, either due to the dilution effect of the main flow or because they have a similar composition as the domestic sewage itself. The same can be noticed with the pH values of the influent to the treatment plant, with values around neutral. The higher concentration of the VFA of the influent to Khirbit As-Samra presented in the table is probably due to some hydrolysis and acidification taking place during the

relatively long transportation time of 8 hrs, before the wastewater reaches the treatment plant. An interesting result for both wastewaters, but especially for the wastewater of Khirbit As-Samra is the high COD_{ss}/VSS ratio with average values of 3.98 and 2.5 for Khirbit As-Samra and Abu-Nusier wastewaters respectively. Values calculated from literature for this ratio are in the range of 1.36-1.6 (Barbosa & Sant'Anna JR, 1989; Encina *et al.*, 1998). The high ratio means either the presence of some compounds that exerts higher COD values than those assumed and used in the conversions above, or that there exists some volatile solids, which are lost during the TSS measurements.

Table (2): General wastewater characteristics for the influents of Khirbit As-Samra and Abu-Nusier over the period between 20th of March and 9th of August. Standard deviations are presented in brackets

Parameter	Unit	Khirbit As-Samra	Abu-Nusier
COD _{tot}	mg/l	1929 (131)	1597 (255)
COD _{ss}	mg/l	1336 (87)	1093 (243)
COD _{col}	mg/l	139 (21)	128 (51)
COD _{dis}	mg/l	453 (23)	376 (111)
TS	mg/l	2100 (300)	1710 (50)
VS	mg/l	1000 (500)	960 (40)
TSS	mg/l	420 (180)	470 (90)
VSS	mg/l	260 (160)	340 (40)
Carbohydrates	mgCOD/l	98 (9.2)	76 (2.1)
Lipids	mgCOD/l	419 (58)	420 (31)
Proteins	mgCOD/l	812 (105)	769
Ammonium	mg/l	24.5 (1.1)	32 (3)
VFA	mgCOD/l	200	150
pH		7.2 (0.1)	7.3 (0.08)

Biodegradability of the wastewater. The biodegradable fractions of the COD_{tot} for both wastewaters are shown in Table 4. It was found that 79% of the COD_{tot} was biodegraded after 224 days of incubation for the influent to Khirbit As-samra, while this value was 76% after 130 days of incubation for the influent to Abu-Nusier treatment plant. The table also shows the biodegradable fraction of the wastewater of Khirbit As-Samra after 130 days of incubation, which is considerably lower than that of Abu-Nusier. Elmitwalli *et al.*, (2001) reported 74% biodegradable fraction of the COD_{tot} for raw sewage after 135 days of digestion at 20°C and the same value after 80 days of digestion at 30°C.

Hydrolysis, acidification, and methanogenesis of both wastewaters. Figure 2 shows the hydrolysis, acidification, and methanogenesis for the two wastewaters incubated at 25°C, while Figure 3 shows the results obtained for the two wastewaters at 15°C. It was found that 57% and 86% of the biodegradable fractions of the influents to Khirbit As-Samra and Abu-Nusier treatment plants respectively were converted into methane after 27 days of digestion at 25°C. However, only 26% and 42% of the biodegradable fractions in the influents to Khirbit As-Samra and Abu-Nusier treatment plants

Table (3): Average percentages – COD basis- of carbohydrates, lipids and proteins for the two influents, compared to data presented in literature. Values in brackets are percentages of TSS

	Khirbit As-Samra	Abu-Nusier	McInery, (1988)	Elmitwalli, (2001)
Carbohydrates	5 (21.8)	5 (15)	(12.8)	9-17
Proteins	45 (28)	48	(27.1)	31-58
Lipids	23 (34)	31 (39)	(34.4)	---

respectively were converted into methane after 35 days of digestion at 15°C. The lower rate of biodegradation for the former at both temperatures compared to the wastewater of Abu-Nusier could be due to some inhibitory effects of some components found in the industrial discharges or activated sludge discharges. Results obtained by the water authority of Jordan, (2000) for both wastewaters show an average BOD₅/COD percentage of 39±5% with maximum and minimum values of 50% and 34% respectively for the influent to Khirbit As-Samra treatment plant. However, they show an average value of 53±10% with a maximum of 65% for the influent to Abu-Nusier treatment plant, which also reflects higher biodegradation rate for the later. Figure 2 also shows the biodegradable fractions of non-inoculated bottles after two weeks of incubation for both wastewaters and for samples tested a year later. The results obtained confirm that the values already presented for Khirbit As-Samra were not a coincident, but rather a general trend, which also reflects the presence of inhibitory substances in the influent to the treatment plant.

Table (4): Biodegradability of the wastewaters of Khirbit As-Samra and Abu- Nusier. Standard deviations are presented in brackets

Time (day)	130	224
Khirbit As-Samra	56.1	78.4 (1.1)
Abu-Nusier	75.8 (8.6)	---

The peaks in the hydrolysis and acidification calculated based on equations 1 and 2 and shown in Figures 2 and 3 could be explained by the occurrence of adsorption-desorption of the soluble substrate on the particulate matter as reported by (Novak *et al.*, 1995; Tsezos and Bell, 1988; Guellil *et al.*, 2001; Fujie *et al.*, 1997; Flemming, 1996). In fact, literature available showed that the hydrolysis of the particulate matter is mostly the rate-limiting step in the digestion process (Zeeman, 1997; Sanders, 2001; Eastman and Ferguson, 1981; Perot and Amar, 1989).

Conversion of the main polymers. Table 5, shows the conversion of each polymer in both wastewaters at the end of the experiments. Figure 4 shows the concentrations of carbohydrates and lipids as a function of time for both wastewaters at the two temperatures. The average conversions of carbohydrates, proteins and lipids for the influent of Khirbit As-Samra were 72%, 55%, and 60% respectively at 25°C, and 74%, 36% and 10% respectively at 15°C. However, the average conversions of carbohydrates, proteins and lipids for the influent of Abu Nusier were 86%, 86% and

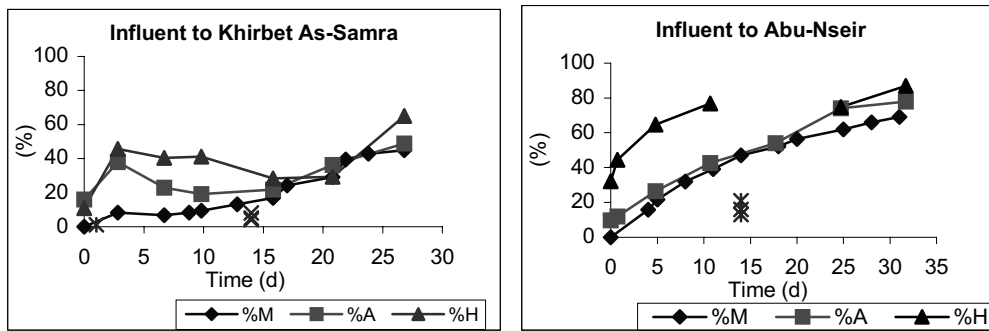


Figure (2): The calculated hydrolysis, acidification and methanogenesis for the two wastewaters at 25°C. (x) Methanogenesis for non-inoculated bottles tested a year later.

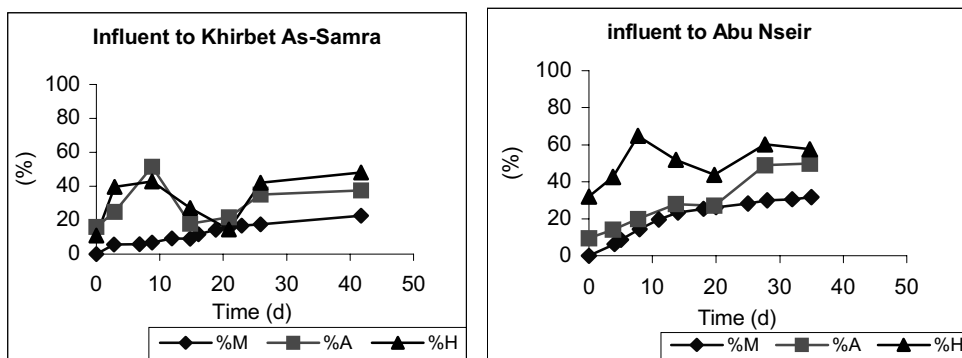


Figure (3): The calculated hydrolysis, acidification and methanogenesis for the two wastewaters at 15°C.

72% respectively at 25°C, and 86%, 46% and 27% respectively at 15°C. It is clear that the degradation of carbohydrates in both wastewaters is high and independent of temperature, while both the degradation of proteins and lipids were limited at the lower temperature. The lower values obtained for polymers in the case of Khirbit As-Samra wastewater compared to those obtained in the case of abu-Nusier wastewater are mainly due to the lower rate of proteins degradation taking into account the percentage contribution of this polymer to the total COD. It should be mentioned that the ammonia followed a strange behavior during the course of biodegradation, and so the conversion of proteins was calculated based on equation (7).

Table (5): Percentage conversion of different polymers for the two wastewaters and at both temperatures

Polymer	Khirbit As-Samra		Abu-Nusier	
	% conversion (25°C) incubation time =27d	% conversion (15°C) incubation time= 42d	% conversion (25°C) incubation time=32d	% conversion (15°C) incubation time= 35
Carbohydrates	72	75	86	86
Proteins	55	36	86	46
Lipids	60	10	72	27

The first order kinetics for the description of Hydrolysis of carbohydrates, proteins and lipids. Table 6 shows the calculated hydrolysis constants for carbohydrates, proteins and lipids in the two wastewaters and at the two temperatures. Since lipids were not degraded in the case of Khirbit As-Samra at 15°C, it was not included in the

table. Both the conversions of lipids for wastewaters of Khirbit As-Samra at 25°C and Abu-Nusier at 15°C did follow first order kinetics, while the influent to Abu-Nusier at 25°C had a poor correlation. The degradation of carbohydrates did not follow a first order kinetics in any of the cases tested. The proteins had relatively good correlations in all cases.

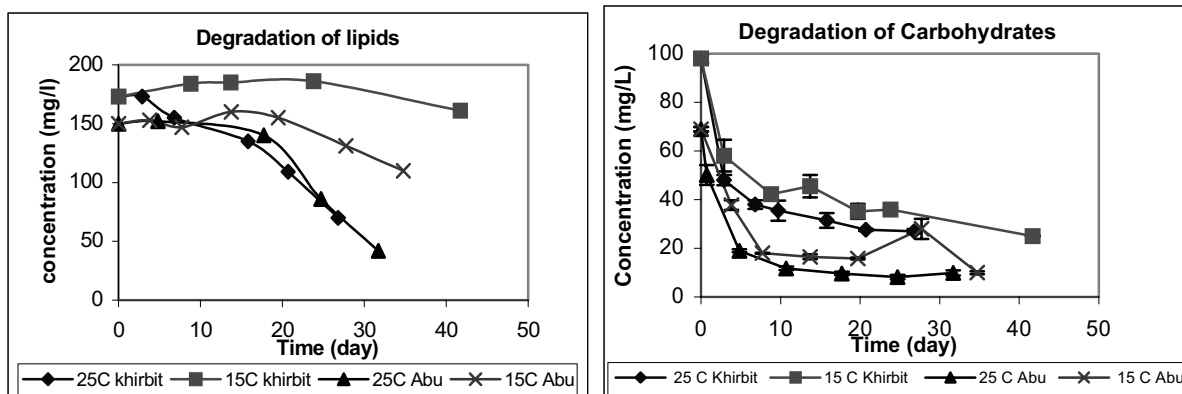


Figure (4): Effluent lipids and carbohydrates concentrations as a function of time for both wastewaters and at the two temperatures.

FINAL DISCUSSION

The results of the anaerobic biodegradation test conducted on the two different wastewaters presented in this study show the potential of anaerobic treatment for the wastewater in Jordan. 79% and 76% of the wastewaters of khirbit As-Samra and Abu-Nusier are biodegradable under anaerobic conditions. 57% and 86% of the biodegradable fractions of the wastewaters of khirbit As-Samra and Abu-Nusier treatment plants were degraded respectively at 25°C after around 27 days of digestion. At 15°C, the rate of biodegradation was slower. Both the lipids and proteins degradations were strongly affected at this low temperature. For the special case of the influent of Khirbit As-Samra treatment plant, it is recommended to put more effort for the control of the industrial discharges, as they are affecting the rate of biodegradation of the wastewater, at least when compared to the influent of Abu-Nusier treatment plant.

Table (6): Hydrolysis constants calculated for the lipids and carbohydrates. Values between parentheses are the correlations (R^2)

	K_h (d^{-1}) Khirbit As-Samra (25°C)	K_h (d^{-1}) Khirbit As-Samra (15°C)	K_h (d^{-1}) Abu-Nusier (25°C)	K_h (d^{-1}) Abu-Nusier (15°C)
Carbohydrates	0.08 (0.42)	0.05 (0.54)	0.07 (0.67)	0.04 (0.69)
Proteins	0.025 (0.89)	0.012 (0.88)	0.08 (0.90)	0.028 (0.82)
Lipids	0.06 (0.89)	No hydrolysis	0.08 (0.76)	0.02 (0.97)

When anaerobic treatment using UASB systems is considered in Jordan, there are two options in general to deal with the lower rate of degradation of wastewaters during winter. The first one is the application of a two stage UASB reactor proposed by

Wang (1994) for the treatment of domestic sewage at ambient temperatures in the range of 13-31°C. In this system, the first stage particularly aims at the removal and partial hydrolysis and acidification of solids, while the second stage aims at the removal of soluble organic matter and granular sludge may develop (Seghezzi *et al.*, 2001). The sludge produced in the first stage will need further stabilization in a separate digester, especially during winter. Elmitwalli *et al.*, (2002) proposed also a staged system by introducing an AF reactor as a first stage in order to enhance the removal of solids. They achieved an average COD_{ss} removal efficiency of 82% at 13°C. However, the application of AF as a first step may face some difficulties during summer due to possible gas production as a result of the occurrence of methanogenesis at lower sludge retention. The other option is to apply longer sludge retention time in the UASB reactor allowing for digestion to proceed at the average winter temperature. The later will need a long HRT for the anaerobic system and consequently higher initial cost compared to the former option. The advantages of the two-stage system over one stage anaerobic reactor, is the lower total HRT, however, the need of operating three separate reactors is a major disadvantage of the former.

In any case, and based on the results obtained in this research, the anaerobic treatment of the wastewater of Khirbit As-Samra using UASB reactor, necessitates the application of 1.5 times the HRT needed for the treatment of completely domestic sewage (Abu-Nusier), in order to allow for sufficient degree of stabilization at both temperatures.

CONCLUSIONS

Both influents to Khirbit As-Samra and Abu-Nusier treatment plants are characterized as strong sewage with a high percentage of COD_{ss} with a value around 70%. The general characteristics of the wastewaters showed the same composition in terms of lipids, proteins, and carbohydrates (percentage of the COD_{tot}). Moreover, both wastewaters have high anaerobic biodegradability with values of 79% and 76% - COD basis- respectively. However, the rate of biodegradation was higher for the influent to Abu- Nusier treatment plant, with 86% of the biodegradable fraction digested after 27 days of incubation at 25°C compared to 57% digested for the influent to Khirbit As-Samra treatment plant. The lower biodegradation rate of the wastewater of Khirbit As-Samra could be due to possible inhibitory effects of the illegal industrial and activated sludge discharges and was attributed to the lower biodegradation rate of proteins, viz. 0.025 d⁻¹ versus 0.08 d⁻¹ for Abu-Nusier wastewater. The lower biodegradation rates during winter suggested either the application of long HRT in the UASB system, or the use of a staged UASB reactor. In the staged UASB system, solids could be removed in the first stage, and then digested separately, while the second stage could act as methanogenic reactor for the removal of soluble COD fraction. In any case, and based on the results obtained in this research, 1.5 times HRT is needed for the anaerobic treatment of the wastewater of Khirbit As-Samra compared to that needed for completely domestic sewage.

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Chapter 3

Effect of SRT and temperature on biological conversions and the related scum forming potential

EFFECT OF SRT AND TEMPERATURE ON BIOLOGICAL CONVERSIONS AND THE RELATED SCUM FORMING POTENTIAL

Primary sludge digestion in a CSTR as a model for the sludge bed of a UASB reactor treating domestic sewage

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ABSTRACT

The sludge bed of a UASB reactor treating domestic sewage was simulated by a completely stirred tank reactor (CSTRs) digesting primary sludge at different sludge retention times (SRTs) and temperatures. The results showed that methanogenesis started only at an SRT between 30-50 days for reactors operated at 15°C, while it started at an SRT between 5-15 days for reactors operated at 25°C. The hydrolysis and methanogenesis increased with increasing both SRT and temperature with a maximum value of 49.8% for hydrolysis and 51.2% for methanogenesis for the reactor operated at 75 days SRT and 25°C. The conversion of each polymer at different SRTs and temperatures is also presented. The tendency of the sludge to form a scum layer was studied for the different SRTs in the range (5 to 75) days. A simple test was developed for the purpose of comparing the scum forming potential at different sludge ages and temperatures. The results showed that the thickness of the scum formed was inversely proportional to the SRT, but also the temperature effects the scum forming potential. Other physical characteristics like SVI and filterability were found to be affected by mixing conditions rather than biodegradation process, by affecting the particle size distribution of the sludge.

KEYWORDS

Digestion, hydrolysis, methanogenesis, primary sludge, scum, SRT, temperature, particle size distribution

INTRODUCTION

Adequate low-cost environmental protection and resource preservation technologies, which aim at minimum energy consumption and maximum recycling of different resources are becoming a challenge that needs the input of workers in different fields. Anaerobic treatment of wastewater is widely accepted as a low cost treatment technology for the treatment of concentrated domestic and industrial wastewater (McCarty, 1981; Haandel and Lettinga, 1994). One of the relatively new treatment technologies is the Upflow Anaerobic Sludge Blanket reactor (UASB) which, has proven to be effective even in the treatment of low strength domestic sewage at tropical conditions (Vieira *et al.*, 1986; Lettinga *et al.*, 1993). However, the anaerobic treatment of domestic sewage is so far not applied at full scale at low temperature conditions (Schellinkhout, 1993; Elmitwalli *et al.*, 1999). For the purpose of applying

the system in regions with fluctuating temperatures, and optimizing the performance of the reactor, some important parameters should be studied, into which, the SRT is of priority. In fact, the SRT is the key parameter affecting the biochemical and probably physical properties of the sludge. It affects the conversion of different polymers during primary sludge digestion and the anaerobic treatment of domestic sewage (Haandel and Lettinga, 1994; Zeeman and Lettinga, 1999). Moreover, the occurrence of methanogenesis -which is a function of the SRT- will affect the conversion process significantly especially the conversion of lipids (Heukelekian and Mueller, 1958; Kumatsu *et al.*, 1991; Sanders, 2001). However, the temperature is a primary factor that determines the SRT needed to achieve methanogenic conditions in a digester or an UASB system. Indeed there are many factors that affect the conversion kinetics of a certain polymer at a given SRT. Substrate conditions (type, concentration, and particle size distribution), environmental conditions (pH, and temperature), mass transfer conditions, and adaptation of the bacterial populations to the feed are among the most important factors. The wide probable combinations of these factors ended up with many different values for kinetic constants and conversion percentages, that differ for each researcher in the field (Eastman and Ferguson, 1981; Pavlostathis and Giraldo-Gomez, 1991; Henze and Mladenovski, 1991; Vavilin *et al.*, 1996; Miron *et al.*, 2000). The lack of knowledge on the conversion of different polymers during primary sludge digestion and treatment of domestic sewage, especially at 15°C, and the formation of scum during the anaerobic treatment of strong domestic wastewater motivated us to conduct this research.

By effecting the extent of digestion of polymers, the SRT will also affect the physical characteristics of the sludge including the particle size distribution (Karr and Keinath, 1978; Olboter and Vogelpohl, 1993; Vesilind and Hsu, 1997; and Kopp *et al.*, 1997), which will determine the entrapment and adsorption capacity of the sludge in a UASB reactor and consequently the performance of the system. Moreover, the particle size distribution (PSD) will affect dewaterability, settlability and probably the potential capacity of a certain sludge to form a scum layer. The literature available on the later subject -scum formation- is scarce, although it is of prime importance as the scum is usually described as one of the main operational problems of anaerobic digesters (Pagilla *et al.*, 1997). Moreover, during the treatment of strong domestic sewage, the production of a scum layer has been also experienced in full scale UASB reactors at Kanpur (India) and Ghana (Haandel and Lettinga, 1994; deMes, personal communication). Different researchers reported several reasons behind the formation of scum, including: insufficient mixing and heating, high grease content in the influent, severe temperature fluctuations, recycling digested solids, high or poorly controlled loading rates, and high concentrations of fatty acids (Lemmer and Baumann, 1988; Pagilla *et al.*, 1997; Yoda and Nishimura, 1997).

In this research, the effect of SRT and temperature on hydrolysis, acidification, and methanogenesis of primary sludge was investigated at two different temperatures, using CSTRs simulating the sludge bed of a UASB reactor (Heertjes and Meer, 1978; Bolle *et al.*, 1986). Moreover, a simple test for measuring the scum forming potential is described, and compared for different SRTs and temperatures. The effect of SRT and temperature on the particle size distribution (PSD) and the following effect on the physical sludge characteristics was investigated.

MATERIALS AND METHODS

Experimental set up for the CSTRs. Two sets of CSTRs were operated at two different temperatures. The first set was operated at 25 ± 0.05 °C and includes five CSTRs operated at 5, 15, 30, 50, and 75 days SRT. The second set contains five reactors with the aforementioned SRTs, however, the set was operated at 15 ± 0.05 °C. The effective volume of each reactor was 5.5 L and contains a stirrer, which is rotating at 30 rpm. The stirrer was operating for 45 minutes every hour. Each reactor was connected to a gas bag with a capacity of 5 L. The reactors were inoculated with digested sludge from a 60 m³ UASB reactor treating domestic sewage at Khirbit As-Samra. The primary sludge, used to prepare the feed, was obtained from the wastewater treatment plant of Irbid/ Jordan, and stored in the refrigerator at 4°C. The primary sludge was diluted to a concentration of 20 g/l and used as a feed. Each day, a certain amount of sludge was pumped from the reactors and a same amount of feed was added. The pH and the gas of each reactor was measured daily. After reaching 'steady state', which was considered to be achieved after 3 SRTs, three successive sets of measurements were carried out. The measurements include gas production and composition, pH, TS, VS, Nkj, NH₄⁺, carbohydrates, dissolved carbohydrates, lipids, VFA, different COD fractions as described by Miron *et al.*, (2000).

Experimental set up for the scum experiment. This experiment was based on the observation of the occurred entrapment of the gas bubbles in or to the sludge particles causing their density to decrease and consequently the sludge particles to float. The thickness of the scum layer formed was used to express the sludge potential for scum formation. In this test, half a Steradent (denature cleaning by Reckitt toiletry products, Hull, England) tablet was placed on the bottom of a 500 ml glass measuring cylinder. A certain amount of sludge that contains 1.6 g of TS was diluted up to 300 ml with tap water and poured in the cylinder. Directly after the gas formation is finished, the height of the scum formed was recorded. The test was standardized after studying the effect of the amount of gas production (number of tablets to be used), the amount of total solids in the sample, the temperature, and the pH on the height of the produced scum. The following conditions were chosen as a standard procedure for determining the scum forming potential: half a Steradent tablet, 1.6 g TS, the same pH and temperature of the sludge sample.

Analytical methods. TS, VS, Nkj were analysed according to the standard methods (APHA, 1995). NH₄⁺ -N was measured using a capillary Ion Analyser (CIA). The sample was membrane filtered using 0.45-micrometer filter paper (cellulose nitrate filters, sartorius) and 1 ml of the sample was transferred to a special vial in the CIA. The detector used is a UV at 214 nm and the voltage was 15 kilo volt. VFA was determined using the distillation method described in the (APHA, 1995). The VFA concentrations of one set of samples were determined using gas chromatograph HP model 5890A equipped with a 2m x 4mm glass column with supelcoport (11-20 mesh) coated with 10% Fluorrad FC 431. The temperature of the injector, the column and the FID were 200, 130 and 280°C respectively. The samples were membrane filtered and 1 ml of each filtrate was preserved with formic acid before the measurements. The total Kjeldahl nitrogen was determined according to the standard methods (APHA, 1995). The lipids and the fractions of the COD were analyzed based on the methods described by Miron *et al.*, (2000). Carbohydrates were determined by

phenol-sulfuric acid method with glucose as a standard (Bardley *et al.*, 1971). For the dissolved carbohydrates, the samples were membrane filtered (Orange Scientific 0.45 μm) before the same procedure was followed. A wet gas meter measured the amount of gas produced. The methane content was analyzed using a Philips PU 4500 gas chromatograph with thermal conductivity detector. The column is packed with Porapak Q and the carrier gas is helium. The temperatures of the injector, column and detector are 72, 72, and 200°C respectively. The sludge volume index (SVI) and the capillary suction time (CST) were determined according to Standard Methods (APHA 1995). For the particle size distribution test, the size of a stable floc is used to define the particles of the sludge, which can not be dispersed by small shearing forces like smooth stirring (Olboter and Vogelpohl, 1993). For those sludges, the floc size is approximately independent from the degree of dilution. For the test, the PSD was first determined using sieve analysis into which 25 ml of sludge was directly taken from each reactor and diluted 6 times with distilled water to avoid clogging of the sieves. The pore sizes of the sieves used were 0.16 mm, 0.09 mm, and the pan. The sieves were shaken by a mechanical vibrator (FRITSCH, (R) analysett) for five minutes. The sludge retained on each sieve after shaking is transferred to previously weighed beakers and placed in the oven at 105°C until a constant weight is obtained. The test was performed in triplicates and was done on three separate samples from each reactor. The test was also repeated and the sludge retained on the pan was collected for further fractionation using the Coulter Counter device. The size range measured by the device was 3.51-112.4 μm , and the distribution is directly recorded.

Calculations. The following equations were used for the determination of hydrolysis, acidogenesis, and methanogenesis respectively.

$$\%hydrolysis = \frac{COD_{CH_4} + (COD_{dis\text{effl}} - COD_{di\text{ sin } f})}{COD_{inf} - COD_{di\text{ sin } f}} * 100\%$$

$$\%acidification = \frac{COD_{CH_4} + COD_{VFA\text{effl}} - COD_{VFA\text{ inf}}}{COD_{inf} - COD_{VFA\text{ inf}}} * 100\%$$

$$\%methanogenesis = \frac{COD_{CH_4}}{COD_{inf}} * 100\%$$

Conversions. 1 gram carbohydrates (assumed as glucose, $\text{C}_6\text{H}_{12}\text{O}_6$) is equivalent to 1.07 g COD (Sayed, 1987). 1 g protein (assumed as $\text{C}_4\text{H}_{6.1}\text{O}_{1.2}\text{N}_x$) is equivalent to g amino acids, 0.16 g Nkj, 0.16g $\text{NH}_4^+\text{-N}$ and 1.5 g COD (Miron *et al.*, 2000). 1 g VFA is equivalent to 1.44 g COD. 1gram lipids is equivalent to 2.91 g COD (Sayed, 1987).

RESULTS AND DISCUSSION

Digestion Process

Effect of SRT and temperature on the digestion. The characteristics of the primary sludge are shown in Table 1. Figure 1 shows the results obtained from the CSTRs for

hydrolysis, acidification, and methanogenesis at both temperatures. The figure shows that methanogenesis starts at an SRT between 5 and 15 days at 25°C, while at 15°C it only starts at an SRT between 30 and 50 days. Miron *et al.*, (2000) also showed that methanogenic conditions were manifested only at an SRT of 8 days at 25°C. The amount of hydrolysis in the figure was calculated based on the dissolved COD and the CH₄-COD, while the LCFAs remained unmeasured. This means that the hydrolysis could be underestimated and conclusions on the rate limiting step based on the results could deviate for lipids. The maximum hydrolysis found at higher temperature amounted to 49.8% while it was only 24.3% at 15°C. The maximum methanogenesis amounted to 51.2% and 25.1% for the higher and the lower temperatures respectively. It should be mentioned here, that when exclusively the biodegradable fraction of the COD is taken into account, obviously the calculated reduction of solids will be even higher.

Table(1): Composition of the influent primary sludge. The first row in mg/l and the second row in mgCOD/l. The numbers in brackets are the percentage of VS (first row) and of COD_{tot} (second row)

	Protein	Lipid	Carbohydrate	VFA	total sum	NH4-N
VS=15620± 336 (77.3%of TS)	5056±187 (32.4)	4503±405 (28.8)	2965±147 (19.0)	934±122 (6.0)	13458 (86.2)	78.3±4.4
COD _{tot} =32769± 2270	7584 (23.1)	13104 (40.0)	3173 (9.7)	1344 (4.1)	25169 (76.8)	

Hydrolysis described on the basis of first order kinetics. Although the hydrolysis of each polymer differs from the other, the overall hydrolysis rate at 15°C followed first order kinetics. The rate constant value ($K_h=0.0051\text{ d}^{-1}$) was determined using the linearised equation of Eastman and Ferguson, (1981), with a good correlation ($R^2=0.96$). However, the correlation coefficient amounting to the hydrolysis rate constant at 25°C, calculated to be 0.021 d^{-1} , appeared to be poor ($R^2=0.81$).

Conversion of different polymers. The conversion efficiencies calculated for lipids, proteins, and carbohydrates are shown in Figure 2. The lipids were removed better

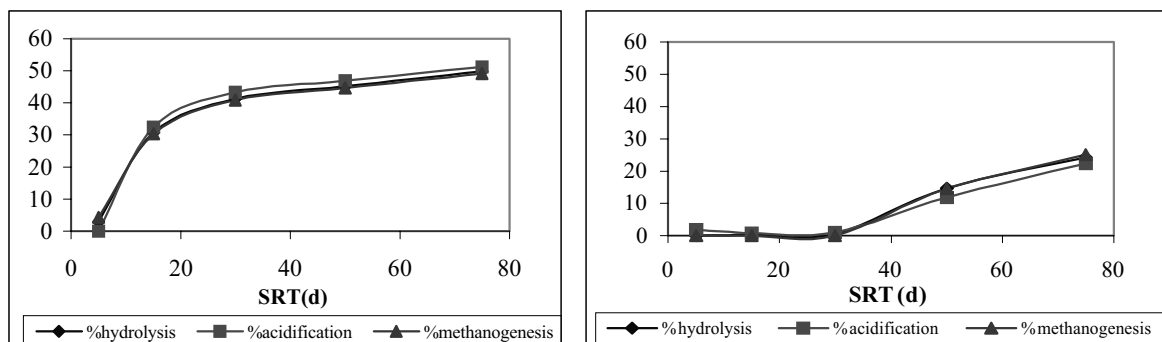


Figure (1): effect of the SRT on hydrolysis, acidification, and methanogenesis at the two temperatures. Left: at 25°C; Right: at 15°C.

than the proteins at the two temperatures imposed. The maximum conversion of lipids was achieved after 75 days at 25°C and accounted for 82% of the lipids content. It should be noted again that the hydrolysis is most probably higher since the LCFA are not included in the calculations. The maximum conversion of lipids at 15°C was also achieved at 75 days SRT and accounted for 75% of the lipids content. It is interesting to mention that O'Rourke, (1968) did not find any conversion of lipids after 60 days of digestion for primary sludge at 15°C. Moreover, the conversion of lipids at both temperatures did not follow first order kinetics. The maximum amount of conversion of proteins was 34% and was obtained at an SRT of 50 days and 25°C. The maximum conversion at 15°C was 21%. The conversion dropped at an SRT of 75 days at both temperatures. Decrease in protein hydrolysis at increased SRT was strange, however, as protein hydrolysis is based on production of $\text{NH}_4^+\text{-N}$, the drop in

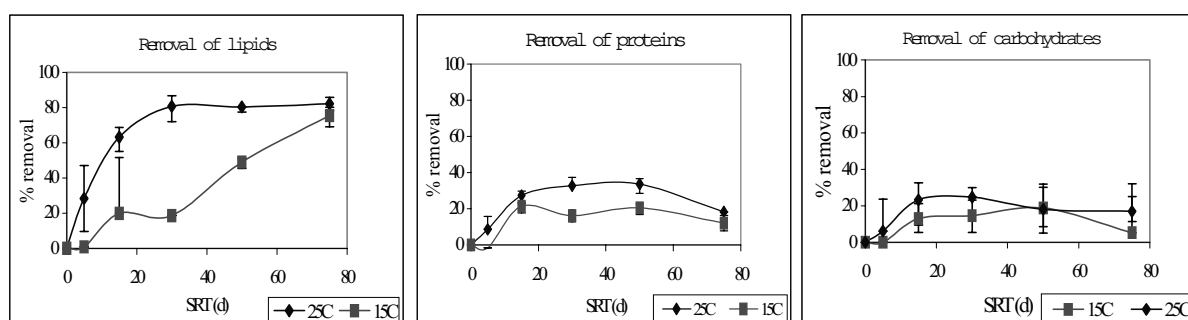


Figure (2): Removal of lipids, proteins and carbohydrates at different SRT's and different temperatures.

hydrolysis might be due to chemical precipitation of $\text{NH}_4^+\text{-N}$ (Miron *et al.*, 2000). The precipitation of ammonia may hold also for the lower SRTs, which should affect the overall calculated conversion of proteins. Although the carbohydrates are known to be easily degraded materials, they were not removed to a high extent in the CSTRs. The maximum conversions were 25% and 19% at 25°C and 15°C respectively.

VFA removal at different SRT's and temperatures. Figure 3 shows the course of volatile acids removal for the reactors at both temperatures. The minimum VFA concentration that could be achieved at 25°C was around 10 mg/l, while at the lower temperature, this was still not reached after 75 days SRT. Assuming that the minimum

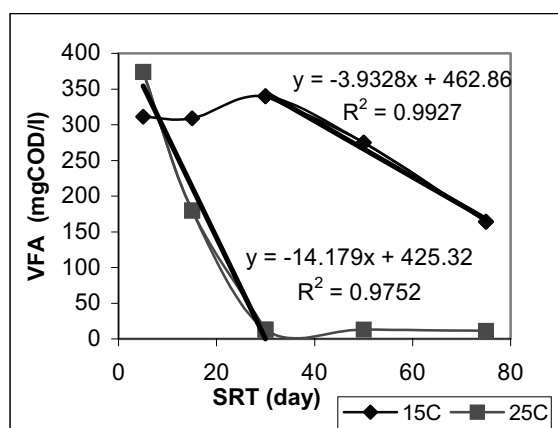


Figure (3): VFA concentration in relation to SRT as assessed at 15°C and 25°C.

possible value at 15°C is the same as the concentration obtained at 25°C –10 mg/l-, then the SRT needed for maximum conversion at 15°C can be estimated at 115 days using the equation presented in figure (3).

COD mass balance at different SRTs and different temperatures. Table 2 shows the COD influent and effluent fractions (CH₄, VFA, proteins, carbohydrates, and lipids) as a function of different SRTs and temperatures. The gap in the mass balance, found to be in the range of 9-34%, could be due to many reasons. Adsorption of lipids to the walls of the reactors is one of the possible reasons, however, after finishing the experiment, the determined lipids accumulated on the walls of the CSTRs operated at 15°C, were less than 0.3%. The most plausible reason is a difference between the assumed and the real g COD/g polymer ratio because *ca.* 20% COD is already lacking in the influent. For the reactors operated at 25°C, no significant increase in the removal of the polymers after 30 days SRT was achieved. However, for the reactors operated at 15°C, there was a limited degradation of lipids and a limited consumption of the VFA as well, even at the highest applied SRT. Increasing the sludge retention time to values higher than 75 days, is expected to increase the degradation of the lipids.

Physical Characteristics of the sludge

Scum Layer formation. The results depicted in Figure 4 show that both SRT and the temperature affect the scum forming potential of the sludge. The results obtained for the scum height were statistically analyzed by t-test at 95% confidence limit, and the effect of each the temperature and the degree of digestion was found to be significant. When the extent of digestion increases, due to increased temperature or SRT, the scum forming potential decreases. The degree of digestion has an effect on the concentration of lipids, which tend to adsorb to sludge particles and float, Figure 4. Temperature can affect the formation of scum in an anaerobic reactor in two ways, viz. directly by affecting adsorption of gas bubbles to the sludge particles or indirectly by affecting the course of the digestion. Both may result in more scum formation at lower temperature. However, in practice sludge with a high scum forming potential, will only produce scum in the presence of gas production. Lower

Table (2): The influent and effluent COD fractions at different SRT's

SRT days	Lipids %		Carbohyd. %		Proteins %		VFA %		CH ₄ -COD %		Missing %	
	15°C	25°C	15°C	25°C	15°C	25°C	15°C	25°C	15°C	25°C	15°C	25°C
0	40	40	9.7	9.7	23.1	23.1	4.1	4.1	0	0	23.1	23.1
5	42.51	26.6	12.21	9.69	23.4	21.82	6.84	8.20	0	0	15.04	33.69
15	36	13.7	8.98	7.92	18.12	17.09	6.71	0.79	0	32.08	30.19	28.42
30	36.9	7.17	8.82	7.77	19.09	15.84	7.45	0.07	0	42.82	27.73	26.32
50	20.92	8.88	8.38	8.46	18.09	15.89	6.07	0.06	14.73	46.49	31.82	20.22
75	14.75	11.33	9.78	8.19	20.03	20.28	3.63	0.125	25.29	50.71	26.51	9.36

temperature and lower SRT (acidogenic conditions) will result in decreased gas production. In the present research, the determination of the scum forming potential

was made at the temperature of the sludge and both direct and indirect effects of temperature are possible.

Effect of SRT and temperature on the particle size distribution. Table 3 shows the results obtained in sieve analysis of sludge from all the reactors. Figure 5 shows the distribution of the fine particles over a wide size range in the order of (3.51- 112.4 μm). It was surprising to find almost no differences in the PSD between the reactors except for the two reactors operated at 50 and 75 days SRT at 25°C, where the percentage of fine particles were in the order of 75%. It looks that the most important factor determining the particle size distribution of the sludge (at a certain range of SRT) is the degree of mixing rather than the degree of digestion or the temperature. According to Karr and Keinath, (1978), different factors affect the physical properties of the sludge by affecting particle size distribution, including biological degradation and mixing conditions. The higher percentages of fine particles at higher ages and temperature (Figure 5), could be due to reduced floc stability for sludge at higher ages against shearing forces produced by mixing, as these ages have the highest ash content compared to the other reactors, with average VS/TS ratio of 0.66 and 0.67 for the reactors operated at 75 and 50 days respectively. For elucidating the effect of mixing, 5L of the primary sludge was mixed using a CSTR for an overnight period at room temperature (20°C), and the PSD for the sludge was measured. The results are shown in Table 3 and Figure 5. The results show that the percentage of fine particles in the primary sludge increased after mixing ending up with the same PSD as those reactors digested at different SRTs and temperatures, which confirm the big effect of mixing over the digestion (for a certain range of SRT) on the particle size distribution.

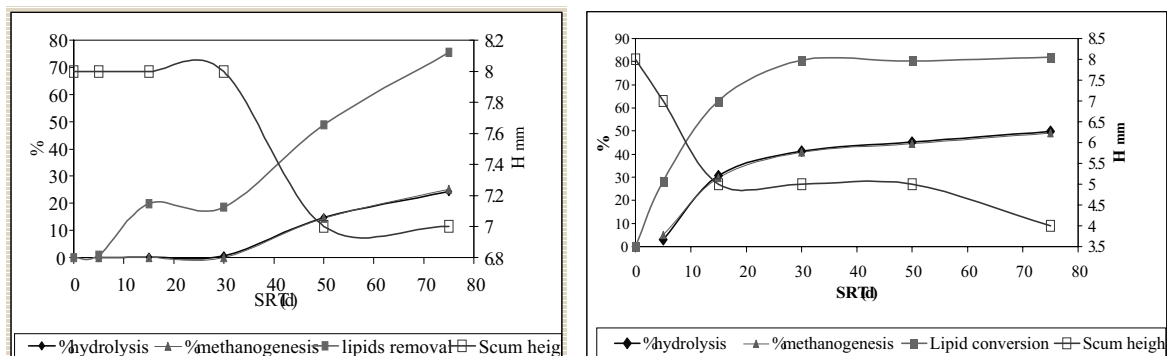


Figure (4): Scum forming potential in relation to SRT applied in the digestion process as assessed at 15°C and 25°C. Left: 15°C; Right: 25°C.

Effect of SRT and temperature on the SVI and filterability of the sludge. Figure 6 shows the SVI for all reactors grown at different SRTs and temperatures. Figure 7 shows the filterability of the sludge for the different ages and temperatures. The SVI was the same for all reactors except for the reactor operated at an SRT of 75 days and at 25°C, where the settlability of the sludge was worse. The filterability first decreased at 15 days for both temperatures, and then improved. For the reactors operated at 25°C, there is an increase in the filterability at higher SRTs. The major improvement at this temperature was reached at 75 days SRT. For the reactors operated at 15°C, the filterability was in the range of 5-7.5 $\text{g}^2 \cdot \text{m}^{-4} \cdot \text{s}^{-2}$.

Table (3): results of sieve analysis for three different sizes and for all reactors. Values between paranthesis are the standard deviations

SRT (d) and Temp.(°C)	>160 micrometer	90<X<160 micrometer	<90 micrometer
Primary 0d	20.3 (2.02)	17.4 (1.68)	62.4 (1.10)
15d 15°C	22.3 (1.34)	9.6 (0.80)	67.7 (1.90)
15d 25°C	20.4 (0.46)	8.9 (0.64)	70.5 (1.47)
30d 15°C	22.3 (3.82)	9.8 (0.34)	69.8 (3.71)
30d 25°C	21.4 (0.42)	9.1 (0.58)	69.4 (0.34)
50d 15°C	21.9 (0.44)	9.3 (0.60)	68.8 (0.36)
50d 25°C	15.5 (1.02)	9.2 (0.44)	75.2 (1.23)
75d 15°C	----	----	----
75d 25°C*	16.2	9.1	74.8
Primary mixed	21.0 (0.69)	10.48 (1.57)	68.6 (1.50)

GENERAL DISCUSSION

Although there exists some literature considering the conversion of different polymers present in the primary sludge (O’ Rourke, 1968; Miron *et al.*, 2000), it is clear that we are still far beyond the complete understanding of the biological processes taking place, as different results are obtained in each case during the digestion of-more or

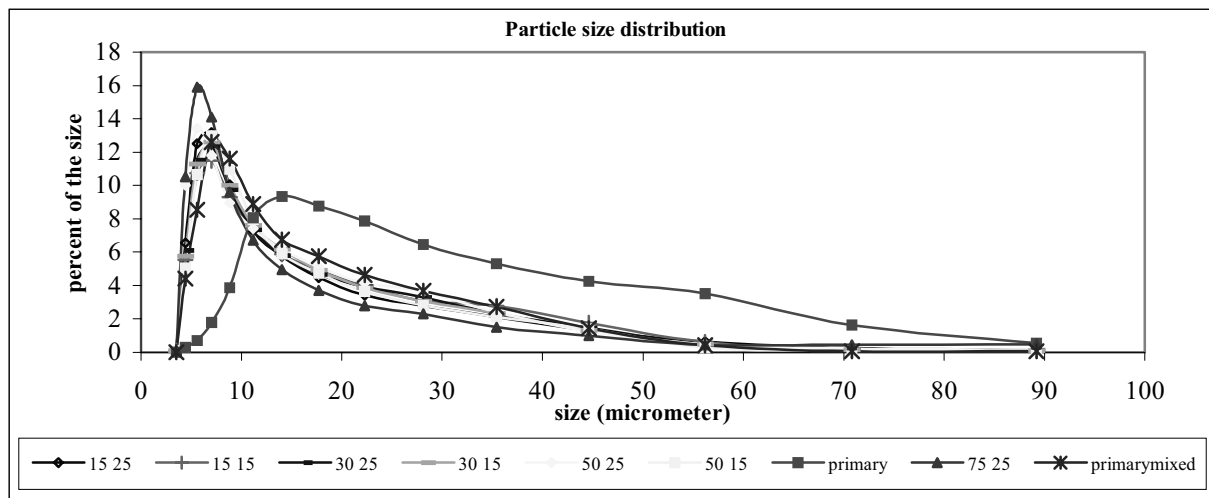


Figure (5): The particle size distribution over the range 3.51-112.4 micrometers for all reactors compared to the primary sludge. The first number in each legend refers to the SRT while the second refers to the temperature.

less- the same feed constituents. The results obtained at 15°C could well be fitted using first order kinetic model, contrary to those obtained at the higher temperature. The poor fit at 25°C was also reported by Miron *et al.*, (2000) in the digestion of primary sludge at 3-15 days SRT. Other models attempt to describe the hydrolysis (known as the rate limiting step in the digestion) as a surface phenomena where the particles are completely covered by bacteria that secrete the hydrolytic enzymes (Hobson, 1987; Vavilin *et al.*, 1996; Sanders, 2001). When the surface based kinetic

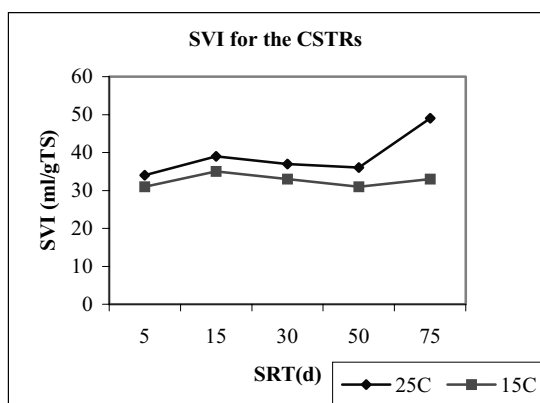


Figure (6): SVI at different SRTs and temperatures.

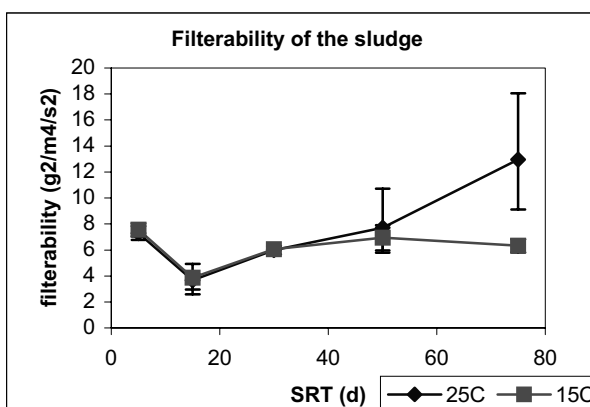


Figure (7): Filterability at different SRTs and temperatures.

models are used, the surface area and the PSD become very important parameters in the conversion process. As the PSD measured in this study was the same for almost all the reactors and at both imposed process temperatures, the CSTRs may face difficulties suggesting them as models for the description of conversion processes for the sludge bed and blanket of the UASB systems. The different mixing conditions may result in a different PSD in a UASB reactor and consequently different hydrolysis rates.

The results of this study revealed the presence of a clear relation between the degree of digestion and the tendency of the sludge to form a scum layer. Especially the degree of lipid's digestion affects the tendency of the sludge to form a scum layer. However, the presence of gas evolution is essential for scum formation. There was also no clear effect for the particle size distribution of the sludge on the formation of scum; all of the reactors (except 50 and 75 days SRT at 25°C) had the same PSD, but different scum forming potential. Moreover, the tendency of the sludge to float could not be related to a certain size, as the reactors operated at 25°C and at SRT of 50 and 75 days had the lowest scum forming potential while their percentage of fine particles was highest.

From the results obtained for the SVI and the filterability of the sludge, it is clear that the PSD is a very important factor affecting these physical characteristics. The SVI was almost the same for all the reactors except for the reactor operated at 75 days SRT and at 25°C. The reason likely can be due to the higher percentage of fine particles in this reactor (Table 3), compared to the other reactors. The same holds for the filterability results. However, the reactor operated at 50 days SRT and 25°C deviates from the general trend, because despite its high percentage of fine particles (75%), its physical characteristics of the sludge were similar to the other reactors.

Based on the above discussion, scum formation in UASB systems could be prevented either by attempting to achieve a 'complete' conversion of lipids (UASB reactor with long SRT) or by preventing the evolution of gas production. The later could be achieved by designing a two stage UASB reactor, where the first stage mainly aims at the entrapment and partial hydrolysis of solids, while the second stage could act as a methanogenic reactor for the final conversion of the hydrolyzed materials from the

first stage. Obviously, the solids entrapped in the first stage generally will need further stabilization in a separate digester. The other option –complete lipid's conversion– could be achieved by applying long SRT to the system allowing for complete conversion of lipids.

CONCLUSIONS

1. The strong effect of temperature on anaerobic sludge digestion was confirmed. Methanogenesis starts at an SRT between 5 and 15 days at 25°C, and between 30 and 50 days at 15°C.
2. Maximum hydrolysis occurs at 75 days SRT and it amounted to 50% at 25°C and 24% at 15°C. Maximum methanogenesis was 51% and 25% respectively at the same conditions.
3. First order kinetics could not describe the hydrolysis of primary sludge COD_{ss} at 25°C, but a good fit ($R^2= 0.96$) for the hydrolysis was found 15°C with a hydrolysis rate constant of 0.005 d⁻¹.
4. The maximum conversion of lipids was 82% and 75% for 25°C and 15°C respectively at 75 days retention time.
5. The scum forming potential of sludge was affected by the digestion process, consequently by temperature and SRT as well.
6. The maximum scum forming potential amounted to 8 mm for sludge digested at 5 days SRT and 15°C.
7. The minimum scum forming potential amounted to 4 mm for sludge digested at 75 days SRT and 25°C.
8. Under the conditions applied in this research, mixing rather than biodegradation was a very important factor affecting the PSD and the physical characteristics of the sludge.

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Chapter 3

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Chapter 4

*Treatment of strong domestic sewage
in a 96 m³ UASB reactor operated at
ambient temperatures*

Two stage versus one stage UASB reactors

TREATMENT OF STRONG DOMESTIC SEWAGE IN A 96 m³ UASB REACTOR OPERATED AT AMBIENT TEMPERATURES

Two stage versus one stage reactor

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ABSTRACT

A 96 m³ UASB reactor was operated for 2.5 years under different conditions to assess the feasibility of treating strong wastewater (average COD_{tot} = 1531 mg/l) at ambient temperatures with averages of 18 and 25°C for winter and summer respectively. During the first year, the reactor was operated as a two-stage system at organic loading rates (OLR) in the range of 3.6-5.0 kgCOD/m³.d for the first stage and 2.9-4.6 kgCOD/m³.d for the second stage. The results of the first stage showed average removals of 51% and 60% for total COD (COD_{tot}) and suspended COD (COD_{ss}) respectively without significant effect of temperature. The performance of the second stage reactor was unstable with poor removal efficiency in the range of 4-10% for the COD_{tot}. The temperature affected the degree of sludge stabilization. During the second year, the first stage in the reactor (60 m³) was operated as a one-stage UASB reactor at half of the previous loading rates. The results showed an average removal efficiency of 62% for the COD_{tot} during summer. The removal efficiency dropped to 51% during winter time. However, the effluent suspended solids were stabilized with VSS/TSS ratio around 0.50 all over the year. Moreover, the sludge developing in the one stage reactor was well stabilized and exerted an excellent settlability. During the last three months of the research, sludge was discharged regularly from the one stage UASB reactor keeping a clear distance of 1.0 m below the gas solids separator (GSS). The results showed no significant improvement in the performance in terms of COD_{tot}.

Based on the results of the COD_{tot} removal and the excellent sludge quality, a one stage UASB reactor operated at OLR of 1.5 kgCOD/m³.d is recommended for the treatment of strong sewage at fluctuating seasonal temperatures in the range of 18-25°C. Combing the UASB reactor with an appropriate physical (-chemical) treatment unit for the removal of effluent particulate matter could supply a total COD removal efficiency in the range of 87-93%.

INTRODUCTION

Anaerobic treatment is becoming more widely accepted for the treatment of domestic wastewater after the knowledge gained during the operation of several municipal anaerobic plants all over the world (Schellinkhout, 1993). It is recognized as a core method for Environmental Protection and Resource Conservation. One of the most

attractive options available for such a treatment is the UASB reactor, which acts as a compact system for removal and digestion of organic components of sewage. Full-scale UASB reactors are in operation in India, Colombia, Brazil and Mexico (Vieira, 1988; DHV Consultants, 1994; Haskoning, 1996; Monroy *et al.*, 2000; Chernicharo *et al.*, 2001; Wiegant, 2001). These UASB reactors are operated at HRTs in the range of 5-19 hrs. The removal efficiencies of COD_{tot}, BOD and TSS achieved are in the range of 51-74%, 53-80%, and 46-80% respectively (Vieira, 1988; Schellinkhout *et al.*, 1993; Seghezzi *et al.*, 1998). The reactors are operated at ambient temperatures in the range of 18-32°C, and organic loading rates in the range of 0.9-3.55 kg/m³.d.

The characteristics of sewage in Jordan with relatively high COD concentration and variations in temperature during the year may affect the treatment efficiency of the UASB reactor. High concentrations of solids may negatively affect the treatment especially at low temperatures when the hydrolysis is slow (Zeeman *et al.*, 1997). However, it has been demonstrated that even at low temperatures, treatment still takes place at OLR of 1.4-1.6 kg/m³.d (Bogte *et al.*, 1993; Lettinga 1996; Elmitwalli *et al.*, 1999). High suspended solids (SS) concentrations may present a risk for scum formation (Wang, 1994), and enhance sludge washout from the reactor (De Smedt *et al.*, 2001). Applying a two-stage anaerobic process, under these conditions, could be an advantageous option, as proposed by Haandel and Lettinga (1994). The first stage can be used for the entrapment and partial hydrolysis of particulate matter, while the second stage is used to digest the hydrolyzed substrate. The sludge of the first stage needs further treatment (Wang, 1994; Elmitwalli, 2002). Wang (1994) operated a two stage UASB reactor for the treatment of sewage with medium strength at moderate temperatures 11-17°C and at different HRTs (2.0, 3.0 and 5.0 hrs). The results showed removal efficiencies in the range of 27-69% and 39-79% for COD_{tot} and COD_{ss} respectively. The first stage performs better than a conventional primary sedimentation tank in retaining SS. Sayed and Fergala (1995) operated a two stage UASB reactor for the treatment of medium strength wastewater at ambient temperatures 18-20°C. They used two compartments for the first stage, which were operated alternatively - two days each- to allow for an additional period for sludge stabilization. They reported that OLRs up to 2.0 kgCOD/m³.d could be applied to the first stage with a maximum removal efficiency of 80% for the coarse materials. Encina *et al.*, (1998) tested a two stage UASB reactor for the treatment of diluted domestic wastewater at a temperature range of 9-26°C. The applied organic loading rates were 1.1-1.5 and 1.0-1.7 kgCOD/m³.d for the first and the second stages respectively. The total removal efficiency of the COD for this system was 40-60% for the entire period of operation.

This article investigates the feasibility of applying UASB reactors in Jordan for the treatment of strong sewage. The main objectives are:

1. To assess the potential of two stage and one stage UASB reactors for the treatment of strong domestic sewage with an average COD concentration around 1500 mg/l and with a high fraction of suspended COD (70-80%).
2. To study the effect of winter and summer temperatures on the performance of the UASB reactor for the two configurations.

3. To assess the sludge characteristics developed in each case, in terms of activity, stability and physical characteristics.

MATERIALS AND METHODS

Pilot reactor description and operational conditions

A 96 m³ two-stage UASB reactor was constructed at the site of Khirbit As-Samra treatment plant north east of the capital Amman. The volumes of the first and the second stages are 60 and 36 m³ respectively. A schematic representation of the reactor is shown in Figure 1. The gas- solids separator (GSS) of the first stage is not symmetrical, viz. with inclinations of 55° with the horizontal axis from one side and 45° from the other. The GSS of the second stage is symmetrical with an inclination of 45°. Each square meter of the bottom of each stage has one inlet point. The wastewater is introduced to the reactor by a 4 inch pipe after passing a coarse screen and a grit chamber. The reactor was started up in June 1997, without the use of inoculum. The two stages contained 14 and 18 gTS/l respectively after four months of operation, however, the methanogenic activity of the sludge - 0.021 gCOD/gVSS.d (at 33°C)- was still low.

The present research was started in January 1999. Table 1 shows the conditions under which the reactor was operated. Winter extends from November until April with average water temperature of 18°C, while summer conditions were considered to prevail during the rest of the year with average water temperature of 25°C. During the first year of operation, the two-stage configuration was tested. During the second year of operation, the one stage configuration was tested. The one stage UASB reactor was considered at steady state conditions starting from April 2000. For the last period of operation, sludge was regularly discharged from underneath the GSS in the one stage UASB reactor keeping a clear distance of 1.0 m below the separator to allow for sludge bed expansion.

Table (1): Operational conditions applied for the two stage and one stage UASB reactors

System		HRT (hrs)	V _{up} (m/hr)	Flow (m ³ /d)	OLR (kg/m ³ .d)	Sludge discharge
Two stage UASB reactor Jan.-Dec. (1999)	First stage	8-10	0.50-0.65	145-180	3.6-5.0	no discharge
	Second stage	5-6	0.76-0.94	145-180	2.9-4.6	no discharge
One stage UASB reactor Apr. 2000-Apr.2001	60 m ³ reactor	23-27	0.19-0.22	53-63	1.4-1.6	no discharge
One stage UASB reactor Apr.- Jul. (2001)	60 m ³ reactor	23-27	0.19-0.22	53-63	1.4-1.6	discharge every 4-7days

Analysis

Gas. The biogas production was monitored daily using a gas meter. The gas composition was analyzed as described in Chapter 3.

Wastewater. The pH and temperature were monitored daily. Grab samples of wastewater for the influent, effluent of the first stage, and effluent of the second stage

were collected twice a week and analyzed for the COD_{tot} , paper filtered COD (COD_{pf}), soluble COD (COD_{sol}), settleable solids, TSS, VSS, and VFA (distillation

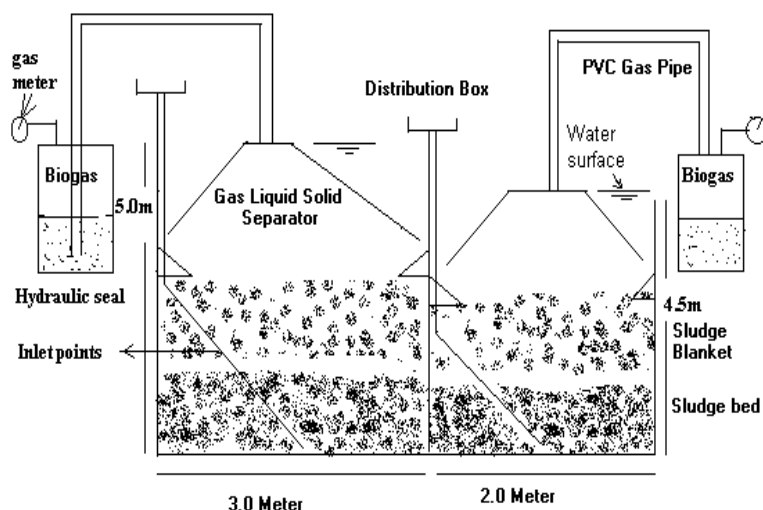


Figure (1): Schematic representation of the 96 m³ UASB reactor.

method) as described in Standard Methods (APHA, 1995). Solids fractionation in TSS, VSS and COD_{pf} tests was performed using Whatman filter papers (No.40). COD_{ss} was considered as the difference between COD_{tot} and COD_{pf} . The COD_{sol} was determined using 0.45-micrometer membrane filters (Orange Scientific). Since grab samples were used to estimate the values of the COD, a correction factor was applied to the test results as described by Haandel and Lettinga, (1994). For this purpose three 24 hrs influent samples were collected during summer and three 24 hrs samples were collected during wintertime.

Sludge. Sludge samples from both stages of the two stage system and from the one stage UASB reactor were collected monthly from different heights over the reactors and analyzed for the total solids (TS) and volatile solids (VS). Composite sludge samples (mixed sample from all depths) were analyzed for maximum specific methanogenic activity (SMA) at 33°C, stability, sludge volume index (SVI) and capillary suction time (CST). The TS, VS, SVI, and CST were determined according to the Standard Methods (APHA, 1995). The specific methanogenic activity (SMA) was determined using serum flasks with 500 ml volume. For each flask, 1.0 gVSS/l of sludge, 1.0 g/l of acetate, 1ml nutrient solution (macro and micronutrients), phosphate buffer, and some yeast extract were added according to Lier, (1995), and the flask was filled to 500 ml with tap water and flushed for 3 minutes with nitrogen to ensure anaerobic conditions. Finally the flask was incubated at 33°C. The gas produced was measured daily by liquid displacement. For sludge stability, the same technique used for the activity test was applied here except that acetate was not added.

Calculations

The percentage hydrolysis, acidification, and methanogenesis were calculated as reported by Elmitwalli *et al.*, (2000). The SRT, the maximum possible removal

Chapter 4

efficiency, the accumulated COD in the reactor and the COD removal efficiency were calculated using the following equations:

$$1. \quad SRT = \frac{VX}{Q_e X_e + Q_w X_w}$$

$$2. \quad \text{Maximum possible removal} = ((COD_{tot \text{ Infl.}} - COD_{pf \text{ Effl.}})/COD_{tot \text{ Infl.}}) * 100$$

$$3. \quad \text{Accumulated COD} = COD_{infl} - (COD_{effl} + COD_{CH4})$$

$$4. \quad \%COD_{rem.} = ((COD_{infl.} - COD_{effl.})/COD_{infl.}) * 100$$

Where: X = sludge concentration in the reactor (gVS/l); V = reactor volume (m³); Q_e = effluent flow rate (m³/d); and Q_w = wasted sludge flow (m³/d); X_e = concentration of sludge washed out with the effluent (gVSS/l); X_w : concentration of discharged sludge (gVSS/l).

RESULTS AND DISCUSSION

Sewage

The characteristics of the wastewater during summer and winter are shown in Table 2. The largest COD fraction consists of suspended COD (69-81%). No significant differences were found between summer and winter wastewater characteristics. Detailed discussion of the sewage characteristics was presented in Chapter 2.

Performance of the two stage and one stage UASB reactor

Two stage UASB reactor

Performance. Table 3 shows the calculated removal efficiencies and the percentage CH₄ recovery for summer and winter conditions over the whole period of operation. The methane content of the biogas in the first stage was 75% and 65% during summer and winter respectively. Considering the first stage, the removal efficiencies of the COD_{tot} and COD_{ss} were 53% and 57% respectively during summer and 50% and 63% respectively during winter. The higher removal efficiency found for the COD_{ss} during winter was likely due to the low gas production. The removal of the colloidal COD (COD_{col}) and soluble COD (COD_{sol}) were distinctly lower during winter than during summer. The maximum possible removal efficiency (equation 2) was 81%. The VSS/TSS ratio for the effluent was 0.62 and 0.67 during summer and winter respectively (Table 4). The effluent VFA concentration accounted for 85 mg/l. Considering the second stage, the average removal efficiencies of the COD_{tot} and COD_{ss} were very low and accounted for 4% and 0.2% respectively during summer and 10% and 9% respectively during winter. However, the maximum possible removal efficiency was 63%. Most of the COD_{tot} was removed in the first stage. The whole system had an average COD_{tot} and COD_{ss} removal efficiencies of 55% and 62% respectively with no significant effect for the temperature, and with a maximum possible removal of 80%.

Hydrolysis, acidification, methanogenesis and SRT. Considering the first stage, the assessed average hydrolysis, acidogenesis and methanogenesis for the whole period of operation are shown in Figure 2. The average calculated hydrolysis was found to be 49% during summer and 16% during winter. The average methanogenesis was found to be 46% during summer and 14% during winter. The calculated SRT was in the range of 26-42 days -depending on the temperature-, and assuming that 85% of the effluent VSS is (X_e), equation (1). In Chapter 3, it was shown that a hydrolysis value of 15% could be obtained at SRT of 50 days during the digestion of primary sludge in CSTR system at 15°C. However, a hydrolysis value of 49% at SRT of 75 days was found during the digestion at 25°C. The values found in the present research for the hydrolysis are similar to those reported for the digestion of primary sludge in Chapter 3 at higher SRTs. In any case, the SRT obtained in the first stage resulted in a considerable amount of gas production (Table 3), which likely affected the removal of solids. Figure 3 shows the mass balance for the COD and the amount of the retained sludge over the whole period of operation. It should be mentioned that some biogas was escaping at the water surface in the first stage, which was not taken into account during the calculations made for the mass balance. When comparing the calculated accumulated solids -equation 3- in the reactor with the ‘constant’ amount of sludge

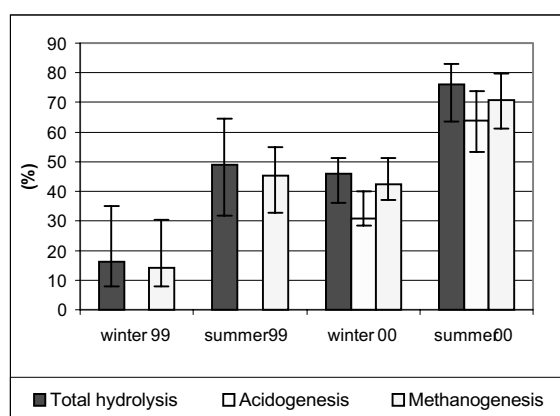


Figure (2): Hydrolysis, acidification and methanogenesis in the first stage of the two stage system and the one stage UASB reactors.

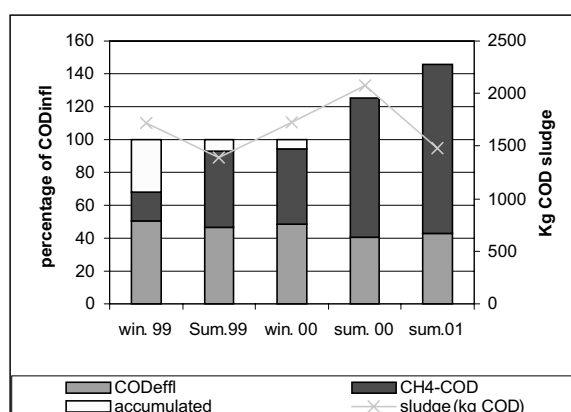


Figure (3): Mass balance for the COD_{tot} in the first stage of the two stage system and the one stage UASB reactors. The COD/VS used in calculating the amount of sludge in kg COD was measured three times during the operation and found to have an average value of 1.6.

measured in the first stage, a non-observed sludge wash out from the system seems to occur. Considering the second stage, the calculations of the SRT, hydrolysis, acidification, and methanogenesis were not possible due to the unstable performance. However, the gas production of the system ranged between 10 and 2 m³/d for summer and winter respectively. It was also impossible to calculate the gas production as l/kgCOD_{rem,d} because of the dramatic fluctuation in the removed COD_{tot}. In general, the low gas production reflects either insufficient sludge age or poorly biodegradable COD in the effluent of the first stage. Table 4 shows the average effluent characteristics for both stages during the whole period of operation. The table shows high VFA concentration in the effluent of the first stage, which suggests that the reason for the poor performance of the second stage was probably the insufficient sludge age.

Table (2): General characteristics of the wastewater of Khirbit As-Samra. Values between brackets present the standard deviation

Parameter	Temp °C	pH	COD _{tot} mg/l	COD _{ss} mg/l	COD _{col} mg/l	COD _{sol} mg/l	TSS mg/l	VSS mg/l	VSS/TSS	VFA as Ac mg/l	Settleable S. (ml/l)
Summer 1999	26 (3.5)	6.88 (0.21)	1505 (354)	1030 (389)	174 (89)	301 (70)	376 (148)	302 (125)	0.72 (0.10)	172 (89)	6.9 (8.5)
Winter 1999	18 (1.6)	7.17 (0.23)	1650 (250)	1383 (221)	157 (90)	236 (49)	417 (142)	373 (182)	0.73 (0.09)	162 (61)	7.0 (5.5)
Summer 2000	25 (3.0)	6.98 (0.13)	1612 (241)	1184 (258)	208 (69)	252 (75)	431 (171)	326 (153)	0.71 (0.12)	183 (72)	11.0 (17)
Winter 2000	18 (2.0)	7.00 (0.16)	1419 (468)	1008 (435)	226 (104)	292 (99)	352 (154)	238 (143)	0.66 (0.14)	194 (57)	5.6 (7.0)
Summer 2001	22 (1.3)	—	1429 (344)	1005 (325)	181 (77)	303 (102)	404 (192)	263 (143)	0.64 (0.08)	169 (20)	5.0 (2.2)

Table (3): Average removal efficiencies of the various COD fractions and the suspended solids in the two stage and the one stage UASB reactors. Values between brackets present the standard deviation

Period	% removals in the First Stage					% removals in the second stage							
	COD _{tot}	COD _{ss}	COD _{col}	COD _{sol}	TSS	VSS	ICH ₄ /kg COD _{rem-d}	COD _{tot}	COD _{ss}	COD _{col}	COD _{sol}	TSS	VSS
ST (99) Apr.-Nov.	53 (16)	57 (22)	57 (30)	25 (18)	46 (22)	47 (26)	261 (116)	4 (29)	0.2 (54)	3 (64)	33 (26)	4 (57)	3 (65)
WT(99) Nov.-Apr.	50 (13)	63 (12)	2 (45)	-7 (71)	41 (34)	42 (26)	109 (71)	10 (21)	9 (36)	-13 (72)	4 (12)	46 (60)	42 (70)
ST (00) Apr.-Nov.	62 (8)	55 (12)	57 (23)	27 (14)	60 (19)	70 (19)	402 (40)	---	---	---	---	---	---
WT(00) Nov.-Apr.	51 (16)	50 (13)	54 (20)	23 (18)	55 (27)	62 (23)	249 (34)	---	---	---	---	---	---
ST(01) Apr.-Jul.	58 (6)	53 (14)	61 (19)	37 (17)	62 (26)	65 (27)	439 (59)	---	---	---	---	---	---

One stage UASB reactor (No sludge discharge)

Performance. The results presented in Table 3 show that the average COD_{tot} and COD_{ss} removal efficiencies were 62% and 55% respectively during summer time, while they dropped to 51% and 50% respectively during winter. However, 80% of the effluent COD was found in the form of highly stabilized suspended solids with an average VSS/TSS ratio of 0.50 all over the year. The maximum possible removal efficiency was in the range of 87-93%. Moreover, the removal efficiencies of the COD_{col} and COD_{sol} improved significantly during winter compared to the values obtained for the two stage system. It should be mentioned that the COD_{sol} concentration measured for a wastewater sample after running the biodegradability test, (Chapter 2), was found to be 173 mg/l, which means that 81% of the COD_{sol} present in the effluent was not anaerobically biodegradable. The gas production was in the range of 27-37 m³/d. The VFA concentration in the effluent of the first stage during summer was low with an average value of 10 mg/l. During winter, the VFA value increased to a concentration around 50 mg/l.

Hydrolysis, acidification, methanogenesis and SRT. The average total hydrolysis was found to be around 76% and 46% for summer and winter respectively. The assessed average methanogenesis was found to be 71% and 42% for summer and winter respectively. The mass balance shown in Figure 3 for the COD indicates that the removal efficiency of the COD_{tot} was higher than the calculated removal based on grab samples. The mass balance also suggests that the accumulated sludge in the first stage was less than the first period of operation and that sludge wash out remained also limited during both winter and summer. The SRT was calculated to be 137 days for winter and 186 days for summer. The excellent sludge retention in the reactor was sufficient to guarantee a high degree of digestion and sludge stabilization as will be described later.

One stage UASB reactor (With regular sludge discharge)

Discharging sludge from underneath the GSS was expected to improve the removal of solids and the performance of the reactor. However, the results found during this period do not show a real significant increase (t-test at 95% confidence limit) in the removal efficiency of COD_{tot} or COD_{ss}, (Table 3). The effluent COD and the methane production accounted for 35 and 71 kgCH₄_{COD}/d respectively. These values are comparable with the values 38 and 69 kgCH₄_{COD}/d calculated during the second period of operation. The higher degree of methanization as shown in Figure 3 can mainly be attributed to the conversion of the accumulated solids during the previous wintertime. It looks that the applied regular sludge discharge from underneath the GSS was not as beneficial to the performance of the system as expected. A real distinct improved COD_{ss} removal efficiency was not achieved. The effect of regular sludge discharge will be discussed in more detail below.

Sludge characteristics of the two stage and the one stage UASB reactors**Two stage UASB reactor**

The total amount of sludge that was retained in both stages during summer and winter are shown in Figure 4 and Figure 5 respectively. For the first stage, the amount of sludge retained was lower during summer than during winter. The average concentrations of sludge in the first and the second stages were 27 and 17 gTS/l respectively during winter and 20 and 25 gTS/l respectively during summer. The average sludge VS/TS ratio for the first and the second stages were 0.69 and 0.70 respectively during winter and 0.66 and 0.59 respectively during summer. The low VS/TS ratio for the second stage during summer (Figure 5) can be explained when assuming that the sludge accumulating in this stage consists mainly of sludge rinsed out from the first stage with the effluent. The results of the VS/TS of the sludge profile at heights of 3.5 and 4.0 m from the bottom of the first stage (Figure 6) showed an average value of 0.60 during summer.

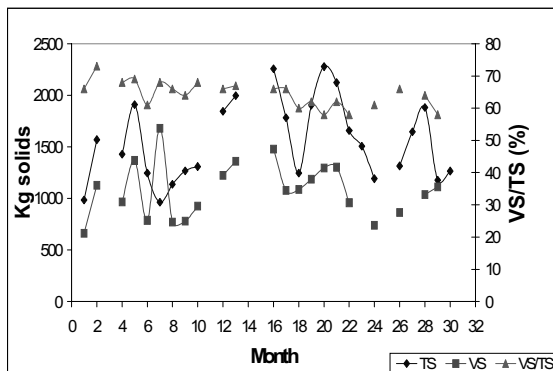


Figure (4): Total amount of sludge in the first stage of the two stage and the one stage UASB reactors.

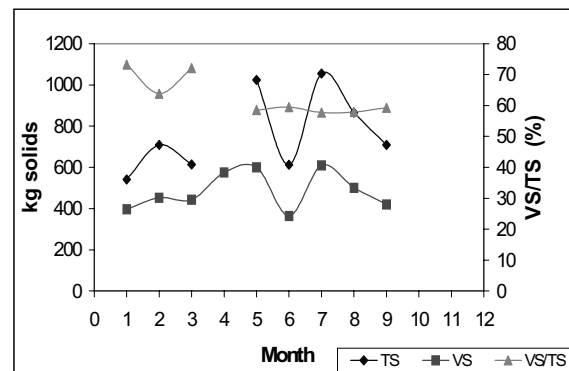


Figure (5): Total amount of sludge in the second stage in the two stage UASB.

The sludge bed height, which is considered as the height with sludge concentration in the range of 80- 90 gTS/l (Heertjes *et al.*, 1978; Bolle *et al.*, 1986) was less than 0.5 m all over the operational period. Sludge concentrations in the range of 72-154 gTS/l were found for the sludge bed. A transition zone between the sludge bed and sludge blanket existed and extended for the upper 1.5 m with sludge concentration in the range of 20- 50 gTS/l. The rest consisted of a blanket with a maximum concentration of 15 gTS/l.

Figure 8 shows some of the physical characteristics of the sludge for both stages. The SVI of the sludge in the first stage reactor ranged from 3.2 ml/gTS at the bottom of the reactor to 10.0 ml/gTS underneath the GSS. For the second stage reactor, the range was 5.0-11.0 ml/gTS. The filterability of the sludge of the first stage was in the range 4-25 g²/m⁴/s² with the highest value at the bottom of the reactor. During the operation, a thick scum layer developed in the first stage reactor at the water-air interface outside the GSS. The scum persisted during the whole period of operation. The layer was thicker (70 cm) during wintertime compared to summer (30-50 cm). It caused a sludge profile inversion at the top of the first stage reactor. The average

concentration of the sludge in the layer was in the range 140-240 gTS/l (not included in Figure 4), which forms almost 15-25% of the total amount of sludge present in the reactor. It was decided to leave the layer for further investigation and analysis. Table 5 shows the composition and characteristics of the scum layer and the sludge of the first stage reactor and the one stage UASB reactor. The results show that the lipids content of the scum varies from 0.75 to 2.0 times the lipids content of the sludge. Moreover, the results of the specific methanogenic activity test show that both the sludge and the scum had the same activity. The stability test results also show the same range of values for both the scum and the sludge. The filterability of the scum was measured once and found to be $25 \text{ g}^2/\text{m}^4/\text{s}^2$, which is in the range of values reported for a well-thickened sludge.

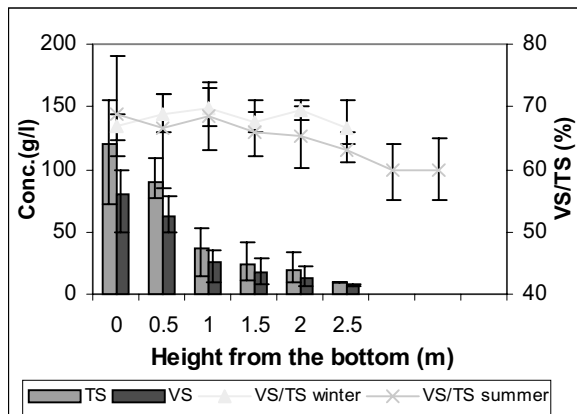


Figure (6): Sludge profile in the first stage of the two stage UASB reactor.

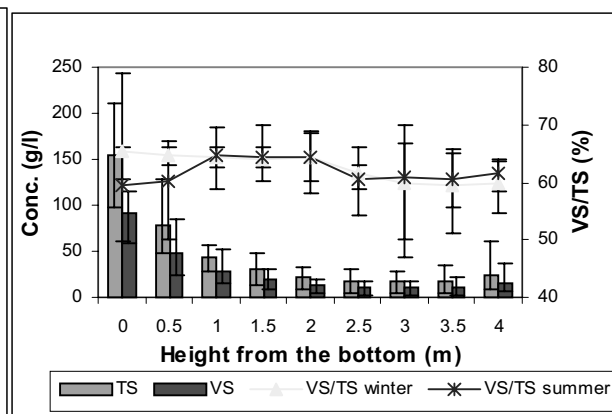


Figure (7): Sludge profile in the one stage UASB reactor.

One stage UASB reactor (No sludge discharge)

The average sludge concentration was 33 gTS/L during winter and 29 gTS/L during summer (scum not included), indicating a higher sludge hold up as compared to the first operational period. The sludge profile shows a thicker sludge bed with sludge distribution similar to those obtained during the first period of operation, Figure 7. The scum production was not affected by lowering the organic loading rate. Considering the physical characteristics of the sludge (Figure 8), the filterability had improved significantly, but, the SVI did not change. The results of the specific methanogenic activity tests performed monthly on sludge samples showed a lag phase of more than two weeks before gas production started, Figure 9. The tests were conducted on seven composite sludge samples obtained during seven months (one sample each month), and it was found that five samples showed a lag phase. The results of the stability test presented in the same figure showed a very low gas production. The occurrence of a lag phase possibly can be attributed to factors like (i) lower amount of viable microorganisms in the sludge when operating the system at very long SRT (ii) higher production of soluble microbial products compared to the first period of operation. The formation of such compounds was reported (Kuo and Parkin, 1996). These compounds might limit the bioavailability of micronutrients to the bacterial cells and - as a result - adversely affect the activity of the bacterial

Table (4): General average characteristics of the effluents of the first and the second stage. Standard deviations are presented between brackets

Item	Two stage reactor		One stage reactor	One stage reactor with sludge discharge
	Concentration (mg/l)		Concentration (mg/l)	Concentration (mg/l)
	Effluent1	Effluent2	Effluent1	Effluent 1
VFA (S)	79(39)	---	10(4)	8(4)
VFA (w)	90(34)		50(26)	
Settable S* (S)	2.5(2.3)	2.6(2.2)	0.7(0.7)	---
Settable S* (w)	2.3(2.5)	2.4(2.6)	1.3(1.8)	
TSS (S)	234(104)	250(197)	180(108)	154(56)
TSS (w)	393(178)	213(156)	182(113)	
VSS (S)	146(77)	169(150)	113(94)	97(68)
VSS (w)	256(147)	190(158)	124(67)	
VSS/TSS [#] (S)	0.62(0.2)	0.57(0.1)	0.5(0.2)	0.5(0.2)
VSS/TSS [#] (w)	0.67(0.1)	0.56(0.2)	0.5(0.2)	
COD _{tot} (S)	717(253)	685(318)	632(106)	620(127)
COD _{tot} (w)	919(327)	762(193)	816(275)	
COD _{ss} (S)	487(270)	439(299)	518(109)	475(175)
COD _{ss} (w)	527(297)	420(194)	620(182)	
COD _{col} (S)	94(62)	74(28)	98(52)	94(62)
COD _{col} (w)		118(77)	123(78)	
COD _{dis} (S)	239(82)	149(57)	210(66)	211(59)
COD _{dis} (w)	234(75)	222(79)	219(61)	

(*) Settable S: settable solids in ml/l. (#) no units

population (Chudoba *et al.*, 1985). However, based on the measured gas production in the reactor, a sludge activity in the range of 0.03-0.07 gCH₄-COD/gVS.d can be calculated (see Figure 9), and (iii) Due to the low concentration of VFA prevailing in the reactor, the sludge is unable to accommodate the exposure to a shock VFA-concentration as applied in the SMA-test.

One stage UASB reactor (With sludge discharge)

During the first month of this period, 25-30% of the total amount of sludge in the first stage was discharged. The rate of sludge discharge was reduced gradually to 5-15 kgCOD/d depending on the concentration of sludge under the GSS and was discharged every 4-7 days. The concentration of the sludge was in the range of 18-30 gTS/l during this period of operation (lower value during the last month), which is still around the normal solids concentration in UASB reactors. Sludge discharge did reduce the production of scum with a height in the range of 5-15 cm during the last month of sludge discharge. This indicates that there should be an unmeasured scum washout from the reactor in the previous periods, and that discharging sludge from the reactor will result in a more stable performance for the system. The stability of the excess sludge was measured once and found to be 20% after seven weeks of incubation. This value was measured for a sludge sample taken at the beginning of April, which means that the sludge was practically less stabilized because of the preceding winter conditions.

GENERAL DISCUSSION

Two-Stage UASB reactor. The 8 hrs HRT applied in the first stage UASB reactor sufficed well to initiate methanogenic conditions, which especially during summer

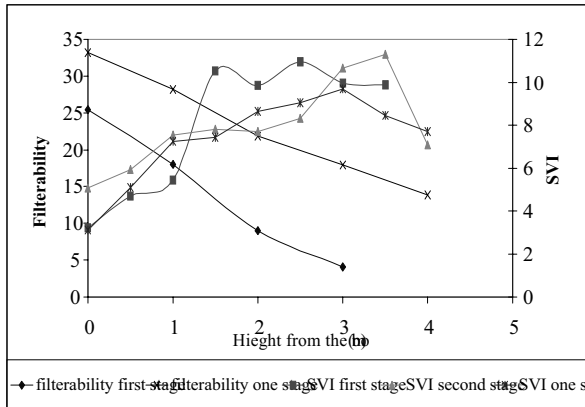


Figure (8): Some physical characteristics of the sludge of the two stage and one stage UASB reactors. Filterability constant in $g^2/m^4/s^2$. SVI in ml/gTS.

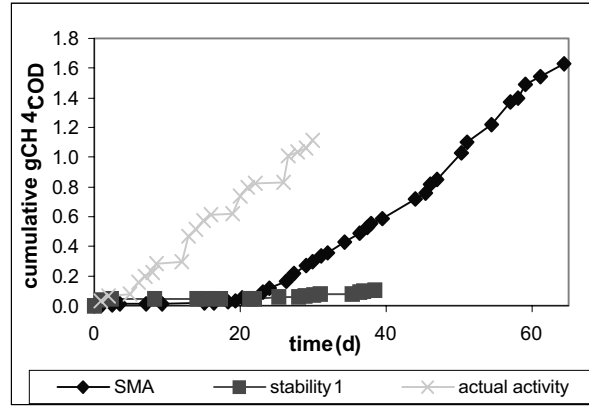


Figure (9): A sample showing the methane production during the SMA, stability tests, and the actual sludge activity in the one stage UASB reactor calculated from biogas measurements.

time resulted in a considerable gas production, and likely due to that in a low removal of the COD_{ss} (57%). This obviously deteriorated the performance of the first stage reactor and also detrimentally affected the stability of the second stage. The washed out solids from the first stage were likely rinsed through the second stage reactor due to the higher up flow velocity prevailing there. Optimisation of the performance of the

Table (5): Comparison between sludge and scum characteristics in the first stage of the two stage and the one stage UASB reactors

	First stage of the two stage reactor		One stage UASB reactor	
	Sludge	Scum	Sludge	Scum
COD (g/l)	----	----	23-45	90-244
COD/VS	----	----	1.42-1.95	
VS/TS % ¹	61-72	55-71	57-66	50-65
Lipids (gCOD/l)	----	----	7-10	22-149
Carbohydrates (gCOD/l)	----	----	4-6	3-15
Proteins (gCOD/l)	----	----	7-17	25-42
Activity $gCH_4-COD/gVSS.d^2$	0.10-0.15	0.07-0.17	Lag phase	Lag phase
Stability $gVS_{degraded}/gVS (%)^1$	12-41	11-63	6-11	7-15
Density (kg/m^3)	----	----	1.01-1.04	0.99
Potential scum height* (mm)	----	----	6.0	6.0

(*) Method described in chapter (3). (1) The higher value is the average for wintertime. (2) The higher value is the average for summer time

system by lowering the HRT to values less than 8 hrs is obviously limited in view of the maximum allowable superficial liquid up flow velocity, which should not exceed 0.5 m/hr. Moreover, in case the first stage reactor would mainly serve for entrapping,

hydrolysing and acidifying suspended solids (as intended in the so called phase reactors), it would be needed to keep the biogas production at a minimum. This would imply a significant lowering of the SRT. However, it is quite questionable to pursue a complete phase separation, independent on the question whether or not this would be possible. As shown in Figure 10, high biogas production will occur around values of SRT where phase separation of the acidogenesis and methanogenesis may occur – around (5-15) days at 25°C- (Chapter 3)-. Controlling the SRT (by sludge discharge) at such narrow span is practically very difficult, and consequently conditions for a minimum biogas production hardly can be achieved (at a maximum removal of the SS). Another potential problem to be faced in the operation of a high loaded first stage UASB reactor concerns the relatively heavy accumulation of substrate ingredients in the reactor. This sometimes could be detrimental for the stability of the anaerobic treatment process. So for instance, solids accumulation might reinforce sludge flotation and it might lead to a higher loss of active biomass as reported by Sayed (1987) during operating a UASB reactor at a space load of 5.0 kgCOD/m³.d. In any case, the application of a two stage UASB reactor needs to be combined with a supplementary sludge digester, because the sludge produced in the first stage reactor generally will need further stabilization, especially when the system is applied at lower ambient temperatures as was clearly shown in the present research. Obviously such a supplementary digester makes the treatment system somewhat more complicated and less attractive for the region.

One Stage UASB reactor. The simplicity of operation of an one stage conventional UASB reactor for treatment of raw sewage and the high degree of sludge stabilization that can be achieved all over the year comprise the major advantages of the one stage UASB reactor. Combining the UASB reactor with a proper physical (-chemical) TSS-separation unit for the removal of washed out COD_{ss}, will provide 87-93% removal efficiency for the COD. An attractive option for a second step could be the application of a filtration unit as proposed by Elmitwilli *et al.*, (2002). The VS/TS ratio of the effluent of the UASB reactor was around 0.50 (during both summer and wintertime) indicating well-stabilized solids and emphasizing the need for only a physical separation unit. The sludge accumulated during winter (with stability average value of 11 gVS_{degraded}/gVS) was digested during the following summer period. Only 6-11% of

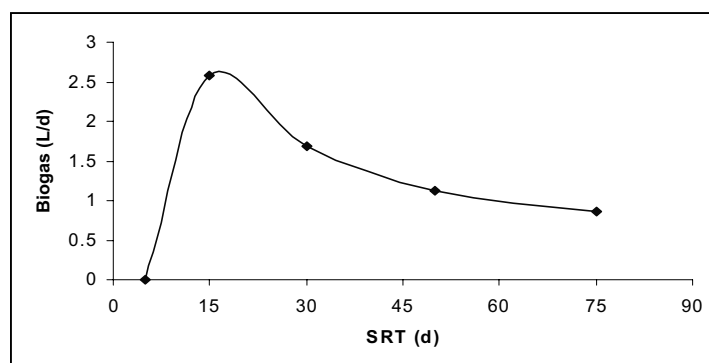


Figure (10): Relation between the SRT and the biogas production during the operation of 5.5l CSTR's (chapter 3) at 25°C.

the sludge was degraded after two months of incubation at 30°C, indicating a highly stabilized sludge. Haskoning (1989) reported that the biogas production rate reaches its endogenic level at about 0.003 gVS_{degraded}/gVS.d. Comparing this value with the results obtained in this research, 0.0012-0.0022 gVS_{degraded}/gVS.d, suggests that the reactor was slightly over designed and that the HRT could be lower. In practice, this reactor could be equivalent to a combination of primary sedimentation tank, aeration tank, and a digester in a conventional activated sludge treatment plant, taking into account the energy required for operating these high technology systems.

CONCLUSIONS AND RECOMMENDATIONS

1. Operation of a two-stage UASB system under high loading rates on the strong sewage of Khirbit As-Samra (i.e. HRT= 8-10 and 5-6 hrs for the first and the second stages respectively, OLR= 3.6-5.0 and 2.9-4.6 kg/m³.d) resulted in average removal efficiencies of 51% and 57% for the COD_{tot} and COD_{ss} respectively during summer and 49% and 63% respectively during winter in the first stage. The performance of the second stage was unsatisfactory.
2. Although the volatile fatty acids present in the effluent of the first stage (during the first period of operation) were not low with values around 85 mg/l, the second stage did not show significant consumption, which might be due to lower SRT than needed for methanogenesis. The amount of gas production was much lower compared to the first stage.
3. The sludge developed in the first stage of the two-stage UASB system has high specific methanogenic activities of 0.10-0.15 gCH₄-COD/gVSS.d at 33°C. The temperature affected the degree of stabilization of the sludge with VS/TS values of 0.66 during summer and up to 0.72 during wintertime.
4. A one-stage UASB reactor operated at loading rates in the range of 1.5-1.8 kg/m³.d (average HRT=24 hrs) resulted in 87-93% maximum COD removal efficiency. The VS/TS ratio in the effluent was around 50% indicating very well stabilized solids. Moreover, 81% of the COD_{sol} present in the effluent was non biodegradable.
5. Keeping a clear distance of 1.0 m underneath the GSS did reduce the scum formation and resulted in a more stable reactor's performance.
6. The sludge developed in the one-stage UASB reactor was stabilized with VS/TS ratio in the range 0.58-0.65 depending on the temperature. Moreover, the results of sludge stability showed that the reactor was slightly over designed and that higher loading rates could be applied to the system. The physical characteristics of the sludge showed a very well settleable and filterable sludge.

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Chapter 5

*Treatment of strong domestic sewage
using a two stage AF/UASB system
and a one stage UASB reactor*

TREATMENT OF STRONG DOMESTIC SEWAGE USING A TWO STAGE AF/UASB SYSTEM AND A ONE STAGE UASB REACTOR

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ABSTRACT

An anaerobic filter (AF) in a two-stage AF/UASB system and a one stage UASB reactor were tested for the treatment of strong sewage with an average COD_{tot} concentration around 1300 mg/l at an ambient temperature of 24±1°C. The AF was used mainly for the removal and partial hydrolysis of the COD_{ss} to produce an effluent that can be treated in a methanogenic UASB reactor. It was operated at an organic loading rate (OLR) of 8.5 kgCOD/m³.d and an up flow velocity of 0.57 m/hr. The results showed average removal efficiencies of 39%, 71% and 75% for the COD_{tot}, COD_{ss} and TSS respectively. Acidification occurred in the AF resulting in an increase of the VFA/COD_{sol} ratio from 33% in the influent to 62% in the effluent, which is advantageous to a subsequent UASB reactor. The discharged sludge had an average VS/TS ratio of 68% indicating a sludge, which needs further stabilization. The performance of the AF depended on the efficiency of sludge discharge. A maximum COD_{ss} removal of 93% was found for the clean media. The one stage UASB reactor was operated at OLR of 1.5 kgCOD/m³.d. The results showed average removal efficiencies of 57%, 66%, and 64% for the COD_{tot}, COD_{ss}, and TSS respectively. The calculated sludge residence time in the UASB reactor was in the range of 136-260 days, which guarantees a high degree of stability. Discussion of the two different anaerobic configurations for strong sewage treatment is presented for summer, but also for winter conditions based on calculations made for the expected performance at lower temperatures.

INTRODUCTION

Anaerobic wastewater treatment is considered as a very simple and energy saving process. In Jordan, as one of the Middle East countries, the conventional water resources are scarce and there is an urgent need for the utilization of unconventional resources like wastewater. The anaerobic wastewater treatment offers potentials in terms of resource conservation (ammonia and phosphorus) for the reuse in agriculture. One of the most attractive anaerobic treatment systems is the UASB reactor. This reactor had been widely used for the pre-treatment of industrial wastewater since it was developed in the seventies (Letting *et al.*, 1980). The system was also successfully introduced as a full-scale application for the pre-treatment of low strength domestic sewage in some tropical regions (Vieira, 1988; DHV Consultants, 1994; Haandel and Lettinga, 1994; Haskoning, 1996; Monroy *et al.*, 2000; Chernicharo *et al.*, 2001; Wiegant, 2001). However, very limited information is

available about the applicability of the system in countries with strong domestic sewage (average $\text{COD}_{\text{tot}} = 1300 \text{ mg/l}$) and fluctuating temperatures ($18 - 25^\circ\text{C}$) like some regions in the Middle East. Although, the technology is very simple, the optimum process performance is still not known. It was reported that high concentrations of solids might negatively affect the treatment, especially at low temperatures when the hydrolysis may become limiting (Zeeman *et al.*, 1997). High suspended solids (SS) concentrations may also present a risk for scum formation (Wang, 1994), and may enhance sludge washout from the reactor (De Smedt *et al.*, 2001). The removal of solids prior to the application of a UASB unit could be advantageous for improving the performance of the UASB reactor (Wang *et al.*, 1994; Sayed *et al.*, 1995; Encina *et al.*, 1998). Seghezzi *et al.*, (2001), noticed granulation of sludge when treating domestic sewage with a low COD_{ss} concentration of around 130 mg/l . They operated a conventional UASB reactor for the treatment of presettled sewage at an HRT of 5 hrs and at temperature conditions in the range of $16-25^\circ\text{C}$. In chapter 4, results obtained during the operation of two stage and one stage UASB reactors for the treatment of strong domestic sewage in Jordan are presented. These results show that the removal efficiency of the COD_{tot} in the two stage UASB reactor was around 50% for the first stage during both summer and wintertime when operating the reactor at high loading rates in the range of $3.5-5.0 \text{ kg/m}^3\cdot\text{d}$. The performance of the second stage was unstable with very low removal efficiencies. The one stage UASB reactor removed 62% and 51% of the COD_{tot} during summer and wintertime respectively at a loading rate of $1.5 \text{ kg/m}^3\cdot\text{d}$. The COD_{ss} constituted about 80% of the total COD of the reactor's effluent during both summer and wintertime.

Considering a staged reactor, it is expected that the performance could be improved by improving the removal of solids in the first stage. According to Elmitwalli *et al.*, (2000), the application of an AF operated at high loading rates could be an attractive option for the removal of solids prior to the treatment in a UASB reactor. However, the success of a high loaded AF in removing solids will depend on the regular discharge of excess sludge and minimization of gas production (low SRT) to avoid the washout of solids. Reticulated polyurethane foam (RPF) was found to be an excellent filter media for the entrapment of solids and colonization of bacteria, even at low temperatures (Fynn and Whitmore, 1982; Huysman *et al.*, 1983; Elmitwalli *et al.*, 2002). Elmitwalli *et al.*, (1999) operated an up flow AF at 13°C and at HRT of 4 hrs, using RPF sheets as a filtering media. The sheets were oriented vertically with no space in between. The results showed an average COD_{ss} removal efficiency of 82%. However, the excess sludge produced in the reactor was unstabilized and therefore needs further digestion. For the purpose of comparison, it was important to investigate the performance of a one stage UASB reactor for the treatment of domestic sewage parallel to AF using reactors of the same scale.

The main objective of the present research is to reconsider the design of a two stage UASB reactor treating strong domestic sewage by optimizing the removal of solids in the first stage using reticulated polyurethane foam as a filter media prior to the application of a methanogenic UASB second stage reactor. A comparison was made with a conventional UASB reactor tested at OLR of $1.5 \text{ kg/m}^3\cdot\text{d}$ for the removal of the various distinguished COD fractions. Based on estimations made for the performance of the two anaerobic reactor's configurations during wintertime, the appropriate system for the treatment of relatively strong sewage is discussed.

MATERIALS AND METHODS

Hypothesis

Considering the Two-stage AF/UASB reactor, the success of the system depends mainly on the efficiency of the first stage in removing and entrapping solids. A removal of 82% of the COD_{ss} fraction -as reported by Elmitwalli *et al.*, (2000)- from a strong sewage will result in a reduction of the loading rate applied in the subsequent UASB unit and consequently will reduce the total volume needed for the treatment. The AF likely will achieve some acidification of the wastewater, which is advantageous for the second step UASB reactor. The same HRT applied by Elmitwalli *et al.*, (2000) was used in this research, however, more frequent sludge discharge was taking place in order to keep the gas production at a minimum. The operational conditions applied to the AF and the UASB reactors are shown in Table 1.

Experimental Setup

Two pilot reactors were built at the site of Abu-Nusier treatment plant, 7 kms north of the capital Amman. The plant treats 100% domestic wastewater from the neighboring complex with a population of around 17,000 capita. The tanks used in the experiment were identical, with a diameter of 0.81 m and an effective height of 2.29 m, (Figure 1). Each tank has five sampling points distributed over the height of the reactor. The filter media used in the AF consisted of reticulated polyurethane foam (RPF) oriented vertically as described by Elmitwalli *et al.*, (2000). The characteristics of the RPF used in the experiment are summarized in Table 2. No gas was collected from the AF since very low gas production was expected. Sludge was discharged from the AF at 4 days interval. The UASB reactor contains a conical gas solids separator (GSS) at the top of the tank with a height of 50 cm. The gas produced was collected in gas bags with a capacity of 10 liters/bag, which are changed after being filled. The gas production is determined by emptying the gas bag via a vacuum pump connected to a wet gas meter. The reactors were continuously fed with fresh wastewater from the main channel supply to the treatment plant. The wastewater passes a screen and a grit chamber before it enters the reactors. The wastewater was introduced at the bottom of each tank using two Masterflex peristaltic pumps. The UASB reactor was inoculated with sludge from the 60 m³ reactor treating domestic sewage located at the site of Khirbit As-Samra treatment plant 50 kms to the east of the Capital Amman. The TS, VS, and stability of the inoculum were 29 g/l, 17 g/l, and 0.06-0.11 gVSS_{biodegraded}/gVSS respectively. Before the start of the experiment, the characteristics of the wastewater were monitored and composite samples were taken four times, each during winter and summer conditions. Grab samples were used for monitoring the performance of the two reactors. Assessment of the AF reactor performance was considered starting from the first day of operation. The UASB reactor was considered in a start up period during the first month of operation (32 days), while the rest of the operational period (55 days), when the reactor had a stable effluent characteristics, was considered as the 'steady state' operation.

Analysis

COD, Settable Solids, TSS and VSS of the wastewater, and the TS and VS of the sludge were analyzed according to the standard methods (APHA, 1995). COD_{ss} was

Table (1): operational conditions of the AF and the UASB reactors

Parameter	UASB	AF
HRT (hrs)	23	4.6
O.L.R (kg/m ³ .d)	1.47	8.5
V _{up} (m/hr)	0.10	0.57
Temp (°C)	24	24
Sludge discharge frequency	---	Every 4days
Operational periods (d)	87	45

Table (2): Characteristics of the RPF used in the experiment. After Elmitwalli *et al.*, (2000)

Parameter	Value
Sheet width (cm)	8
Total sheet thickness (mm)	20
Base thickness (mm)	10
Knob thickness (mm)	10
Specific surface area (m ² /m ³)	500
Density (kg/m ³)	19-22
Number of pores (pore/inch)	7-15
Pore size (mm)	2.5

considered as the difference between the total COD (COD_{tot}) and the paper filtered COD (COD_{pf}). All the paper filtration of wastewater samples was performed using Whatman filters (No.40). The COD_{sol} was considered as the fraction passing 0.45-micrometer membrane filters (Orange Scientific). NH₄⁺-N was measured according to (APHA, 1995; 4500F-NH₃). The volatile fatty acids (VFA) concentrations were

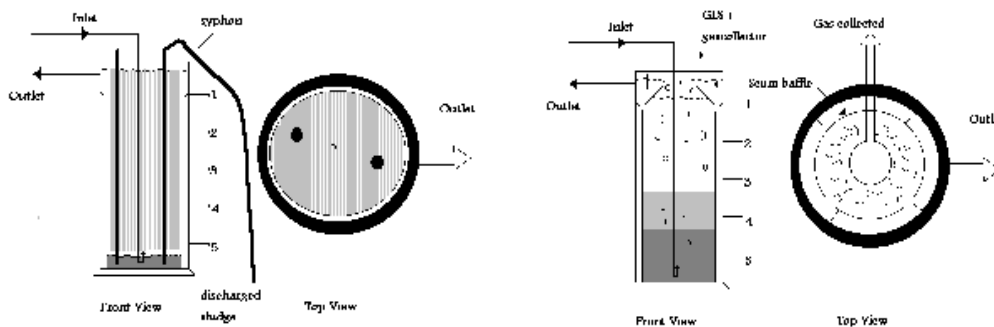


Figure (1): Schematic diagram of the reactors. Left: front and top views of the anaerobic filter; right: front and top views of the UASB reactor.

determined using gas chromatograph HP model 5890A equipped with a 2mX4 mm-glass column with supelcoport (11-20 mesh) coated with 10% Fluorrad FC 431. The temperature of the injector, the column and the FID were 200, 130 and 280°C respectively. The samples were membrane filtered and 1ml of each filtrate was preserved with formic acid before the measurements. The total Kjeldahl nitrogen and the lipids were determined according to the standard methods (APHA, 1995). For the lipids, the sohxlet extraction method by petroleum ether was used (APHA, 1995). Diatomaceous earth solution (10 g/l) was used as a filter medium. 100 ml of this solution was paper filtered and the earth material was used for the adsorption of lipids. Carbohydrates were determined by phenol-sulfuric acid method with glucose as a standard (Bardley *et al.*, 1971). The methane content was analyzed using a Philips PU

Chapter 5

4500 gas chromatograph with thermal conductivity detector. The column is packed with Porapak Q and the carrier gas is helium. The temperatures of the injector, column and detector are 72, 72, and 200°C respectively. The COD fractions of the sludge samples were analyzed according to Miron *et al.*, (2000). The SVI and the CST of the sludge were determined following the procedure described in the standard methods (APHA, 1995). The specific methanogenic activity (SMA) was determined using serum flasks with 500 ml volume. For each flask, 1.0 gVSS/l of sludge, 1.0 g/l of acetate, 1ml nutrient solution (macro and micronutrients), phosphate buffer, and some yeast were added according to Lier, (1995) and the flask was filled to 500 ml with tap water and flushed for 3 minutes with nitrogen to ensure anaerobic conditions. Finally the flask was incubated at 33°C. The gas produced was measured daily by liquid displacement. The biodegradability of the wastewater was determined in triplicates using 0.5 l serum flasks. Each flask was filled up with a 24 hrs composite wastewater sample. No inoculum was used in the test. The same macro and micro-nutrient, yeast, and buffer used for the methanogenic activity test were also used for the biodegradability test. The bottles were also incubated at 33°C for five months.

Assumptions

1g lipids=2.91gCOD (Sayed, 1987); 1g protein=0.16gNkj=1.5gCOD (Miron et al., 2000); and 1g carbohydrates=1.07gCOD (Sayed, 1987).

Calculations

$$1. \quad SRT = \frac{VX}{Q_e X_e + Q_w X_w} \quad \dots (1)$$

Where: V is the effective reactor's volume (m^3); X is the VS concentration of the sludge in the reactor (kg/m^3); Q_e is the flow rate (m^3/d); Q_w is the flow rate of the sludge discharged; X_e is the VSS concentration in the effluent (kg/m^3); and $Q_w X_w$ for the AF was calculated as total amount of sludge discharged during the operational period as ($kgVS$) divided by the operational period in days.

$$2. \quad SRT_{\min AF} = \frac{VX}{Q_e X_e + Q_{w1} X_{w1}} \quad \dots(2)$$

Where: $Q_{w1}X_{w1}$ = amount of the discharged sludge (kg) –assuming discharge of all accumulated solids in the reactor- over the period of operation divided by the duration of operation in (days).

$$3. \quad H(\%) = \left(\frac{COD_{CH_4} + COD_{diseffl} - COD_{di\ sin\ f}}{COD_{tot\ inf} - COD_{di\ sin\ f}} \right) * 100 \quad \dots(3)$$

$$4. \quad A(\%) = \left(\frac{COD_{CH_4} + COD_{VFAeffl} - COD_{VFA\ inf}}{COD_{\inf} - COD_{VFA\ inf}} \right) * 100 \quad \dots(4)$$

$$5. \quad M(\%) = \left(\frac{COD_{CH_4}}{COD_{\inf l}} \right) * 100 \quad \dots(5)$$

RESULTS AND DISCUSSION

Wastewater. The characteristics of the wastewater of Abu- Nusier are shown in Table 3. The average temperatures were 25 and 16°C for summer and winter respectively. The wastewater is characterized by high concentration of COD with an average value of 1292 mg/l during summer and 1183 mg/l during wintertime. 50-60% of the COD is found in the suspended form. COD_{ss}/COD_{tot} ratio, Settable solids, and VFA concentrations are lower for the influent of Abu- Nusier compared to those of Khirbit As-Samra treatment plant reported in Chapter 4. Detailed discussion of the wastewater characteristics can be found in Chapter 2.

Performance of the anaerobic filter (AF). Figure 2 shows the removal efficiencies of COD_{tot} and COD_{ss} for the AF during the experimental period. Table 4 shows the detailed results for both reactors with the influent and effluent characteristics. The average removal efficiencies of the COD_{tot} and COD_{ss} , of the AF were 39% and 71% respectively, which are considerably lower than the removal efficiencies reported by Elmitwalli *et al.*, (2000) at the same applied HRT. The main reason for the lower performance was the production of biogas, which resulted in the formation of a scum layer. Since the reactor did not contain scum baffles at the top, solids particles were escaping with the effluent, lowering the COD_{ss} removal efficiency. The data presented in Table 4 also show production of colloidal COD, while Elmitwalli *et al.*, (1999), achieved 35% removal efficiency of the colloidal COD fraction during the treatment of domestic sewage at 4 hrs HRT and 13°C. A mass balance made for the COD in the reactor is shown in Figure 3. Since the biogas was not collected in the AF reactor, the missing fraction in the COD balance was assumed to be the produced methane. The calculated hydrolysis, acidification, and methanogenesis were 44%, 42%, and 30% respectively. The SRT calculated using equation (1) was around 19 days based on an average sludge concentration of 15 g/l (Elmitwalli *et al.*, 2000) and an average sludge discharge rate of 0.168 kgVS/d (Table 5). The results obtained here are in agreement with those reported in Chapter 3 in the digestion of primary sludge in CSTRs at 25°C.

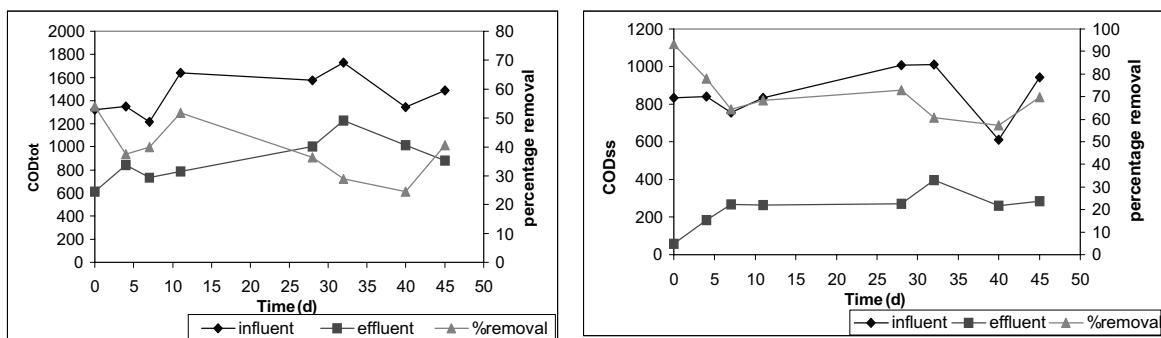


Figure (2): Influent and effluent values and the removal efficiencies of the COD_{tot} and COD_{ss} during the operation of the AF. Left: COD_{tot} ; Right: COD_{ss} .

The results obtained show values in the range of 31-41%, 33-43%, and 30-41% for hydrolysis, acidification, and methanogenesis at sludge residence time in the range of 15-30 days. The VFA/ COD_{sol} ratio increased from 33% in the influent to 62% in the

Table (3): average characteristics of the influent for both Abu Nusier and Khirbit As-Samra treatment plants

Infl.	Parameter	pH	COD _{tot} mg/l	COD _{ss} mg/l	COD _{col} mg/l	COD _{dis} mg/l	TSS mg/l	VSS mg/l	Sett.S ml/l	Lipids ¹ mg/l	Prot. ¹ mg/l	NH ₄ ⁺ mg/l	Carb. ¹ mg/l	VFA ¹ mg/l
Abu-Nusier Summer	Average	7.39	1292	760	119	412	364	281	6.0	421	543	43 ²	131	120
	St. Dev.	0.08	108	58	33	131	27	33	1.1	66		22		5
Abu-Nusier Winter	Average	7.6	1183	608	174	401	420	330	4.5	443	619	43 ²	----	104
	St. Dev.	0.21	152	216	91	30	90	90	1.2	62	100	10		30

(1) Presented as COD values; (2) Water Authority of Jordan (2000).

effluent of the reactor, which is advantageous to a subsequent UASB reactor. The data in Table 5 show the characteristics of the discharged sludge. The concentration of the discharged sludge was in the range of 3.5-10.2 gTS/l. Its average VS/TS ratio was 0.68 indicating unstabilized sludge, which needs further digestion. It also had good settling characteristics with an average SVI of 29 ml/gTSS, while the filterability with an average of $0.011 \text{ kg}^2/\text{m}^4/\text{s}^2$ was low. The later value is lower than that reported by Elmitwalli *et al.*, (2000) and lower than the value reported for primary sludge (Miron *et al.*, 2000).

Performance of the UASB reactor. Figure 4 shows the COD_{tot} and COD_{ss} of the UASB reactor during the operational period. The average removal efficiencies for the COD_{tot} and COD_{ss} were 58% and 65%, respectively. There was also a considerable removal of COD_{col} (Table 4). The same removal for the colloidal fraction was also reported during the operation of the 60 m^3 UASB reactor at Khirbit As-Samra during summer time. The VFA concentration in the effluent of the reactor was 50 mg/l, which is considerably higher than (10 mg/l) obtained in the previous study with a UASB reactor operated at Khirbit As-Samra treatment plant under the same conditions (Chapter 4). The reason could be attributed to mass transfer limitations in the reactor due to the lower up flow velocity with an average value of 0.1m/hr, which is half of the value calculated for Khirbit As-Samra UASB reactor. The biogas produced contained 76.5% methane. Some escape of the biogas was always noticed at the water surface outside the GSS. It was not possible to collect this gas, which made the accurate measurement of gas impossible. Figure 5 shows the sludge profile in the reactor. Most of the sludge was accumulated at the bottom with a concentration in the range of (100-150 g/l). The sludge concentration at a height of 0.45 to 0.95 m from the bottom was in the range 40- 80 g/l. For the rest of the reactor height, sludge concentrations had values less than 2.0 g/l. The calculated average SRT was in the range of 136-260 days, which is considered high and should guarantee the removal of all VFA present in the system. Sludge characteristics are shown in Table 6. The table shows that the sludge is well stabilized with a VS/TS ratio of 61%. The filterability

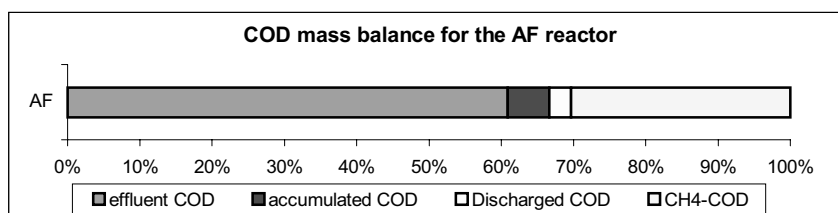


Figure (3): COD_{tot} mass balance over the AF reactor. The COD of the sludge was calculated assuming that $1\text{gVSS}=1.5\text{gCOD}$ (Chapter 4)

had a maximum value of $15 \text{ g}^2/\text{m}^4/\text{s}^2$. The methanogenic activity test showed a lag phase of more than three weeks following the procedure described above. The presence of lag phase did not allow any calculations for the activity. A toxicity of 'high' acetate concentration used in the test was suspected to be the main cause of the lag phase due to different sludge loading rate compared to that imposed in the reactor. Consequently, another experiment was performed to assess the sludge activity under different acetate concentrations, namely, 30, 50, 80, and 100 mg/l. The results showed that in the best case, only 50-60% of the acetate added was consumed after one month of incubation for the lowest acetate concentration used (30 mg/l). This result showed

that the concentration of the acetate used was not toxic for the sludge tested. The occurrence of lag phase was also reported in Chapter 4 for sludge samples obtained in operating the 60 m³ reactor at the same OLR. More research is needed to investigate the reason of the lag phase.

Table (4): Results for the AF reactor and the UASB reactor operated at 24°C under the imposed operational conditions

Parameter	UASB HRT= 23hrs			AF HRT=4hrs		
	Infl. mg/l	Effl. mg/l	removal (%)	Infl. mg/l	Effl. mg/l	removal (%)
COD _{tot}	1412 (155)	602 (126)	58 (9)	1458 (179)	888 (193)	39 (10)
COD _{ss}	830 (146)	304 (114)	65 (12)	855 (134)	248 (97)	71 (11)
COD _{col}	174 (62)	86 (46)	49 (32)	180 (28)	204 (97)	-15 (57)
COD _{sol}	409 (109)	212 (72)	44 (23)	423 (122)	436 (160)	-4 (28)
VFA as COD	129 (15)	50 (7)	—	139 (14)	268 (43)	—
TSS	451 (121)	203 (132)	62 (20)	442 (118)	107 (61)	75 (11)
VSS	332 (110)	85 (46)	72 (17)	344 (105)	65 (51)	80 (12)
VSS/TSS (%)	74 (8.6)	57 (6.5)	—	77 (5.9)	60 (11)	—
Sett. S (ml/l)	10 (2)	1.6 (1.3)	83 (16)	11 (2)	1.2 (1.8)	95 (6.7)

Table (5): Characteristics of the discharged sludge from the AF

Parameter	TS g/l	VS g/l	VS/TS %	Filterability kg ² /m ⁴ /s ²	SVI Ml/g TS	Amount discharged Kg/d
Value	3.5-10.2	2.5-8.1	68	0.011	29	0.168

Table (6): General characteristics of the sludge in the UASB reactor. (*) for sludge at the bottom

Parameter	Value
VS/TS (%)	60
Filterability* g ² /m ⁴ /s ²	15
SVI (ml/gTSS)	13-18

GENERAL DISCUSSION

Although frequently the sludge was discharged from the AF, i.e. with a time interval of 4 days, this discharge rate was not sufficient to prevent the occurrence of methanogenic conditions, mainly due to accumulation of sludge at the bottom of the reactor, which resulted in a relatively high SRT. Calculating the SRT_{min} (equation 2) by efficient discharge of all the sludge present at the bottom of the reactor resulted in a value of 11 days SRT. In fact, this value may still result in a considerable amount of gas production, (Chapter 3), and consequently affect the removal of COD_{ss} . The

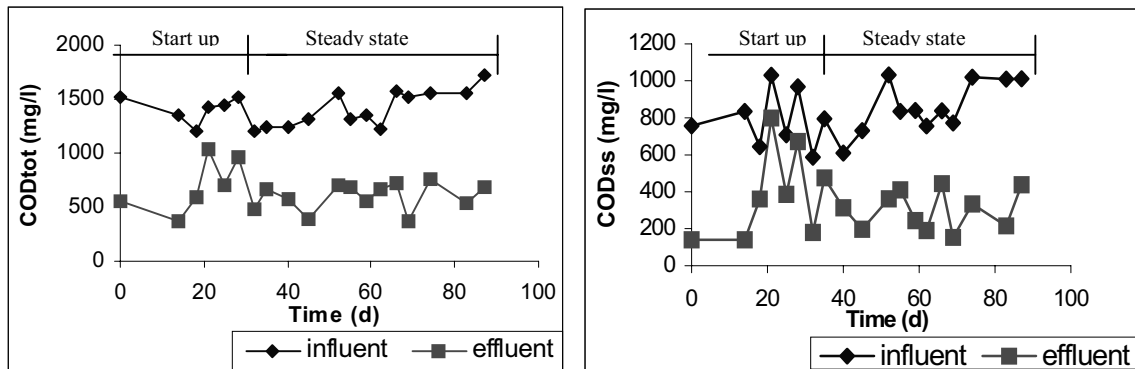


Figure (4): the COD_{tot} (Left) and COD_{ss} (Right) values for the influent and the effluent of the UASB reactor

application of lower HRT could reduce the gas, however, Elmitwalli *et al.*, (2000) reported that the removal of solids at lower HRT may significantly deteriorate. In any case, the AF reactor was able to remove a considerable percentage of the suspended COD (71%), and should supply higher values during winter. It should be mentioned that the reactor was operated for relatively short period of time and problems related to clogging cannot be assessed, however, Elmitwalli, (2000) operated the reactor with the same filter media at 13°C for 140 days without reporting any clogging problems associated with the filter media. Considering the UASB reactor, it can be assumed that the COD_{ss} present in the effluent mainly consists of washed out sludge from the reactor (very low VSS/TSS ratio) and that the reactor is effective in removing incoming COD_{ss} present in the influent. It should be taken into account that the reactor was not filled with sludge, consequently, steady state conditions of operation were not achieved. Moreover, comparing the digestion processes in both systems, it can be easily seen that the very high SRT in the UASB reactor would provide high degree of sludge stabilization. This is not the case for the AF reactor. However, the performance of the UASB reactor will deteriorate during wintertime as reported in Chapter 4, during the operation of 60 m³ UASB reactor at the same OLR, and higher VFA concentrations in the effluent can be expected. Table 7 and Table 8 show some calculations and assumptions made and the expected effluent characteristics for two anaerobic reactor configurations (Two stage AF/UASB reactor and one stage UASB reactor) for the treatment of strong sewage at both summer and winter temperatures.

Looking at the tables, it is clear that operating a two stage AF/UASB reactor at HRT of 4+8 hrs respectively would supply a total COD removal efficiency in the range 70-82% during both summer and wintertime. However, the main disadvantages of this

Table (7): Assumptions and calculations used for effluent quality estimations of different anaerobic reactors configurations

□ AF+UASB reactor operated during summer.

1. The removal efficiencies obtained for the AF in this study for different COD fractions are used.
2. As 70-80% of the COD_{ss} can be removed in the first step, the limiting design parameter for the UASB reactor will be the upflow velocity rather than the SRT (Chapter 1). An HRT of 8hrs could be calculated for the second step UASB reactor based on a design upflow velocity of 0.5m/hr, and a total reactor's height of 4m.
3. The OLR applied to the UASB reactor can then calculated to be $2.66\text{kgCOD}/\text{m}^3\cdot\text{d}$. The SRT is calculated to be 102 days based on equation (2) presented in Chapter (1) and assuming that TSS_{bed} is 70g/l, Y is $0.18\text{gVSS}/\text{gCOD}_{rem}$, and H_s is 1.2m.
4. The removal efficiencies of the COD_{ss} and COD_{col} in the UASB reactor are usually in the range 53-80%, and 50% respectively (chapter2&4). The effluent COD_{sol} will be around 200mg/l (measurement obtained at the end of the wastewater biodegradability test, chapter 4), which limits the removal of this fraction at 54%.
5. The removal efficiency of the COD_{tot} for the second stage UASB reactor will be in the range 53-64% and calculated as the following:

$$\%COD_{tot} = \frac{COD_{tot\,in} - (COD_{ss} + COD_{col} + COD_{sol})_{out}}{COD_{in}} * 100 \quad \dots$$

(5)

□ AF+UASB reactors operated during winter.

1. The removal efficiencies that could be achieved for COD_{ss} and COD_{col} fractions using the AF were obtained from Elmitwalli et al., (1999). They operated an AF at 4hrs HRT and 13°C for the treatment of raw sewage and obtained 82% and 35% removal efficiencies for the COD_{ss} and COD_{col} respectively. No removal of COD_{sol} is suggested as lower SRT value compared to Elmitwalli, (2000) is expected.
2. The SRT in the UASB reactor is calculated to be 143 days using equation (2) presented in Chapter (1) and with the same assumptions presented for summer conditions above.
3. The removal efficiency of the COD_{ss} will be assumed to be in the range of 50-80% as described above. The removal efficiency of the COD_{col} will be assumed 48% as found by Elmitwalli (2000). They reported that the removal efficiency of the COD_{col} improved in the second stage UASB reactor viz. from 24% to 48%, when the suspended fraction of the COD is removed from the sewage. For the COD_{sol} , a value of 200 mg/l as discussed before is expected. The resulting removal efficiency of 47-59% for the COD_{tot} is calculated based on equation (5).

□ Conventional UASB reactor

The removal efficiencies obtained in this study are used in the calculations made for the conventional UASB reactor operated at 23hrs HRT during summer. However, removal efficiencies obtained during operating a 60m^3 reactor at 24hrs HRT and at winter conditions were used to calculate the expected concentrations of the COD fractions in the effluent (Chapter 4). Removal efficiencies of 51%, 50%, and 54%, were obtained for the COD_{tot} , COD_{ss} , and COD_{col} respectively. A value of 172-200mg/l was used for COD_{sol} .

configuration are: firstly, there is a need to operate two extra separate units, one for sludge thickening and one for digestion due to the resulted low sludge concentration produced in the AF reactor. Secondly, a limited removal of the VFA in the UASB reactor during wintertime can be expected (Chapter 4). Interestingly, the COD_{sol} in the effluent of the system constitutes a considerable fraction (50 and 66%) during both

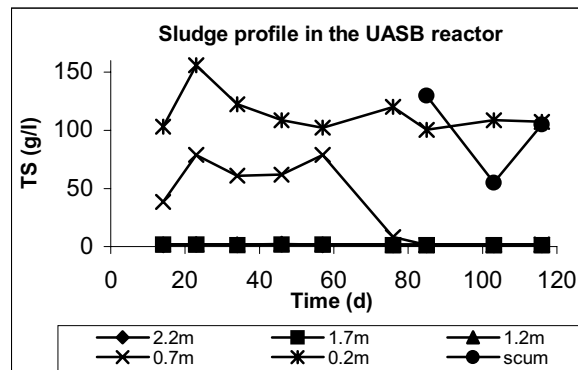


Figure (5): Sludge profile in the UASB reactor

Table (8): Expected and calculated effluent qualities for AF+UASB reactor and a conventional UASB reactor operated at summer and winter conditions

Parameter *	Summer			Winter		
	AF+UASB reactors		Conventional UASB reactor	AF+UASB reactors		Conventional UASB reactor
	AF	UASB		AF	UASB	
HRT (hrs)	4	8	23	4	8	23
COD _{tot}	888	324-419	633-694	633	288-333	689
COD _{ss}	248	50-117	282-415	150	30-75	415
COD _{col}	204	102	79	111	58	79
COD _{sol}	436	172-200	200-284	409	200	172-200

(*) Values are in mg/l.

summer and wintertime. Table 9 shows the Jordanian standards for wastewater reuse in agriculture. Obviously, a combination of AF/UASB reactor operated at HRT of 4+8 hrs would supply an effluent meeting the standards for agricultural reuse in terms of organic pollutants.

The single-stage UASB reactor has the advantage of retaining sludge for a very long SRT providing sufficient digestion and stabilization, even during wintertime. Longer HRT is needed compared to the staged reactor in order to obtain sufficient COD reduction. However, it should be mentioned that the reactor is operating now at 14 hrs HRT -as concluded in Chapter 2- and results obtained so far showed that similar removal efficiencies of COD_{tot} and COD_{ss} could be achieved compared to those obtained at 23 hrs HRT. The washed out sludge in the effluent of the UASB reactor can be entrapped in a second reactor e.g. physical unit. This may come up with another proposed attractive third configuration for the system, which combines the UASB reactor with an 'AF' for the entrapment of the solids escaping from the UASB reactor. The possibilities for gas production will be very limited in the AF when used as a second step, and consequently the performance should be stable during both winter and summer. The most important question in this case is related to the ability

of the AF to remove the digested sludge at the same removal efficiency as for the primary influent solids. It is important to mention that the durability of the polyurethane foam as a filtering media should be tested over long period of operation.

Table (9): Maximum concentrations of some parameters of the reclaimed wastewater for the agricultural reuse according to Jordanian standards

Quality parameter (mg/l)	Vegetables eaten cooked	Fruit trees &cereal crops	Fodder and pastures	Fish and aquaculture
BOD ₅	150	150	250	---
COD	500	500	700	---
TSS	200	200	250	25
TDS	2000	2000	2000	2000
pH	6.0-9.0	6.0-9.0	6.0-9.0	6.0-9.0
TFCC MPN/100ml	1000	1000	---	1000

CONCLUSIONS AND RECOMMENDATIONS

1. The average COD_{ss} removal efficiency in an AF reactor operated for treatment of strong domestic sewage at HRT of 4 hrs and at a temperature of 25°C was found to be 71%. The excess sludge discharged had a concentration fluctuating between 2.5-10.2g/l with an average VS/TS ratio of 0.68. Further stabilization for the excess sludge is needed. However, the excess sludge, with a SVI of 29ml/gTSS, showed good settling characteristics.
2. The UASB reactor provided average removal efficiencies of 58% and 65% for the COD_{tot} and the COD_{ss} respectively at a loading rate of 1.5kg/m³.d (HRT=23hrs) and a temperature of 25°C. The reactor provided long SRT in the range of 136-260 days and the sludge had good settling characteristics with a SVI value of 13-18ml/gTSS.
3. The application of a two stage AF/UASB reactor operated at 4+8 hrs HRT for the treatment of strong domestic sewage would provide a total COD removal efficiency in the range of 70-82% under both summer and winter conditions.

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Chapter 6

*Summary, general discussion,
conclusions and recommendations*

ANAEROBIC TREATMENT OF STRONG DOMESTIC SEWAGE AT FLUCTUATING TEMPERATURE CONDITIONS

Staged versus conventional UASB reactor

Summary, general discussion, conclusions and recommendations

INTRODUCTION

Anaerobic treatment of strong domestic sewage using UASB systems could be problematic when considering its generally high suspended COD concentration (COD_{ss}). High suspended solids (SS) concentrations may limit the application of high volumetric loading rates especially at low temperatures when the hydrolysis is limiting (Wang, 1994; Zeeman *et al.*, 1997; Elmitwalli, 2002). Moreover, high SS concentrations may present a risk for scum formation (Wang, 1994), and enhance sludge washout from the reactor (De Smedt *et al.*, 2001; Zeeman *et al.*, 2001). Some researchers recommended to separate solids prior to the application of a methanogenic UASB reactor. Wang, (1994) recommended a staged reactor, which combines a hydrolysis up flow sludge blanket reactor followed by an expanded sludge bed reactor for the treatment of domestic sewage at ambient temperatures. The system provided removal efficiencies of 51-71% of the total COD and 71-83% of the suspended solids at HRT of 3+5 hrs. Elmitwalli *et al.*, (2002) also recommended a staged reactor by applying an anaerobic filter for the removal of suspended solids from the sewage prior to the application of a second stage anaerobic hybrid reactor. The proposed system removed 70% of the total COD at 13°C and an HRT of 4+8 hrs. The first stage removed 82% of the COD_{ss} . However, low temperature anaerobic treatment of domestic sewage is so far not applied at full scale. On the other hand, conventional UASB reactors for raw sewage treatment were applied at full scale in tropical countries. Those reactors were operated at organic loading rates (OLR) in the range of 0.79-2.24 kgCOD/m³.d, and an HRT mostly in the range of 5-10 hrs. The achieved removal efficiencies in these systems were in the range of 50-80% for COD_{tot} and 50-76% for SS. The feasibility of applying UASB systems for strong sewage treatment at fluctuating temperature conditions motivated this research.

This thesis describes the results obtained in experiments concerning the anaerobic treatment of strong domestic sewage at fluctuating temperatures in Jordan. Chapter 2 deals with wastewater characteristics and the biodegradability of sewage and biodegradation rates of the main polymers (proteins, carbohydrates, and lipids) in the influents of two treatment plants in Jordan. Batch experiments were performed at two different temperatures representing summer and winter conditions. Chapter 3 describes the effect of the sludge residence time (SRT) and temperature on biological conversions of different polymers with emphasis on the effect of the degree of digestion on the formation of scum. A quite useful simple test was developed for measuring the potential of certain sludge to form a scum layer. The test was used to compare between different sludge samples obtained from 10 CSTRs operated at different SRTs and temperatures. Chapter 4 presents the results obtained during 2.5 years of operation of 96 m³ UASB reactor treating strong domestic sewage. A comparison was made between the performance of a two and one stage UASB reactor configurations. The comparison was based on the performance data, but also on the characteristics of the sludge developed in both cases. In view of the results obtained in the experiments presented in this chapter, it was decided to study the performance of

the anaerobic filter reactor (AF) investigated earlier by Elmitwalli *et al.*, (2002). However, the experiments presented in Chapter 5 in this research focuses on summer conditions because of the expected negative effect of gas produced at lower SRT. In the last chapter, we summarise and discuss the main results obtained in our investigation and finally the main conclusions and recommendations will be presented.

STRONG SEWAGE CHARACTERISTICS AND BIODEGRADATION RATES OF THE MAIN POLYMERS

Adequate knowledge of wastewater characteristics is a prerequisite for a proper design of a treatment system. The results obtained in this chapter showed that wastewater of Khirbit As-Samra and Abu-Nusier can be characterized by high total COD (COD_{tot}) concentrations, in the range of 1500-2000 mg/l, with a high fraction present in the suspended form. For both wastewaters we found a high anaerobic biodegradability with average values of 79% and 76% for Khirbit As-Samra and Abu Nusier respectively. However, the rate of biodegradation of the wastewater of Khirbit As-Samra was found to be lower than that obtained for Abu-Nusier, mainly due to the lower biodegradation rate of proteins, viz. 0.025 d⁻¹ and 0.090 d⁻¹ at 25°C for Khirbit As-Samra and Abu-Nusier wastewaters respectively. It should be mentioned that the wastewater of Khirbit As-Samra contains some illegal industrial discharges, which probably particularly affected the degradation rates of the proteins, but also the lipid fractions. This lower degradation rate indicates that the volume of the anaerobic reactor needed for Abu-Nusier will be smaller as compared to that needed for Khirbit As-Samra. At lower temperatures, both lipids and proteins biodegradation rates are negatively affected for each wastewater. Values of 0.012 d⁻¹ and 0.028 d⁻¹ were obtained for biodegradation rates of proteins for Khirbit As-Samra and Abu-Nusier wastewaters respectively, while no degradation was observed for lipids in the wastewater of Khirbit As-Samra and a value of 0.020 d⁻¹ was found for the biodegradation rate of lipids in the wastewater of Abu-Nusier. Applying UASB reactors at these lower temperature conditions can be done either by using a two stage UASB system as proposed by Wang, (1994) and described above, or by using a large one stage UASB reactor, because this would guarantee a sufficient conversion of organic material during winter.

EFFECT OF SRT AND TEMPERATURE ON BIOLOGICAL CONVERSIONS IN PRIMARY SLUDGE AND THE RELATED SCUM FORMING POTENTIAL

The sludge bed in UASB reactors was simulated using CSTR systems (Heertjes *et al.*, 1978; Bolle, 1986). Two sets of experiments were conducted at 15°C and 25°C, which represent the average winter and summer conditions in Jordan respectively. Each set consists of 5 CSTRs operated at 5, 15, 30, 50, and 75 days SRTs, and the digestion of different polymers was followed. Of particular interest was our investigation to assess the sludge potential to form a scum layer in relation to the degree of sludge digestion. Moreover, some other physical characteristics, like the particle size distribution, the SVI and the filterability of the sludge were determined.

The results revealed that methanogenesis started only at an SRT between 30-50 days for reactors operated at 15°C, while it started at an SRT between 5-15 days for

reactors operated at 25°C. The lipids were removed better than proteins at both temperatures with maximum values of 82% and 75% after 75 days of digestion at 25°C and 15°C respectively. For SRT value exceeding 15 days at 25°C, a slight increase in the biodegradation was obtained.

Both SRT and temperature affect the extent of scum formation. The degree of digestion has a clear effect on the concentration of lipids. Latter compounds tend to adsorb on sludge particles and have a strong tendency for floatation, Figure 1. However, we found that sludge with a high scum forming potential only will produce scum in the presence of gas production. There was no clear effect for the particle size distribution (PSD) of the sludge on the formation of scum; all of the reactors (except those operated at 50 and 75 days at 25°C) had the same PSD, but different scum forming potential. Other physical characteristics, like the SVI and the filterability of

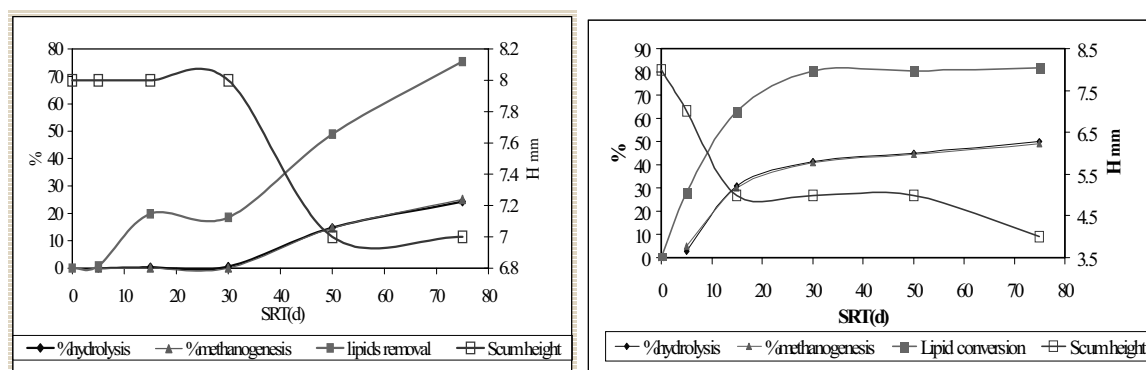


Figure (1): Scum forming potential in relation to SRT applied in the digestion process as assessed at 15°C and 25°C. Left: 15°C; Right: 25°C.

the sludge were mainly affected by the PSD.

Scum formation in UASB systems therefore could be prevented by either attempting to achieve a high degree of lipid's conversion (long SRT) or by preventing gas production. The latter could be achieved by designing a two stage UASB reactor, where the first stage mainly aims at the entrapment and partial hydrolysis of solids, while the second stage serves as a methanogenic reactor. Obviously, the solids entrapped in the first stage will need further stabilization in a separate digester. The other option –complete lipid's conversion- could be achieved by applying long SRT to the system allowing for complete conversion of lipids.

TREATMENT OF STRONG SEWAGE IN a 96 m³ UASB REACTOR OPERATED AT FLUCTUATING TEMPERATURE CONDITIONS

Two stage UASB reactor

Based on results obtained in the previous chapters, it was decided to investigate the feasibility of applying a staged versus a conventional UASB reactor for the treatment of strong domestic sewage at ambient temperatures. In the two-stage UASB system, HRTs in the range of 8-10 hrs and 5-6 hrs were applied for the first and the second stages respectively, corresponding to organic loading rates (OLR) in the range of 3.6-5.0 kgCOD/m³.d and 2.9-4.6 kgCOD/m³.d respectively. The performance was

followed during a period of one year of operation. The results of the first stage showed average removal efficiency of 51% for the total COD (COD_{tot}) without significant effect of temperature. The performance of the second stage reactor was disappointing, because only poor removal efficiency was achieved, viz. in the range of 4-10% for COD_{tot}. Although the system gave removal efficiencies in the range of the values reported in the literature (Table 1), the high gas production in the first stage probably was the main cause for the low removal of COD_{ss}. The relatively high concentration of dispersed sludge in the mixed liquor entering the settler compartment irrevocably lead to a high wash-out of dispersed sludge from the system and to a continuing heavy built up of scum. The scum layer was thicker during wintertime than in summertime, which is in agreement with results obtained in Chapter 3. Obviously, sludge washout from the first stage affected the performance of the second stage. Most of the treatment clearly was taking place in the first stage.

Considering the sludge developing in both stages, a relatively high specific methanogenic activity was found for the first stage with average values of 0.10 and 0.15 gCH₄-COD/gVS.d (at 33°C) for winter and summer respectively. The temperature clearly affected the degree of sludge stabilization. Stability results for the sludge of the first stage showed values of 12 and 41 gVS_{degraded}/gVS during summer and winter respectively indicating that the sludge needs further stabilization mainly during wintertime. The SRT calculated in the first stage amounted to values of

Table (1): The performance of the 60 m³ first stage UASB reactor of Khirbit As-Samra in comparison with results obtained from literature

Reference	Temp. (°C)	Vol. (m ³)	HRT (hrs)	OLR (kg/m ³ .d)	COD _{totin} (mg/l)	COD _{ssin} (mg/l)	% rem. COD _{tot}	% rem. COD _{ss} ²
Khirbit As-Samra summer	25	60	8-10	3.6-5.0	1505	1030	53	57
Khirbit As-Samra winter	18	60	8-10	3.6-5.0	1650	1383	50	63
Wang (1994)	13-31	170	2.5-5	4.75	495	316	41-48	(75-84)
Wang (1994)	9-21	0.2	3.0	5.2	650	329	38	50-65
Berends ¹ (1996)	25	0.085	4.0	13	2149	1713	58	60
Berends ¹ (1996)	15	0.085	4.0	13	2149	1713	58	55
Encina <i>et al.</i> (1998)	9-26	4.3	6.1	1.1-1.5	470	250	40-60	---

(1) For the purpose of increasing the incoming COD_{tot}, the influent was mixed with primary sludge; (2) values between parenthesis represent SS

approximately 26 and 42 days for summer and winter respectively. The values found for the average hydrolysis, acidification, and methanogenesis for the first stage are summarized in Table 2. The table also provides the results obtained during primary sludge digestion in CSTRs at different temperatures (Chapter 3), and the results obtained by other researchers. Obviously, the achieved conversions in the system of Khirbit As-Samra were in agreement with the values obtained in Chapter 3 for the same range of SRT and temperature.

Conventional one stage UASB reactor

The first reactor was operated as a conventional UASB reactor (60 m³) at an average HRT of 24 hrs and an average OLR of 1.5 kg/m³.d for another year. The results showed an average removal efficiency of 62% for the COD_{tot} during summer, while the removal efficiency dropped to 51% during wintertime. Table 3 shows the removal efficiencies of the total and suspended COD obtained in this research in comparison with results reported in literature. It can be seen that the removal efficiencies obtained here were in the range of values reported during the operation of conventional UASB reactors in tropical countries. The COD_{ss} in the effluent of the UASB reactor of Khirbit As-Samra represented around 80% of the total COD.

Table (2): The percentage hydrolysis, acidification and methanogenesis occurring in the first stage UASB reactor in Khirbit As-Samra in comparison with other reactors

Reference	Temp. (°C)	SRT (d)	Hydrolysis (%)	Acidification (%)	Methanogenesis (%)
Khirbit As-Samra Summer	25	26	49	---	46
Khirbit As-Samra Winter	18	42	16	---	14
CSTR's (chapter 3)	25	30-75	41-50	49	43-51
CSTR's (chapter 3)	15	50	15	12	15
Wang (1994)	19	34.5	0.7	7.0	---
Berends (1996)	15-25	7-8.7	7-9	---	0.03-0.4

However, it should be emphasized here, that the solids washed out with the effluent were quite well stabilized with an average VSS/TSS ratio around 0.5 all over the year. Consequently, by removing these solids in a subsequent stage, e.g. simply by using a settler or a lagoon, a maximum removal efficiency -as defined in equation (2), Chapter 4- of 87-93% could be achieved. Since major part of the SS present in the effluent settle quite well, really high treatment efficiencies are achievable in practice. Consequently, the application of an anaerobic pre-treatment step is an attractive option for Jordan situation.

During the last three months of operation of the first reactor, excess sludge was discharged on a regular basis from underneath the gas solids separator (GSS). In the sludge discharge procedure we applied, it was attempted to keep the sludge concentration below 7 gTS/l in a zone 1.0 m beneath the GSS device. Although sludge discharge indeed resulted in the elimination of the scum layer formation, a real significant improvement of the COD_{tot} and COD_{ss} removal efficiencies was not found. The SS concentration in the effluent of the reactor remained relatively high, or in other words the system needs to be improved with respect to its SS separation capabilities, unless the washout of the stabilized SS would not be detrimental. The latter certainly is the case when applying a lagoon as 'polishing' step. However, sludge discharge most likely results in a more stable performance of the system, as wash out of scum layer sludge will remain low.

Table (3): Performance of the 60 m³ conventional UASB reactor of Khirbit As-Samra in comparison with results obtained from literature for full scale reactors

Reference	Vol. (m ³)	Temp. (°C)	HRT (hrs)	OLR Kg/m ³ .d	COD _{totin} (mg/l)	COD _{ssin} * (mg/l)	% rem. COD _{tot}	%rem.* COD _{ss}
This research Summer	60	25	24	1.5	1612	1184	62	55
This research Winter	60	15	24	1.5	1419	1008	51	50
Lettinga (2001)	64	25	6	1.1	267	155	50-75	---
Vieira&Garcia (1992)	120	18-30	5-15	---	113-593	(44-512)	60	(70)
Van Starckenburg <i>et al.</i> , (2001)	4660	20-31	8	1.10	400-450	(360)	49-65	(50-76)
Schellinkhout, (1993)	3,350	24	5.2	1.9-2.0	330-450	(210-300)	45-50	---
Wiegant <i>et al.</i> , (2001)	11,200	26-29	6	---	---	---	61	(51)

(*) Values between parentheses represent SS

The results obtained in the tests for characterizing the sludge in the reactor show that the sludge indeed is well-stabilized with average values of 0.0012 and 0.0022 gVS_{degraded}/gVS.d for summer and winter conditions respectively. According to a report of Haskoning, dealing with the research carried out with sewage of Cali, Colombia, (1989), the biogas production rate reaches its endogenic level at about 0.003 gVS_{degraded}/gVS.d. The high values calculated for the SRT, viz. 186 and 137 days for summer and winter respectively, guaranteed a high degree of conversion.

Table (4) summarizes the results obtained for hydrolysis, acidification, and methanogenesis for the sludge in the Khirbit As-Samra UASB reactor, and those obtained in other investigations. Obviously, the reactor of Khirbit As-Samra was

Table (4): Percentage hydrolysis and methanogenesis (based on total influent COD) calculated for Khirbit As-Samra UASB reactor in comparison with values obtained from literature

Reference	Temp. (°C)	SRT (d)	Hydrolysis (%)	Methanogenesis (%)
This research	25	186	76	71
This research	18	137	46	42
Vieira&Garcia (1992)	18-30	---	---	36
Schellinkhout, (1993)	24	---	---	45 ¹
Lettinga, (2001)	25	---	---	33-50

(1) Calculated based on the available data.

superior in terms of conversion of organic material compared to results obtained from literature even at the lower temperature prevailed during wintertime.

TREATMENT OF STRONG DOMESTIC SEWAGE USING A TWO STAGE AF/UASB REACTOR AND A ONE STAGE UASB REACTOR

The results obtained in Chapter 4 clearly indicate that, particularly the two stage UASB reactor needs an optimisation. This could be achieved by improving the removal of solids in the first stage reactor, using the filter system as proposed by Elmitwalli *et al.*, (2002). We therefore decided to operate an AF for the removal of COD_{ss} prior to subjecting the wastewater to further treatment in a UASB reactor. For the purpose of comparison, we also operated a one stage UASB reactor. Two reactors were built at the location of Abu-Nusier treatment plant with an effective volume of 1.18 m³ for each reactor. The reactors so far were operated only during summer at an average temperature of 24°C. The AF was operated at 4.6 hrs HRT and the UASB reactor at 23 hrs HRT. Sludge discharge was made every 4 days from the bottom of the reactor. The results show average removal efficiencies of 39% and 71% for COD_{tot} and COD_{ss} respectively, which are significantly lower than the values obtained by Elmitwalli *et al.*, (2002). The calculated average values for hydrolysis, acidification, and methanogenesis were 44%, 42%, and 30% respectively. The calculated SRT was around 19 days.

Considering the excess sludge produced in the AF reactor, the results show a concentration in the range of 3.5-10.2 gTS/l. The average VS/TS ratio was 68% indicating that the sludge needs further digestion. The excess sludge had good settling characteristics with an average value of 29 ml/gTSS.

Considering the results of the UASB reactor, average removal efficiencies of 58% and 65% for the COD_{tot} and COD_{ss} respectively were obtained. Moreover, a considerable removal of COD_{col} was found with an average value of 49% similar to that obtained in the 60 m³ UASB reactor operated at Khirbit As-Samra. The calculated SRT was between 136-260 days.

Based on the results obtained for both reactors, a comparison can be made between a two-stage AF/UASB reactor and a conventional UASB reactor for the treatment of strong domestic sewage during both summer and winter conditions. Some assumptions had to be made and are shown in details in Table 7 in the chapter. Table 5 shows the resulted and expected effluent qualities for each condition.

Considering the results in the table, it is clear that operating a two stage AF/UASB reactor at HRT of 4+8 hrs would provide a total COD removal efficiency between 70 and 82% during both summer and wintertime. However, the disadvantage of this reactor configuration is that there is a need for the operation of two extra units, one for sludge thickening and one for digestion because the sludge produced in the AF reactor is relatively low in concentration and the stability of the solids is also low.

Table (5): Expected and calculated effluent COD values for AF+UASB reactor and a conventional UASB reactor operated at summer and winter conditions with strong domestic sewage (chapter 5) as influent

Parameter*	Summer			Winter		
	AF+UASB reactors		Conventional UASB reactor	AF+UASB reactors		Conventional UASB reactor
	AF	UASB		AF	UASB	
HRT (hrs)	4	8	23	4	8	23
COD _{tot}	888	324-419	633-694	633	288-333	689
COD _{ss}	248	50-117	282-415	150	30-75	415
COD _{col}	204	102	79	111	58	79
COD _{sol}	436	172-200	200-284	409	200	172-200

(*) Values are in mg/l.

The single-stage UASB reactor operated at an HRT of 23 hrs, offers the advantage that it retains sludge with an SRT so that the system is enabled to provide a sufficient digestion and stabilization even during wintertime. Moreover, the simplicity of this system (both in design and operation) makes it attractive option for full-scale application. In order to improve the overall treatment efficiency, the washed out sludge present in the effluent could be entrapped in a second physical unit. However, a longer HRT is needed compared to the staged reactor concept.

FINAL DISCUSSION

The possible successful application of the two-stage UASB system depends highly on its efficiency in removing solids in the first stage. In order to achieve this, the gas production in this stage should be kept at a minimum. This could be accomplished by reducing the SRT. However, as was shown in Chapter 4, the maximum gas production at 25°C occurs at SRT around 15 days, while it already starts at this temperature at an SRT between 5-15 days, Chapter 3. It is quite difficult to control the sludge age within this range. Referring to the model developed by Zeeman *et al.*, (1999) presented in Chapter 1, (equation 4), it can be shown that at HRT= 8 hrs, COD_{ss} = 1000mg/l, R = 85% and H = 49%, SRT can be calculated in the range of 8-15 days for a sludge concentration in the range of 10-20 gVS/l. This concentration of the sludge was chosen based on the results obtained in Chapter 4. Obviously, the first stage UASB reactor will not be capable to remove a significant fraction of solids as was originally aimed at. Applying an AF as a first stage reactor for the removal of solids looks an attractive option as shown above.

The choice between a staged AF/UASB system and a conventional UASB reactor should be done on the basis of a feasibility study, depending on the scale of application. While the staged system could be preferred over a conventional UASB reactor in the case of centralized sanitation, where sludge thickening and digestion could be economically feasible, a conventional UASB reactor could be preferred in the case of decentralized sanitation, where sludge handling could be problematic.

CONCLUSIONS

1. The strong domestic sewage of Khirbit As-Samra and of Abu-Nusier as well, both contain a high fraction of anaerobically biodegradable COD, with average values of 79% and 76% respectively. The biodegradation rate of protein is considerably lower in the case of Khirbit As-Samra as compared to Abu-Nusier wastewater.
2. Both, the SRT and the temperature have a significant effect on scum formation. At higher temperatures and SRTs, less scum is formed, while lower temperatures and SRTs show a stronger tendency of the sludge to form a scum layer. However, the presence of gas is a prerequisite for scum formation.
3. The two-stage UASB pilot reactor was capable to remove an average total COD of 51% in the first stage, and the temperature did not have a significant effect in the range of 18-25°C, when operated at average HRTs between 8-10 hrs. The performance of the second stage was rather poor, mainly because most of the treatment takes place in the first stage reactor. The sludge produced during winter needs further stabilisation.
4. A first stage AF reactor operated at 4.6 hrs HRT gave 71% COD_{ss} removal efficiency during summer time. A combined AF/UASB reactor system is expected to provide a total COD removal efficiency of 70-80% during both summer and winter. However, the excess sludge produced in the AF, needs further treatment.
5. The 60 m³ conventional UASB pilot plant provides an average COD_{tot} removal efficiency of 62% during summer and 51% during winter, when operated at 24 hrs HRT for the treatment of strong sewage at 18-25°C ambient temperatures. The main polluting COD fraction in the effluent concerns COD suspended matter, but this matter with its VSS/TSS ratio of 0.5 is well-stabilised.

RECOMMENDATIONS

1. The feasibility of applying the combination of the AF/UASB system should be investigated for the treatment of strong domestic sewage.
2. The application of the best physical (-chemical) treatment unit for the removal of the COD_{ss} present in the effluent of the conventional UASB reactor should be further investigated. The application of a filter using polyurethane foam as a filter media could be an attractive option.
3. The full scale application of an one stage conventional UASB reactor for pre-treatment of sewage in Jordan is recommended, because the system is simple in operation, low cost in construction, and it will eliminate most of the presently prevailing problems, such as odour nuisance, poor treatment efficiency, consumption of high energy.

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Samenvatting, discussie, conclusies
en aanbevelingen

Samenvatting

ANAËROBE ZUIVERING VAN GECONCENTREERD HUISHOUELIJK AFVALWATER BIJ FLUCTUERENDE TEMPERATUREN Gefaseerde versus conventionele UASB reactor

Samenvatting, discussie, conclusies en aanbevelingen

INLEIDING

Geconcentreerd huishoudelijk afvalwater bevat in het algemeen hoge concentraties CZV zwevende stof (CZV_{ss}), wat problematisch kan zijn bij zuivering met behulp van een UASB systeem. Het hoge zwevende stof gehalte kan een beperking vormen voor de volumebelading, vooral bij lage temperaturen wanneer de hydrolyse de beperkende stap wordt (Wang, 1994; Zeeman *et al.*, 1997; Elmitwalli, 2002). Een hoog zwevend stof gehalte kan tevens drijfslagvorming veroorzaken (Wang, 1994), en slibuitspoeling bevorderen (De Smedt *et al.*, 2001; Zeeman *et al.*, 2001). Door sommige onderzoekers wordt aanbevolen de zwevende stof te af te scheiden van het afvalwater alvorens behandeling in een methanogene UASB reactor. Wang (1994) stelt voor een gefaseerde reactor te gebruiken, bestaande uit een hydrolyse up-flow slibdeken reactor gevolgd door een geëxpandeerde slibdeken reactor, voor behandeling van huishoudelijk afvalwater bij omgevingstemperatuur. Dit systeem gaf bij hydraulische verblijftijden van 3 + 5 uur een verwijderingsrendement van 51-71% voor totaal CZV en 71-83% voor zwevende stof. Ook Elmitwalli *et al.* (2002) stelt voor een gefaseerd systeem te gebruiken. In dit geval een anaëroob filter voor de verwijdering van zwevende stof gevolgd door een anaëroobe hybride reactor. Het verwijderingsrendement bedroeg 70% van de totaal CZV bij 13°C en een verblijftijd van 4 + 8 uur. Het anaëroob filter verwijderde 82% van de CZV_{ss} . Tot nu toe wordt anaëroobe zuivering van huishoudelijk afvalwater niet full-scale toegepast bij lage temperaturen, in tropische gebieden daaraantegen wel. Deze reactoren worden bij een organische belasting van 0.79-2.24 kg/m³.d. en een hydraulische verblijftijd van ongeveer 5-10 uur bedreven. De behaalde verwijderingsrendementen van deze systemen zijn ongeveer 50-80% voor totaal CZV en 50-76% voor zwevend stof. De toepasbaarheid van UASB systemen voor geconcentreerd huishoudelijk afvalwater bij variërende omgevingstemperatuur wordt in dit proefschrift onderzocht.

Dit proefschrift beschrijft de resultaten van onderzoek naar anaëroobe zuivering van geconcentreerd huishoudelijk afvalwater in Jordanië. Hoofdstuk (2) behandelt de afvalwaterkarakteristieken en biologisch afbreekbaarheid en de biologische afbraaksnelheid van de belangrijkste polymeren (eiwitten, koolhydraten en vetten) van twee zuiveringen in Jordanië. Batch experimenten zijn bij twee temperaturen uitgevoerd, als simulatie van winter en zomer condities. Hoofdstuk (3) beschrijft het effect van de slibverblijftijd en de temperatuur op de biologische omzetting van diverse polymeren, met nadruk op het effect dat de omzettingsgraad op de schuimvorming heeft. Om het drijfslagvormingspotentieel van slib te bepalen is een handzame methode ontworpen. Deze methode is gebruikt om het slib te vergelijken van 10 volledig gemengde reactors, die bij verschillende slibverblijftijden en temperaturen zijn bedreven. In hoofdstuk (4) worden de resultaten beschreven van 2,5 jaar zuivering van geconcentreerd huishoudelijk afvalwater in een 96m³ UASB

reactor. Er is een vergelijking gemaakt tussen een 1 en 2 trapssysteem. De vergelijking van deze systemen betreft zuiveringsrendementen en ook ontwikkeling van het slib in beide gevallen. Op basis van deze resultaten is onderzoek gedaan naar het effect van een anaërobe filter (AF) reactor, zoals eerder door Elmitwalli (2002) uitgevoerd. Hoofdstuk (5) spitst zich toe op zomer omstandigheden en het verwachte negatieve effect van de gasproductie op de slibverblijftijd. In het laatste hoofdstuk (6) wordt een algehele samenvatting, discussie van gedaan werk gegeven en worden aanbevelingen gedaan.

KARAKTERISTIEKEN VAN GECONCENTREERD HUISHOUELIJK AFVALWATER EN BIOLOGISCHE AFBRAAKSNELHEID VAN DE BELANGRIJKSTE POLYMEREN

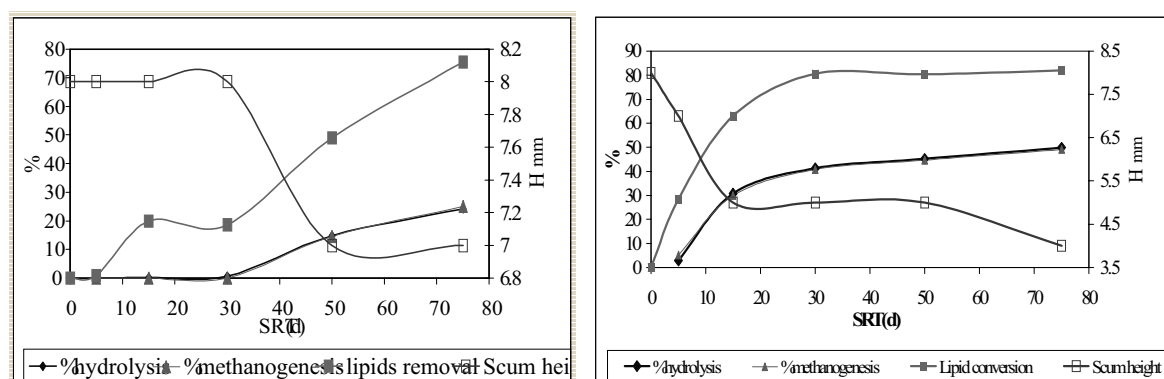
Voldoende kennis van de afvalwaterkarakteristieken is een voorwaarde voor een goed ontwerp van het zuiveringssysteem. De resultaten in dit hoofdstuk laten zien dat het afvalwater van Khirbit As-Samra en Abu-Nusier een hoog totaal CZV gehalte bevatten (1500-2000 mg/L), met een grote fractie zwevende stof. De anaërobe afbreekbaarheid van beide afvalwaters was hoog, gemiddeld 79% en 76% voor respectievelijk Khirbit As-Samra en Abu-Nusier. De afbraaksnelheid van het afvalwater van Khirbit As-Samra was lager dan die van Abu-Nusier, wat voornamelijk te wijten was aan de lagere afbraaksnelheid van de eiwitten, te weten: 0.025 d^{-1} en 0.090 d^{-1} bij 25°C voor respectievelijk Khirbit As-Samra en Abu-Nusier afvalwater. Opgemerkt moet worden dat het afvalwater van Khirbit As-Samra illegale industriële lozingen bevatte, die waarschijnlijk de afbraaksnelheid van eiwitten, maar ook die van vetten beïnvloedden. Wegens de lagere afbraaksnelheid in Khirbit As-Samra zal een grotere UASB reactor nodig zijn dan in Abu-Nusier. Lagere temperaturen hebben een negatief effect op de afbraaksnelheden van vetten en eiwitten. De afbraaksnelheid van eiwitten waren respectievelijk 0.012 d^{-1} en 0.028 d^{-1} in Khirbit As-Samra en Abu-Nusier, die van vetten waren 0 en 0.020 d^{-1} . Toepassing van UASB reactors bij deze lage temperatuur omstandigheden is mogelijk bij gebruik van een tweetraps UASB reactor zoals eerder beschreven of voorgesteld door Wang (1994), of door gebruik te maken van een grote enkelvoudige UASB reactor, zodat onder winter omstandigheden voldoende conversie van organisch materiaal plaats vindt.

EFFECT VAN SLIBVERBLIJFTIJD EN TEMPERATUUR OP DE BIOLOGISCHE OMZETTINGEN IN PRIMAIR SLIB EN HET GERELATEERDE DRIJFLAAGVORMINGSPOTENTIEEL

Het slibbed in een UASB reactor is nagebootst door gebruik van volledig gemengde reactor systemen (Heertjes *et al.*, 1986; Bolle, 1986). Twee experimenten zijn uitgevoerd bij 15°C en 25°C als representatie van Jordaanse winter en zomer condities. Elk experiment bestaat uit 5 volledig gemengde reactoren bedreven bij 5, 15, 30, 50 en 75 dagen slibverblijftijd, waarbij de afbraak van de diverse polymeren is gevolgd. Speciale aandacht ging uit naar het drijfslagvormingspotentieel in relatie tot de mate van slibvergisting. Verder zijn fysische parameters zoals de deeltjes grootteverdeling, slib volume index en de filtreerbaarheid van het slib bepaald. De data lieten zien dat de methanogenese op pas gang kwam na een slibverblijftijd tussen 30-50 dagen bij een temperatuur van 15°C , bij 25°C duurde dit 5-15 dagen. Vetten werden beter

verwijderd dan eiwitten bij beide temperaturen, maximaal 82% en 75% na 75 dagen vergisting bij respectievelijk 25 en 15°C. Bij slibverblijftijden boven 15 dagen werd een lichte toename van de biodegradatie gezien.

Zowel de slibverblijftijd als de temperatuur hebben een effect op de drijfslaagvorming. De mate van vergisting heeft een duidelijk effect op de vet concentratie. Vet heeft sterk de neiging slibdeeltjes te adsorberen en te drijven (figuur 1). Slib met een sterk vermogen tot drijfslaagvorming zal alleen daadwerkelijk een drijfslaag vormen bij gasproductie. Er was geen duidelijk



Figuur (1): Drijfslaagvormingspotentieel in relatie tot de toegepaste slibverblijftijd bij 15 en 25°C. Links: 15°C; Rechts: 25°C.

verband tussen de deeltjes grootteverdeling en drijfslaagvorming. Alle reactoren (met uitzondering van slibverblijftijden van 50 en 75 dagen bij een temperatuur van 25°C) hadden vergelijkbare deeltjes grootteverdelingen. De andere parameters zoals de slib volume index en de filtreerbaarheid werden voornamelijk beïnvloed door de deeltjes grootteverdeling.

Drijfslaagvorming in UASB systemen kan worden voorkomen door te streven naar een hoge mate van vetomzetting (lange slibverblijftijd) of door het voorkomen van gasproductie. Dit laatste kan worden bereikt door een tweetraps UASB reactor te ontwerpen, waarbij in de eerste trap dient voor afvang en voor-hydrolyse van deeltjes en de tweede trap voor methanogenese. Het ligt voor de hand dat de afgevangen deeltjes in de eerste trap verdere stabilisatie behoeven in een afzonderlijke reactor. De andere optie, een volledige conversie van vetten, kan worden bereikt door toepassing van lange slibverblijftijden.

BEHANDELING VAN GECONCENTREERD HUISHOUELIJK AFVALWATER IN EEN 96M³ UASB REACTOR, BEDREVEN BIJ FLUCTURENDE TEMPERATUUR

Tweetraps UASB reactor

Op basis van voorgaande resultaten is besloten de toepasbaarheid van een tweetraps reactor te vergelijken met een conventionele UASB reactor voor de behandeling van geconcentreerd huishoudelijk afvalwater bij omgevingstemperatuur. In het tweetrapsysteem werden hydraulische verblijftijden van 8-10 uur voor de eerste en 5-6 uur voor de tweede trap toegepast, wat overeen komt met een organische belasting van respectievelijk 3.6-5.0 en 2.9-4.6 kgCOD/m³.d. Het systeem werd gedurende een jaar gevolgd. De eerste trap behaalde gemiddeld een totaal CZV verwijdering van 51%, zonder noemenswaardig effect door de temperatuur. De resultaten van de tweede trap waren teleurstellend wat betreft het verwijderingsrendement; slecht 4-10% voor totaal CZV. Het systeem verwijderingsrendementen gaf die overeen komen met de literatuur (tabel 1). De hoge gasproductie in de eerste trap was waarschijnlijk de voornaamste oorzaak van de lage verwijdering van zwevende stof CZV (CZV_{ss}).

Tabel (1): Zuiveringsrendementen van de 60 m³ eerste trap van de UASB reactor in Khirbit As-Samra in vergelijking met literatuur data

Referentie	Temp (°C)	Volume (m ³)	HRT (uur)	OLR (kg/m ³ .d)	CZV _{totaal} in (mg/L)	CZV _{ss} in (mg/L)	verwijdering CZV _{totaal} (%)	verwijdering CZV _{ss} (%)
Khirbit As-Samra	25	60	8-10	3.6-5	1505	1030	53	57
Khirbit As-Samra	18	60	8-10	3.6-5	1650	1383	50	63
Wang (1994)	13-31	170	2.5-5	4.75	495	316	41-48	(75-84)
Wang (1994)	9-21	0.2	3.0	5.2	650	329	38	50-60
Berends ¹ (1996)	25	0.085	4.0	13	2149	1713	58	60
Berends ¹ (1996)	15	0.085	4.0	13	2149	1713	58	55
Encina <i>et al.</i> (1998)	9-26	4.3	6.1	1.1-1.5	470	250	40-60	---

(1) Influent gemengd met primair slib om CZV_{totaal} te verhogen; (2) waarden tussen haakjes is zwevend stof.

De relatief hoge concentratie gesuspendeerd slib dat in de bezinker van de eerste trap terecht kwam leidde tot uitspoeling van het slib, wat een forse drijfslaagopbouw tot gevolg had. Deze drijfslaag was in de winter dikker dan in de zomer, in overeenkomst met de resultaten beschreven in hoofdstuk 3. Uiteraard had de slibuitspoeling van de eerste trap invloed op het rendement van de tweede trap. De meeste verwijdering vond in de eerste trap plaats.

Het opgebouwde slib in de eerste trap had relatief een hoge methanogene activiteit: 0.10 en 0.15 gCH₄-CZV/g OS.d., bij 33°C voor respectievelijk winter en zomer. De temperatuur had duidelijk invloed op de slibstabilisatie. De stabilisatie van het slib uit de eerste trap was 0.12 in de zomer en 0.41 g OS_{vergistbaar}/g OS in de winter, waar uit blijkt dat het slib in de winter verdere vergisting behoeft. De berekende slibverblijftijd van de eerste trap was ongeveer 26 en 42 dagen in het zomer- en winterseizoen. De gevonden waarden voor de gemiddelde hydrolyse, verzuring en methanogenese van de eerste trap staan weergegeven in tabel 2. Verder staan in deze tabel de resultaten van de slibvergisting in de volledig gemengde reactoren bij verschillende temperaturen (hoofdstuk 3) en literatuur gegevens.

Tabel (2): Het percentage hydrolyse, verzuring en methanogenese in eerste trap UASB reactor in Khirbit As-Samra in vergelijking met literatuur data

Referentie	Temp (°C)	Slibverblijftijd (d)	Hydrolyse (%)	Verzuring (%)	Methanogenese (%)
Khirbit As-Samra	25	26	49	----	46
Khirbit As-Samra	18	42	16	----	14
Gemengde reactor ¹	25	30-75	41-50	49	43-51
Gemengde reactor	15	50	15	12	15
Wang (1994)	19	34.5	0.7	7	----
Berends (1996)	15-25	7-8.7	7-9	----	0.03-0.4

De resultaten van Khirbit As-Samra komen overeen met de waarden in hoofdstuk 3 bij overeenkomstige slibverblijftijd en temperatuur.

Conventionele UASB reactor

De eerste trap UASB reactor (60m³) is gedurende een jaar als een conventionele UASB reactor bedreven, bij een hydraulische verblijftijd van 24 uur en een organische belading van 1.5 kg/m³.d. Het gemiddelde zuiveringsrendement van totaal CZV was gedurende de zomer 62% en daalde in de winter naar 51%. Tabel 3 geeft de gemiddelde verwijderingsrendementen van totaal en zwevend stof (ss) CZV en gegevens uit de literatuur.

Tabel (3): Zuiveringsrendementen van de 60 m³ conventionele UASB reactor in Khirbit As-Samra in vergelijking met literatuur data

Referentie	Temp (°C)	Volume (m ³)	HRT (uur)	OLR (kg/m ³ .d)	CZV _{totaal} in (mg/L)	CZV _{ss} in (mg/L)	verwijdering CZV _{totaal} (%)	verwijdering CZV _{ss} (%)
Khirbit As-Samra	25	60	24	1.5	1612	1184	62	55
Khirbit As-Samra	18	60	24	1.5	1419	1008	51	50
Lettinga (2001)	25	64	6	1.1	267	155	50-75	----
Vieira&Garcia (1992)	18-30	120	5-15	----	113-593	(44-512)	60	(70)
Van Starckenburg <i>et al.</i> (2001)	20-31	4660	8	1.1	400-450	(360)	49-65	(50-76)
Schellinkhout (1993)	24	3350	5.2	1.9-2.0	330-450	(210-300)	45-50	----
Wiegant <i>et al.</i> (2001)	26-29	11200	6	----	----	----	61	(51)

Waarden tussen haakjes is zwevend stof.

De verwijderingsrendementen van Khirbit As-Samra zijn vergelijkbaar met resultaten van conventionele UASB reactoren in tropische omstandigheden. Het zwevend stof gehalte in Khirbit As-Samra vertegenwoordigt 80% van de totaal CZV. Het dient echter vermeld te worden dat het uitgespoelde slib in het effluent redelijk gestabiliseerd was; de organisch stof : totaal vast materiaal ratio was ongeveer 0.5 gedurende het hele jaar. Dus, door verwijdering van vast materiaal in een vervolg zuiveringstrap, bijvoorbeeld een bezinker of lagoon, kan een maximaal rendement van

87-93% worden gehaald (volgens vergelijking (2) hoofdstuk 4). Sinds de meeste deeltjes in het effluent redelijk bezinken zijn hoge zuiveringsrendementen haalbaar in de praktijk. De toepassing van een anaëroobe voorbehandelingstrap is een aantrekkelijke optie voor Jordaanse omstandigheden.

Gedurende de laatste 3 maanden van het experiment werd regelmatig slib gespuid uit het compartiment onder de 3 fasenscheider. Getracht is de slibconcentratie 1 meter onder de 3 fasenscheider onder de 7 g vaste stof/L te houden. Hoewel het spuien van slib de drijfslagvorming voorkwam, was er weinig verbetering te zien in zuiveringsrendementen van totaal en zwevend stof CZV. Het zwevend stof gehalte in het effluent bleef relatief hoog. Met andere woorden het systeem dient verbeterd te worden wat betreft de slibafscheiding tenzij dit niet nadelig wordt geacht. Dat is zeker het geval indien er een lagoon nazuivering wordt toegepast.

Karakterisering van het slib uit de reactor liet zien dat er sprake was van verregaande slibstabilisatie, met gemiddelde waarden van 0.0012 en 0.0022 g OS_{vergistbaar}/g OS.d voor respectievelijk zomer en winter omstandigheden. Onderzoek naar huishoudelijk afvalwater in Cali, Colombia (Haskoning, 1989) liet zien dat de endogene ademhaling van het slib werd bereikt bij 0.003 g OS_{vergistbaar}/g OS.d. De berekende hoge slibverblijftijden, te weten 186 en 137 dagen voor zomer en winter, garandeerden een hoge mate van omzetting. Tabel 4 geeft de gevonden waarden voor de gemiddelde hydrolyse, verzuring en methanogenese van het slib in de UASB reactor in Khirbit As-Samra en literatuur gegevens.

Tabel (4): Het percentage hydrolyse, verzuring en methanogenese gebaseerd op totaal influent CZV van de UASB reactor in Khirbit As-Samra in vergelijking met literatuur data

Referentie	Temp (°C)	Slibverblijftijd (d)	Hydrolyse (%)	Methanogenese (%)
Khirbit As-Samra	25	186	76	71
Khirbit As-Samra	18	137	46	42
Vieira&Garcia (1992)	25	----	----	36
Schellinkhout (1993)	15	----	----	45 ¹
Lettinga (2001)	19	----	----	33-50

¹ Berekend op basis van beschikbare data

Zoals in de tabel te zien is waren de resultaten van Khirbit As-Samra goed wat betreft de conversie van organisch materiaal, zelfs bij lagere temperaturen.

ZUIVERING VAN GECONCENTREERD HUISHOUELIJK AFVALWATER MET BEHULP VAN EEN ANAËROOB FILTER/USB REACTOR EN EEN EENTRAPS UASB REACTOR

De resultaten in hoofdstuk 4 laten duidelijk zien dat het zuiveringssysteem optimalisatie behoeft, vooral de tweetraps reactor. Dit zou bewerkstelligd kunnen worden door de deeltjesafvang van de eerste trap te verbeteren met behulp van een filter systeem zoals wordt voorgesteld door Elmitwalli *et al.* (2002). Er is daarom besloten een anaëroob filter (AF) voor het afvangen van deeltjes te gebruiken alvorens het afvalwater in een UASB reactor verder te behandelen. Ter vergelijking is ook een eentrap UASB reactor gebruikt. De twee reactoren zijn gebouwd in Abu-Nusier, met een effectief volume van 1.18 m³ per reactor. De reactoren zijn gedurende de zomer bedreven bij een gemiddelde temperatuur van 24°C. Het AF had een hydraulische verblijftijd van 4.6 en de UASB bij 23 uur. Slib werd elke 4 dagen gespuid vanuit de reactor bodem. De gemiddelde zuiveringsrendementen voor CZV totaal en zwevende deeltjes waren respectievelijk 39 en 71%, wat significant lager is dan de resultaten van Elmitwalli *et al.* (2002). De berekende gemiddelde waarden voor hydrolyse, verzuring en methanogenese waren 44, 42 en 30%. De berekende slibverblijftijd was ongeveer 19 dagen.

Het spuislib uit de AF had een concentratie van 3.5-10.2 g droge stof/L. De gemiddelde organisch stof : droge stof ratio was 68%, wat betekent dat verdere stabilisatie nodig is. De bezinkingseigenschappen van het slib waren goed met een gemiddelde waarde van 29 ml/ g droge stof.

De zuiveringsrendementen van de UASB reactor waren gemiddeld 58 en 65% voor totaal en zwevend stof CZV. Verder werd een gemiddelde verwijdering van colloïdaal CZV gevonden van 49%, wat overeenkomt met de resultaten van de 60 m³ reactor in Khirbit As-Samra. De berekende slibverblijftijd was tussen 136-260 dagen.

Een vergelijking tussen het tweetraps AF/UASB systeem en een conventionele UASB voor behandeling van geconcentreerd huishoudelijk afvalwater bij zomer en winter omstandigheden kan worden gemaakt. Hiervoor moesten enige aannames worden

Tabel 5: Verwachte en berekende effluent CZV concentraties voor een AF/UASB reactor en een conventionele UASB reactor, bij winter en zomer omstandigheden, beladen met geconcentreerd huishoudelijk afvalwater als influent (hoofdstuk 5)

parameter	zomer			winter		
	AF+UASB reactor		Conventionele UASB reactor	AF+UASB reactor		Conventionele UASB reactor
	AF	UASB		AF	UASB	
HRT (uur)	4	8	23	4	8	23
CZV _{totaal}	888	324-419	633-694	633	288-333	689
CZV _{ss}	248	50-117	282-415	150	30-75	415
CZV _{colloïdaal}	204	102	79	111	58	79
CZV _{opgelost}	436	172-200	200-284	409	200	172-200

gedaan welke zijn vermeld in tabel 7 van het hoofdstuk. In tabel 5 (dit hoofdstuk) geeft de verwachte effluent resultaten voor de diverse condities. Uit de resultaten in tabel 5 blijkt dat het tweetraps AF/UASB systeem met hydraulische verblijftijden van 4 en 8 uur een zuiveringsrendement voor totaal CZV geeft tussen 70-82% gedurende

zowel de zomer als de winter periode. Nadeel van deze configuratie is dat er twee extra units nodig zijn, een voor het indikken van slib en een voor vergisting want de slibconcentratie en stabilisatie graad zijn laag.

Het eentraps UASB systeem bij een hydraulische verblijftijd van 23 uur had als voordeel dat de slibretentie voldoende was om vergisting en stabilisatie van het slib in de zomer en in de winter voldoende hoog te houden. Verder maakt de eenvoud van het systeem, wat betreft ontwerp en onderhoud, het een aantrekkelijke optie voor full-scale toepassing. Om de zuiveringsefficiëntie van het systeem te verbeteren zou het met het effluent uitgespoelde slib afgevangen kunnen worden voor verdere behandeling.

EINDDISCUSSIE

Het succesvol toepassen van een tweetraps systeem hangt in sterke mate af van de efficiëntie van zwevende stof verwijdering door de eerste trap. Voor een goede efficiëntie van de eerste trap dient de gasproductie tot een minimum beperkt te worden. Dit kan worden bereikt door de slibverblijftijd te beperken. Echter, zoals in hoofdstuk 4 te zien is, treedt bij 25°C gasproductie op bij een slibverblijftijd tussen 5-15 dagen en de maximale gasproductie bij 15 dagen. Refererend aan het model ontwikkeld door Zeeman *et al.* (1999) zoals beschreven in hoofdstuk 1, vergelijking 4, kan men berekenen dat bij een hydraulische verblijftijd = 8 uur, CZV zwevende stof = 1000 mg/L, R = 85% en H = 49% de slibverblijftijd resulteert tussen 8-15 dagen voor een slibconcentratie van 10-20 g organisch stof/L. De concentratie van het slib is gekozen op basis van de resultaten uit hoofdstuk 4. De eerste trap zal niet in staat zijn voldoende zwevende stof te verwijderen als bedoeld was. Toepassing van een anaëroob filter als eerste trap lijkt dan een aantrekkelijke optie.

De keus tussen een gefaseerd AF/UASB systeem of een conventionele UASB reactor dient te worden gemaakt op basis van een haalbaarheidsstudie, afhankelijk van de toepassingschaal. Een gefaseerd systeem kan de voorkeur verdienen in geval van gecentraliseerde zuivering, waar het indikken en vergisten van slib economisch haalbaar is. Een conventionele UASB reactor kan de voorkeur genieten wanneer er sprake is van decentrale sanitatie, waar slib behandeling een probleem zou kunnen vormen.

CONCLUSIES

1. Het relatief geconcentreerde huishoudelijk afvalwater van Khirbit As-Samra en Abu-Nusier bevat een hoog gehalte aan anaëroob afbreekbaar CZV, respectievelijk ongeveer 79 en 76%. De afbraaksnelheid van eiwit is lager van Khirbit As-Samra afvalwater dan dat van Abu-Nusier.
2. Zowel slibverblijftijd als temperatuur hebben een significant effect op de drijfslagvorming. Bij hogere temperatuur en langere slibverblijftijden wordt is de drijfslagvorming minder. De aanwezigheid van gasproductie is een vereiste voor drijfslagvorming.
3. Van de tweetraps UASB reactor was de eerste trap in staat gemiddeld een totaal CZV van 51% te verwijderen, waarbij de temperatuur tussen 18-25°C weinig effect had bij een hydraulische verblijftijd van 8-10 uur. De tweede

- trap deed het niet zo goed, voornamelijk door de zuivering in de eerste trap. Het winterslib behoefde verdere stabilisatie.
4. Het anaëroob filter als eerste trap bij een hydraulische verblijftijd van 4.6 uur liet een zwevende stof CZV verwijdering zien van 71% gedurende de zomer. Verwacht wordt dat een gecombineerd AF/UASB systeem een CZV totaal verwijderingsrendement van 70-80% zal halen gedurende de zomer en winter. Het spuislib uit het anaëroob filter heeft verdere behandeling nodig.
 5. De 60 m³ conventionele UASB reactor gaf een gemiddelde totaal CZV verwijdering van 62% in de zomer en 51% in de winter, bij een hydraulische verblijftijd van 24 uur en omgevingstemperatuur. De voornaamste CZV fractie in het effluent bestaat uit zwevende stof, wat echter met een organisch stof : droge stof ratio van 0.5 goed gestabiliseerd is.

AANBEVELINGEN

1. De haalbaarheid voor het toepassen van een gecombineerd AF?UASB systeem voor de zuivering van geconcentreerd huishoudelijk afvalwater dient te worden onderzocht.
2. De toepassing van fysisch/chemische behandeling van het effluent van de conventionele UASB om zwevend stof te verwijderen dient te worden onderzocht. Een polyurethaan filter zou een aantrekkelijke optie kunne zijn.
3. De full-scale toepassing van een conventionele UASB reactor als voorzuivering van rioolwater is in Jordanië aan te bevelen. Het systeem is eenvoudig in operatie, de constructie kosten zijn laag en de meest urgente problemen, zoals stankoverlast, lage zuiveringsrendementen en hoge energie consumptie worden opgelost.

List of abbreviations

A	Acidification
AF	Anaerobic filter
BOD ₅	5-days biochemical oxygen demand (mg/l)
COD _{bl}	COD of the blank (mg/l)
COD _{diseffl}	COD of the dissolved effluent (mg/l)
COD _{disinfl.}	COD of the dissolved influent (mg/l)
COD _{col}	Colloidal solids chemical oxygen demand (mg/l)
COD _{effl.}	Effluent COD
COD _{infl.}	Influent COD
COD _{pf}	Paper filtered COD (mg/l)
COD _{sol}	Soluble solids chemical oxygen demand (mg/l)
COD _{ss}	Suspended solids chemical oxygen demand (mg/l)
COD _{tot}	Total chemical oxygen demand (mg/l)
CST	Capillary suction time (sec.)
CSTR	Completely stirred tank reactor
EGSB	Expanded granular sludge bed
F/M	Food to microorganisms ratio
GSS	Gas solids separator
HRT	Hydraulic retention time (days or hrs)
Infl.	Influent
K _h	First order hydrolysis constant (day ⁻¹)
M	Methanogenesis
MCM	Million cubic meter
OLR	Organic loading rate (kg/m ³ .d)
PSD	Particle size distribution
Rem.	Removal (%)
SMA	Specific methanogenic activity (gCOD/gVSS.d)
SRT	Sludge residence time (day)
SS	Suspended solids (mg/l)
SVI	Sludge volume index (ml/gTSS)
Temp.	Temperature (°C)
TS	Total solids (mg/l)
TSS	Total suspended solids (mg/l)
UASB	Up flow anaerobic sludge blanket
VFA	Volatile fatty acids (mgCOD/l)
Vol.	Volume (m ³ or Liters)
VS	Volatile solids (mg/l)
VSS	Volatile suspended solids (mg/l)
V _{up}	Up flow velocity (m/hr)

Curriculum vitae

The author of this dissertation, Maha Mohammad Halalsheh, was born on 24th of October 1969 in Islam Abad. In 1992, she obtained her Bachelor degree from the department of Civil Engineering, University of Jordan. She had a training year in the Ministry of public works in Amman. In 1996, she obtained her Master degree in Environmental Engineering from the same department in the University of Jordan. She worked for the department on a project funded by the EU and supervised by the Technical University of Denmark. In 1997, she worked for the Water and Environmental Study and Research Center –WESRC- in the University of Jordan. In February, 1998, she got a scholarship from the University of Jordan funded by the Dutch government to study at the sub-Department of Environmental Technology in Wageningen University.

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