Lesson B3

Anaerobic sewage treatment

Author: Nidal Mahmoud

Institute for Water Studies (IWS)
Birzeit University

Revised by Dr. Yavuz Özoguz
data-quest Suchi&Berg GmbH

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Overview and Summary

Today sewage is the largest pollutant on a global scale, as particularly in developing countries, only a small fraction of the sewage produced is treated. Sewage treatment by conventional means, including secondary aerobic biological treatment, is efficient. But this efficiency is at the price of high capital and running cost and technology requirement. Alternatively, anaerobic treatment has been proven to be an admirable process and considered as the core of sustainable waste management. This lesson covers some of the fundamental principles of the anaerobic processes. Then the concept of high rate systems has been introduced and the advantages and drawbacks of applying those systems has been introduced. The application of the Upflow Anaerobic Sludge Blanket (UASB) reactor in tropical and low and moderate temperature countries has been presented. The key issues and approaches of UASB reactor design including guidelines for the design of the physical components of the reactor are discussed, in addition to a design example.

1. Introduction

1.1 Definition of anaerobic process

The fermentation process in which organic material is degraded and biogas (composed of mainly methane and carbon dioxide) is produced, is referred to as anaerobic digestion. Anaerobic digestion processes occur in many places where organic material is available and redox potential is low (zero oxygen). This is typically the case in stomachs of ruminants, in marshes, sediments of lakes and ditches, municipal land fills, or even municipal sewers.

The anaerobic ecosystem is the result of complex interactions among microorganisms of several different species. The major groupings of bacteria and reaction they mediate are:

- fermentative bacteria
- hydrogen-producing acetogenic bacteria
- hydrogen-consuming acetogenic bacteria
- carbon dioxide-reducing methanogens
- aceticlastic methanogens.

The reactions they mediate are presented in figure 2 and discussed in the following sections.

1.2 Anaerobic degradation of organic polymers

Most of the substrate in the complex wastewaters is present as particulate matter, e.g 45 – 75% of domestic sewage, and 80% in primary sludge. The main biopolymers in sewage are proteins, carbohydrates and lipids. The anaerobic degradation pathway of organic matter is a multi step process of series and parallel reactions. This process of organic matter degradation proceeds in four successive stages, namely (1) Hydrrolysis, (2) Acidogenesis, (3) Acetogenesis and (4) Methanogenesis. The processes are discussed below (see figure 1).

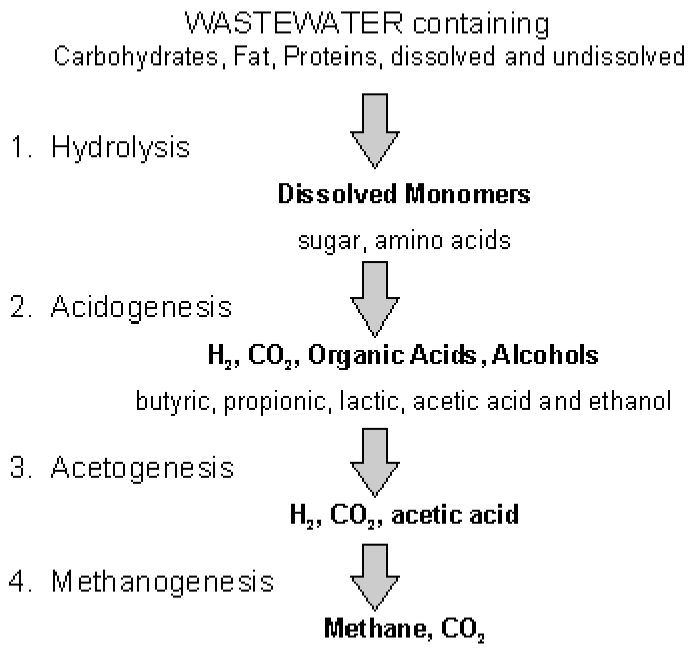

Figure 1: Anaerobic Microbiology

1.2.1 Hydrolysis

Since bacteria are unable to take up particulate organic matter, the first step in anaerobic degradation consists of the hydrolysis of polymers through the action of exo-enzymes to produce smaller molecules which can cross the cell barrier. During the enzymatic hydrolysis process, proteins are hydrolyzed to amino acids, polysaccharide to simple sugars and lipids to long chain fatty acids (LCFA). Hydrolysis is in most cases, notably with sewage as substrate, rate-limiting for the overall process of anaerobic degradation of organic matter and is very sensitive to temperature. For that reason, design of the anaerobic reactors for sewage treatment is usually based on the hydrolysis step.

1.2.2 Acidogenesis

During the acidogenesis, the hydrolysis products which are relatively small, soluble compounds are diffused inside the bacterial cells through the cell membrane and then are either fermented or anaerobically oxidized. These processes occur by a complex consortium of hydrolytic and non-hydrolytic microorganisms which are the source of energy for the acidifying population. The acidification products consist of a variety of small organic compounds, mainly so-called volatile fatty acids (VFA's) (acetate and higher organic acids (like propionate and butyrate), H_2, CO_2, some lactic acids, ethanol and ammonia (see figure 2). Given that VFA's are the main end products, fermentative organisms are usually designated as acidifying or acidogenic microorganisms.

1.2.3 Acetogenesis

The short chain-fatty acids, other than acetate, that are produced in the acidogenesis step are further converted to acetate, hydrogen gas and carbon dioxide by the acetogenic bacteria. β-oxidation is the mechanism of anaerobic oxidation of long chain fatty acids with as products hydrogen and acetate. The available H_2 and CO_2 is partly converted into acetate by the homoacetogenic bacteria. Both propionate and butyrate are important intermediates in anaerobic digestion, and then are converted by the hydrogen producing acetogenic bacteria into acetate and hydrogen (see table 1).

Table 1: Some acetogenic reactions (propionate and butyrate degradation) and the corresponding free energy change ($\Delta G^{\circ\prime}$)

Reactions	$\Delta G^{\circ\prime}$ (KJ/mole)
$CH_3\text{-}CH_2\text{-}COO^- + 3H_2O \rightarrow CH_3COO^- + HCO_3^- + 2H^+ + 2H_2$	+ 76.1
$CH_3\text{-}CH_2\text{-}CH_2\text{-}COO^- + 2H_2O \rightarrow 2\ CH_3COO^- + 2H^+ + 2H_2$	+ 48.1

The acetogenic bacteria are obligate hydrogen producers and their metabolism is inhibited by hydrogen. Studies carried out with these bacteria have shown the narrow association between the H_2-producing acetogenic bacteria and the H_2-consuming methanogenic bacteria, thereby regulating the H_2 level in their environment. This is of vital importance as these reactions are thermodynamically unfavorable (positive ΔG°') unless the hydrogen partial pressure is maintained at an extremely low pressure. Methanogenic bacteria utilize molecular hydrogen in the usual anaerobic digester so rapidly that the hydrogen partial pressure can be kept as low as 10^{-4} atm which is enough to ensure the active performance of the hydrogen producing acetogenic bacteria. This means that the degradation of higher fatty acids depends largely on the activity of methanogenic bacteria. Microbial association in which a H_2-producing organism can grow only in the presence of H_2-consuming organism are called syntrophic association. The coupling of formation and use of H_2 is called interspecies hydrogen transfer (HTS).

1.2.4 Methanogenesis

During the fourth and last stage of anaerobic degradation of organic matter, a group of methanogenic bacteria both reduce the carbon dioxide by hydrogen and decarboxylate acetate to form methane (CH_4) (figure 2). The methanogenic bacteria are obligate anaerobes, able to utilize only certain determined substrates. They use organic substrate or specific carbon source such as acetate, H_2 and formate. Some strains are autotrophic, using only CO_2 or CO as carbon source. Generally, 70 - 80 % of the methane formed from the organic materials originates from acetate. The rest is mainly derived from H_2 and CO_2.

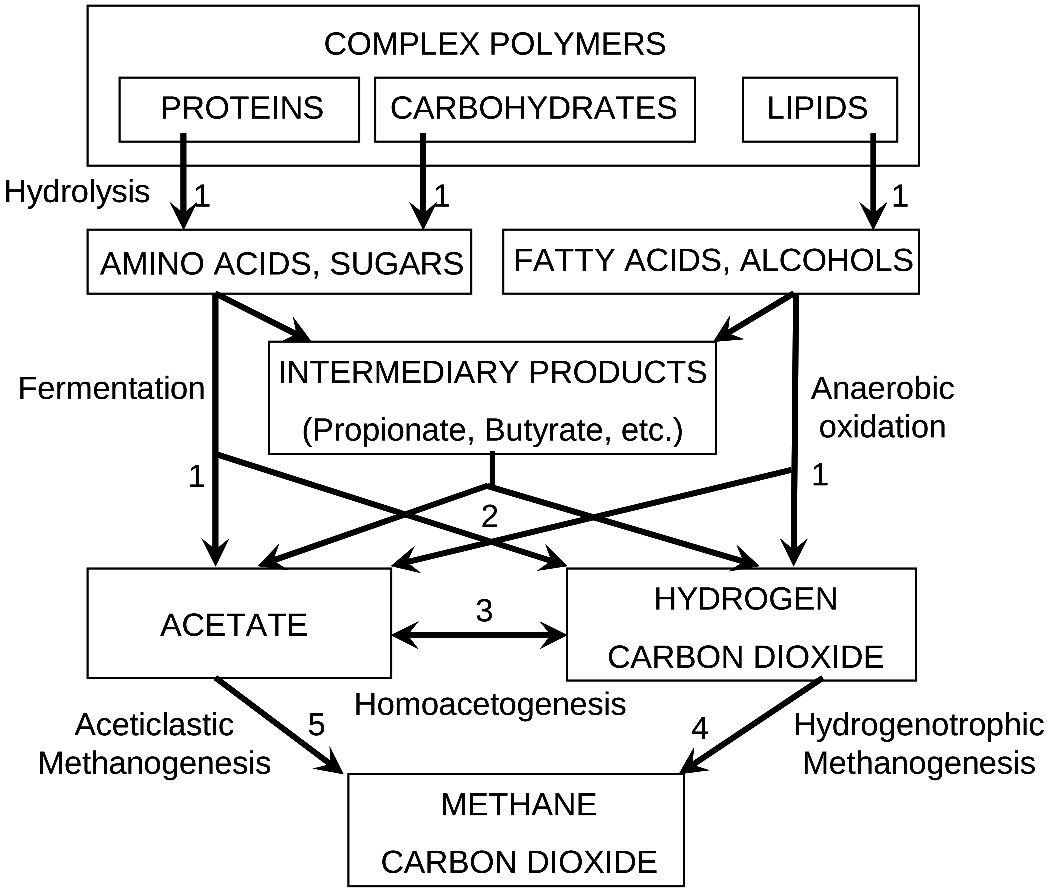

Figure 2: Reactive scheme for the anaerobic digestion of polymeric materials. Numbers indicate the bacterial groups involved, see sec. 1.1

2. Anaerobic Treatment technology

2.1 High rate systems

One of the major successes in the development of anaerobic wastewater treatment was the introduction of high-rate reactors in which biomass retention and liquid retention are uncoupled. The anaerobic high–rate systems enables the application of a relatively high loading rate, while maintaining long SRT at relatively short HRT due to sludge immobilisation. The main advantages and drawbacks of the anaerobic high rate systems applied for sewage treatment are shown in Table 2. In these systems, wastewater flows through the anaerobic sludge where purification takes place through complex bio - physical - chemical interrelated processes. Organic matter is converted into biogas and sludge.

Table 2: Advantages and drawbacks of anaerobic sewage treatment in anaerobic high rate systems

Advantages	Drawbacks
A substantial saving in operational costs as no energy is required for aeration; on the contrary energy is produced in the form of methane gas, which can be utilized for heating or electricity production. The process can handle high hydraulic and organic loading rates. Thus, the applied technologies are compact. The technologies are simple in construction and operation; so they are low cost. The systems can be applied everywhere and at any scale as little if any energy is required, enabling a decentralized application. The excess sludge production is low, well stabilized and easily dewatered so does not require extensive costly post treatment. The valuable nutrients (N and P) are conserved which give high potential for crop irrigation.	Need for post treatment, depending on the requirements for effluent standards. No experience with full-scale application at low/moderate temperatures. Considerable amount of produced biogas, i.e. CH_4 and H_2S remains in the effluent especially for low strength wastewater (sewage). Produced CH_4 during anaerobic sewage treatment is often not utilised for energy production.

Different high–rate systems were developed over the last three decades including the anaerobic filter, the upflow anaerobic sludge blanket (UASB), the fluidised and expanded bed reactors and the baffled reactors.

2.1 Upflow anaerobic sludge blanket (UASB) reactor

The UASB reactor is the most widely and successfully used high rate anaerobic technology for treating several types of wastewater. The success of the UASB reactor can be attributed to its capability to retain a high concentration of sludge and efficient solids, liquid and water phase separation. The UASB reactor consists of a circular or rectangular tank in which waste (water or sludge) flows in upward direction through an activated anaerobic sludge bed which occupies about half the volume of the reactor and consists of highly settleable granules or flocs. During the passage of this blanket the purification takes place by solids removal and then organic matter is converted into biogas and sludge. The produced biogas bubbles transfer to the top of the reactor, carrying water and solid particles (i.e. biological sludge and residual solids). These bubbles strike the degassing baffles at the upper part of the reactor, leading to an efficient gas - Solid separation (GSS). The solid particles drop back to the top of sludge blanket, while the released gases are captured in an inverted cone (GSS) located at the top of the reactor. Water passes through the apertures between the degassing baffles carrying some solid particle which settle there due to increase of the cross sectional area and return back to the sludge blanket, while water leaves the settlers over overflow weirs. A schematic diagram of the UASB reactor is shown in figure 3.

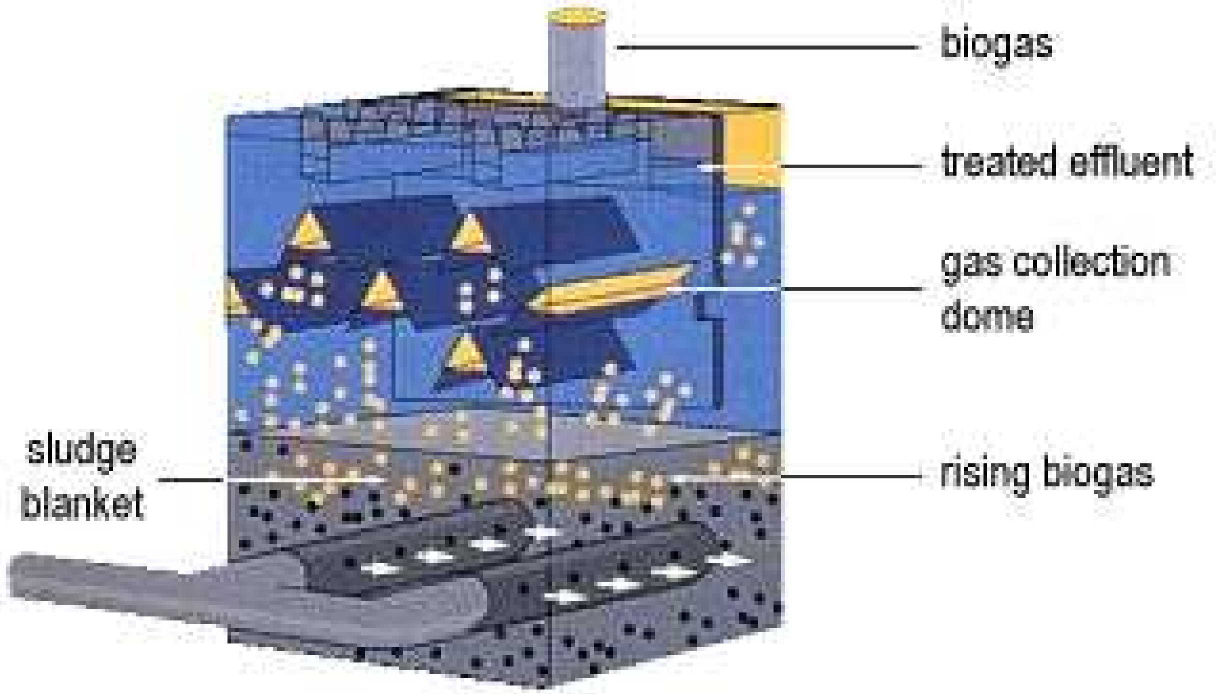

Figure 3: Schematic diagram of the UASB reactor

2.1.1 Application of the UASB Reactor in tropical countries

The experience with the applicability of the UASB reactor for sewage treatment in tropical countries started by the pilot plant constructed in Cali-Columbia during the period 1982–1983. The results obtained from the operation of the Cali plant showed the feasibility of the system under the prevailing environmental and sewage characteristics. After that, hundreds of UASB reactors for treatment of sewage at both full scale and pilot scale (Table 3 & 5) have been operational in several tropical countries like India, Columbia, Brazil and Mexico. The ambient temperature in these countries is rather high throughout the year (20-35 °C) and the wastewater strength is rather low.

2.1.2 Application of the UASB Reactor at moderate and low temperature

The application of the UASB reactor for sewage treatment is surely not limited to countries of hot climate. The results of several researches on bench scale and pilot scale systems operated at low temperatures have opened new perspectives (Table 4& 5) but no full-scale application has so far been realised.

Table 3: Results of anaerobic raw sewage treatment in pilot-scale UASB reactors under tropical conditions (≥20 °C) (from Mahmoud, 2002)

Volume	Temp	HRT	Influent CODt	% Removal		Reference
Liter	°C	(hr)	(mg/l)	CODt[$]	SS[$$]	
106	20-23	4	424	60	69	Vieira and Souza (1986)
120	20	18	550	55-75	-	Lettinga *et al.* (1980)
118	20	8	500	75a	-	Grin *et al.* (1983)
160	20	6	1076	64	88	Mergaert *et al.* (1992)
106	21-25	4.7	265	50	73	Vieira (1988)
106	35	4	300	65	61	Vieira (1988)

Table 4: Results of sewage treatment in pilot-scale UASB reactors at low temperature (≤20 °C) (from Mahmoud, 2002)

Volume	Temp	HRT	Influent CODt	% Removal		Reference
Liter	°C	(hr)	(mg/l)	CODt[$]	SS(CODss)[$]	
120	7-8	9-14	464-700	57	72	Man *et al.* (1986)
110	12-18	18	465	65	(73)	Monroy *et al.* (1988)
120	12-20	7-8	190-1180	30-75	60	Man *et al.* (1988)

Table 5: Some case studies from existing UASB plants with influent and effluent characteristics in different countries

Country	Volume	Temperature	HRT	Influent COD	Effluent COD[$]	% Removal
	m^3	°C	(hr)	(mg/L)	(mg/L)	COD
Colombia	64	24-26	4-6	267	110	65
Colombia	6600	25	5.2	380	150	60-80
Brazil	120	23	4.7-9	315-265	145	50-70
Brazil	67.5	23	7	402	130	74
Brazil	810	30	9.7	563	185	67
India	1200	20-30	6	563	146	74
Jordan	60	25	23-27	1600	600	62
Jordan	60	18	23-27	1400	700	51

[$]Calculated from the influent COD and removal efficiency

2.1.3 Design considerations of the UASB reactor

2.1.3.1 Retention time and temperature

The design and performance of an anaerobic reactor strongly depends on the solids retention time, operational temperature, and the biodegradability and concentration of the entrapped solids, which are interrelated parameters. Domestic sewage is a complex type of wastewater, characterised by a high fraction suspended solids and mostly of relatively low temperatures. The hydrolysis of retained particles is in general considered as the rate-limiting step of the overall digestion process and is highly influenced by process temperature and solids retention time. When using UASB reactors, the SRT should be long enough to provide methanogenic conditions as illustrated in Table 6. The reduction in operational temperature does not only retards the hydrolysis step but also leads to a significant decrease in the maximum growth and substrate utilisation rates.

Table 6: Hydraulic retention time *(HRT, in days) to be applied, to achieve the indicated SRT (days) assuming 50% or 75% CODss removal at the treatment of domestic wastewater with a concentration of 1 g COD/l of which 65% is suspended, at different % hydrolysis and sludge concentration in the UASB reactor of 15 g VSS/l (see sec. 3)*

% CODss removal	% Hydrolysis of removed SS	SRT				
		25	50	75	100	150
50	25	0.28	0.56	0.84	1.12	1.68
75	25	0.42	0.84	1.26	1.68	2.52
50	50	0.19	0.38	0.57	0.76	1.14
75	50	0.28	0.56	0.84	1.12	1.68
50	75	0.09	0.18	0.27	0.36	0.54
75	75	0.14	0.28	0.42	0.56	0.84

2.1.3.2 Organic loading rate and upflow velocity

A part from the calculation model proposed by Zeeman and Lettinga (1999) (see Table 6), the volume of the UASB reactor can be determined based on organic loading and upflow velocity. The reactor volume based on acceptable organic loading rate (OLR) is given by:

$$V = \frac{QxC}{OLR} \qquad \textbf{(1)}$$

with:
V: volume of the reactor, m^3
Q: influent flow rate, m^3/d
C: influent COD, kg COD/m^3
OLR: acceptable organic loading rate, kg COD/m^3.d

The acceptable organic loading rate depends largely on the biodegradability of sewage, on the operational temperature and the average sludge retention time (See table 6). For design purposes OLR given in Tables 3 and 4 can be used for preliminary dimensioning of the UASB reactor under different sewage and environmental conditions. In addition to reactor sizing based on OLR, the upflow velocity (equation 2) should be less than the admissible upflow velocity (Table 6).

$$V_{up} = \frac{H}{HRT} \qquad \textbf{(2)}$$

with:
Vup: upflow velocity, m/hr
H: reactor height, m
HRT: Hydraulic retention time, hr

2.1.3.3 Physical components

The major physical components of a UASB reactor that require careful consideration are the feed inlet distribution, outlet and gas collector. Some important design criteria of UASB reactors treating sewage are presented in Table 7. The required good contact between influent wastewater and sludge is achieved by the even feed distribution at the bottom of the reactor, the turbulence brought about by the natural biogas production and high upward velocity. The in-built Gas Solids Separator (GSS) installed at the top of the reactor takes care of separation/collection of the biogas. A number of important guidelines regarding the design of the GSS are given in Table 8.

Table 7: Some design criteria of UASB reactors treating sewage (see fig. 2)

Min. average HRT	4 hrs
height	4-5 m
Feed inlet points	1 inlet per 1 to 4 m^2
Feed distribution	Each inlet pipe from a separate compartment
Static pressure in feed inlet box	Up to 50 cm
Upflow velocity in aperture	Average daily 4 m/hr During 2-4 hrs 8 m/hr
Upflow velocity	0.5 m/hr

Table 8: Summary of tentative guidelines for the design of the gas-solids-separator device

- The slope of the settler bottom (i.e. the inclined wall of the gas collector) should be between 45-60 °.
- The surface area of the apertures between the gas collectors should be 15-20% of the reactor surface area.
- The height of the gas collector should be between 1.5-2 m at reactor heights of 5-7 m.
- To facilitate the release and collection of gas bubbles and to combat scum layer formation, a liquid-gas interface should be maintained in the gas collector.
- To avoid up-flowing gas bubbles to enter the settler compartment, the overlap of the baffles installed beneath the apertures should be 10-20 cm.
- Generally, scum layer baffles should be installed in front of the effluent weirs.
- The diameter of the gas exhaust pipes should be sufficient to guarantee the easy removal of the biogas from the gas collection cap, particularly in case of foaming.
- In the upper part of the gas cap, anti-foam spray nozzles should be installed in the case the treatment of the waste water is accompanied with heavy foaming.

Adapted from Lettinga and Hulshoff Pol (1991)

2.1.4 UASB reactor design for sewage treatment: design example

The final removal efficiency and conversion of organic compounds to methane gas in UASB reactors depend on both physical and biological processes. For sewage, removal of suspended solids occurs by physical processes like settling, adsorption and entrapment. The subsequent hydrolysis and methanogensesis of the removed solids depends on the process temperature and the prevailing SRT. Zeeman and Lettinga (1999) developed a model for the calculation of the HRT when a certain SRT is a pre-requisite, and this model can be used for preliminary sizing of a UASB reactor. The SRT is determined by the amount of sludge that can be retained in the reactor and the daily excess sludge production. The daily excess sludge production is determined by the biomass yield and the removal and conversion of suspended solids. At a certain temperature the SRT will determine whether methanogenesis will occur or not. So when the required SRT is known, the corresponding HRT can be calculated provided that the sludge concentration in the reactor (X), the fraction of the influent SS that is removed (R) and the fraction of the removed SS that is hydrolysed (H) are known. The HRT of a UASB reactor can be calculated with the following formulas:

SRT = X/Xp **(3)**

X: sludge concentration in the reactor (kg COD/m^3); 1 g VSS = 1.4 g COD
Xp: sludge production (kg COD/m^3.d)

Xp = O*SS*R*(1-H) **(4)**

O: organic loading rate (kg COD/m^3.d); SS = CODss / CODinfluent;
CODss: suspended COD
R: fraction of CODss removed

HRT = C/O (days) **(5)**

C: COD concentration in the influent (g COD/l)

HRT = (C *SS/X)*R*(1-H)*SRT **(6)**

SRT: sludge retention time (days)
H: fraction of removed solids that are hydrolysed

The previous model was used for the calculation of the required HRT for the application of a UASB reactor for sewage treatment Shams City where sewage temperature is 15 ºC. The total COD of the domestic sewage produced from Shams City is 1600 mg/L, of which 60% is in the suspended form (particle size bigger than 4.4 μm). Calculate the required HRT of a UASB reactor to treat this sewage.

The following input data were taken into consideration:
R = 0.8; around 85% of total suspended solids (TSS) removal efficiency can be achieved in a UASB reactor at an upflow velocity (Vup) of 0.6 m/hr.

SRT = 30 days; expected minimum SRT to achieve methanogenic conditions during winter time (data should be obtained fro literature or from available local data). At these conditions:

H = 0.15; 15% of the TSS can be hydrolysed.
X = 15 g VSS/l = 21 g COD/l
SS= 0.60
C = 1.600 g COD/l

Accordingly, the model calculation reveals that a HRT of 22 hour is required.

3. Comparison of anaerobic and aerobic treatment

In the wastewater engineering field organic pollution is measured by the weight of oxygen it takes to oxidize it chemically, referred to as the "chemical oxygen demand" (COD). COD is basically a measure of organic matter content or concentration. The best way to appreciate anaerobic wastewater treatment is to compare its COD balance with that of aerobic wastewater treatment, as shown in figure 4 below.

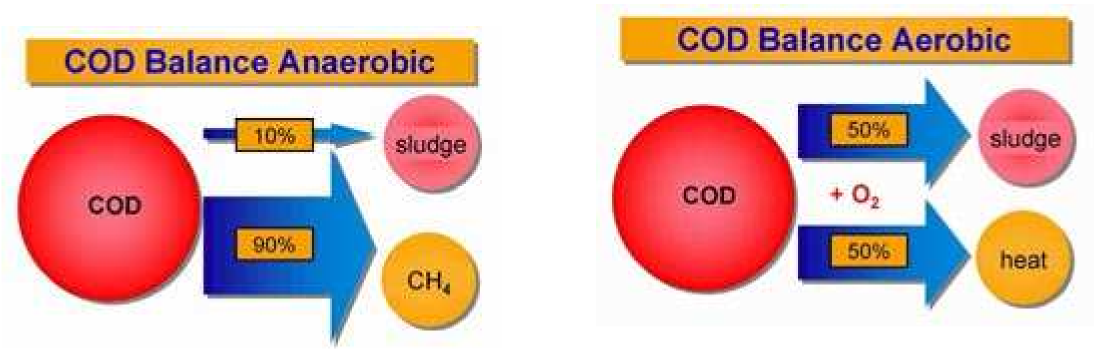

Figure 4. Comparison of the COD balance during anaerobic and aerobic treatment of wastewater containing organic pollution

The COD in wastewater during anaerobic treatment is highly converted to methane, which is a valuable fuel. Very little COD is converted to sludge. No major inputs are required to operate the system. Nevertheless it depends on stable preconditions as i.e. temperature to make the process stable.

The COD in wastewater during aerobic treatment is highly converted sludge, a bulky waste product, which costs lots of money to get rid of in developed countries with less area, but can be of interest as low-cost fertilizer in developing countries if the sludge is not contaminated. Elemental oxygen has to be continuously supplied by aerating the wastewater. The process itself can be more stable.

4. References

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Mahmoud, N., 2002. Anaerobic pre-treatment of sewage under low temperature (15 °C) conditions in an integrated UASB-digester system PhD thesis, Department of Environmental Technology, Wageningen University, Wageningen, The Netherlands.

Zeeman, G., Lettinga, G., 1999. The role of anaerobic digestion in closing the water and nutrient cycle at community level. *Water Sci.Technol*., 39 (5), 187-194.

5. Links

- Anaerobic Granular Sludge Bed Technology Pages www.UASB.org

- Comparison of high-rate anaerobic wastewater treatment reactors: http://www.cepis.ops-oms.org/muwww/fulltext/repind54/anadow/anadow.html