Anaerobic treatment of municipal wastewater using the UASB-technology

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Abstract The anaerobic treatment of municipal wastewater enables new applications for the reuse of wastewater. The effluent could be used for irrigation as the included nutrients are not affected by the treatment. Much more interesting now are renewable energies and the retrenchment of CO_2 emission. With the anaerobic treatment of municipal wastewater, not only can the CO_2 emission be reduced but "clean" energy supply can be gained by biogas. Most important for the sustainability of this process is the gathering of methane from the liquid effluent of the reactor, because the negative climate-relevant effect from the degassing methane is much higher than the positive effect from saving CO_2 emission. In this study, UASB reactors were used with a flocculent sludge blanket for the biodegradation of the carbon fraction in the wastewater with different temperatures and concentrations. It could be shown that the positive effect is much higher for municipal wastewater with high concentrations in hot climates.

Keywords COD balance; flocculent sludge; greenhouse gas; methane solubility; municipal wastewater; UASB reactors

Introduction

The anaerobic treatment of domestic organic waste is widespread in many countries, particularly in warm climates. Because these countries often lack energy, the focus lies not on the environmental protection but on the energy recovery in the form of biogas. If the municipal wastewater is evenly treated, aerobic techniques are most common and so energy is required. In contrast, the anaerobic treatment of municipal wastewater not only produces highly demanded energy but it also protects the environment.

In a joint project with other German research institutes funded by the Federal State Ministry for Education and Research (BmBF), the task of ISAH is the investigation of the anaerobic process as an environmentally sound technique for the treatment of municipal wastewater. Therefore, three UASB reactors were installed at the experimental laboratory of ISAH in a pilot and half-technical scale. This type of reactor is already approved for the treatment of industrial wastewater.

The main objective of the project was the cleaning of the wastewater, in particular the production of biogas as an energy source as well as the reclamation of the nutrients (i.e. nitrogen and phosphorus) contained in the wastewater as fertilisers in agriculture. For this the anaerobic treatment is predestined as the fraction of N and P passes almost unabated to the reactor. As shown in Table 1, only a small amount is used for the anaerobic metabolism by the microorganisms.

Materials and methods

The ISAH experiment is situated at the municipal WWTP of Hannover–Herrenhausen. Recent municipal wasterwater was collected and pumped in the UASB-pilot plant. The investigations were carried out with presettled municipal wastewater, the composition of

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Table 1 Degradation of nitrogen and phosphorus in treated municipal wastewater, with granulated sludge from the anaerobic wastewater treatment plant of a distillery as the inoculum of the USAB reactor (Abdel-Halim, 2005)

Temperature [°C]	Total nitrogen elimination		Total phosphorus elimination	
	[%]	[mg/L]	[%]	[mg/L]
30	16.9	10.5	3.6	0.4
20	10.1	6.3	3.4	0.3
14	8.8	5.5	3.2	0.3

which is shown in Table 2. Toxic or inhibiting substances are not included. The reactors were inoculated with flocculent sludge of the anaerobic digester of the municipal WWTP. This inoculum was also used for the SMA-batch-tests (Specific Methanogenic Activity) which were executed at the ISAH and are well known. The average SS was 25 g/L with an organic fraction of 66%. Toxic or inhibiting substances have not been detected during the SMA tests.

Pilot plants

The pilot plant consisted of two identical and parallel operated reactors with appartus such as pumps, gas meters and power units (see Figure 1). The UASB reactors were made of PVC with a height of 1600 mm and a volume of 0.115 m^3 of which a maximum of 0.095 m^3 were useable for the sludge blanket.

For each reactor, the input was pumped with a flexible-tube pump and could be varied from nearly 0 to 0.75 m^3/d. Moreover, the input was tempered by an external heat exchanger at temperatures between 10 and 25°C. To raise the upstream velocity, and if necessary run the recirculation, a second flexible-tube pump was on standby.

Effluent tanks were installed to quantify the daily volumetric load of the reactors. The produced biogas was measured with drum type gas meters.

Analytics

The analytics during the operation of these pilot plants focused on the carbon fraction of the wastewater. The prior experiments at ISAH have shown that there is an adequate supply of nutrients through the wastewater. Table 3 indicates the whole range of examined analyses.

Results and discussion

Table 4 shows the results from 400 days of operation of both reactors. In the start-up phase the inoculum was treated with high upstream velocity to wash out the suspended solids and accumulate the flocculent parts of the sludge. The recycle was reduced to a maximum upstream velocity of v_{up} of 0.9 m/h afterwards. The HRT was constantly reduced in both reactors to determine the achievable minimum. In the penultimate phase this was achieved with an HRT of 4 h. After this, the HRT was raised again to 10 h.

Table 2 Composition of the municipal wastewater at the WWTP Hannover-Herrenhausen after primary settlement (DWA, 2000; Hinken, 2005; von Sperling and Chernicharo (2005))

Source	COD [mg/L]	BOD [mg/L]	TOC [mg/L]	NH_4-N [mg/L]	org. N [mg/L]	tot. P [mg/L]
WWTP Hannover-Herrenhausen	573.3	279.1	143.5	40.4	21.9	9.9
von Sperling and Chernicharo, raw	600	300	–	25	20	7
von Sperling and Chernicharo, modified with A-131	450	225	–	25	18	6

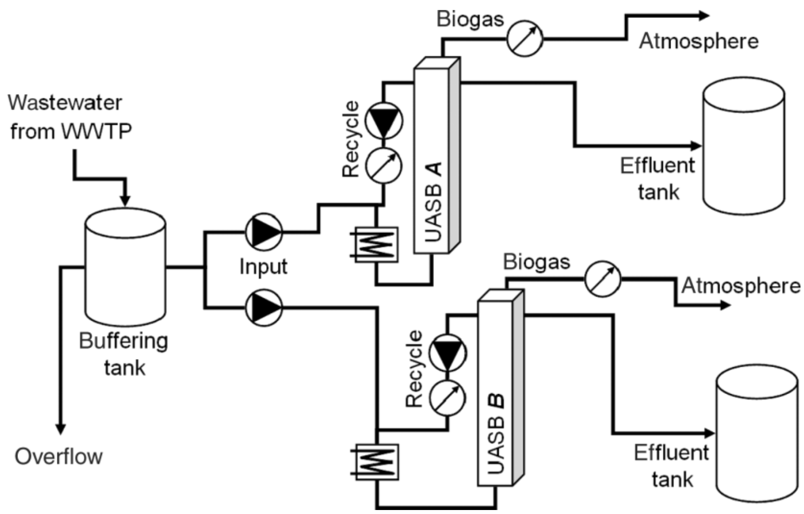

Figure 1 Flow scheme of the pilot plant at ISAH experimental place

After the first start up phase, in which the inoculum from the anaerobic digester had to adapt to the conditions in the UASB-tanks reactors, a methane yield of more than $200\,L_N\,CH_4/kg\,COD_{removed}$ was reached.

COD fraction

For the interpretation of the results the total COD_{tot} is fractionated as follows:

$$COD_{tot} = COD_{part} + COD_{diss} + COD_{CH_4} \quad (1)$$

with COD_{part}, (particulate COD), calculated as the difference of COD_{tot} and $COD_{diss,tot}$ minus $COD_{CH_4,gas}$; COD_{diss}, (dissolved COD), calculated as the difference of $COD_{diss.tot}$ and dissolved methane as $COD_{CH_4,diss}$; COD_{CH_4}, (methane as COD), calculated as the sum of $COD_{CH_4,gas}$ (measured methane in biogas) and $COD_{CH4,diss}$.

With these fractions was generated a simplified balance model of the anaerobic COD-elimination within the UASB reactor on the following assumptions:

- COD_{part} will remain mostly in the reactor and partially be hydrolysed, but a part of it is washed out depending on HRT.
- The remaining fraction of the COD_{part} will be disintegrated and hydrolysed to COD_{diss} in the reactor.
- COD_{diss} will, according to the maximum SMA of the sludge, be converted to COD_{CH4},

With these assumptions the COD degradation could be confirmed by the balance model with a total error of lower than 10% (relating to the total COD elimination).

Wash-out of particulate COD_{part}

Above all, the wash-out of the COD_{part} depends on the HRT. In order to quantify the amount of wash-out of COD_{part}, the empirical equation from von Sperling and

Table 3 Measured parameters in the pilot plants

Measuring point	Measured parameter
Influent	SS, total and dissolved COD, pH
Reactor	SS; VSS, Temp, pH
Biogas	Q, CH_4, CO_2
Effluent	SS, total and dissolved COD

Table 4 Selected operation data from the reactors (mean values from both plants)

Phase	HRT [h]	SLR [kgCOD/(kgVSS·d)]	CH_4 [L_N/$kgCOD_{rem}$]	Temp [°C]	COD-elimination [%]		
					tot.	diss.	part.
1 Start-up	31	0.11	152	25	70	74	67
2 Start-up	25	0.13	255	23	59	55	62
3 Steady state	25	0.14	247	25	65	63	66
4 Steady state	17	0.12	207	26	70	64	75
5 Steady state	9	0.14	222	25	66	73	59
6 Max. load	4	0.33	209	22	56	65	48
7 Low temp.	10	0.12	287	21	60	77	47

Chernicharo (2005) was transferred from effluent solids concentration to the load of COD_{part}. Equation 2 and Figure 2 provide the modified formula for the washed out COD:

$$L_{COD,part} = 5.9 \cdot V_{Reactor} \cdot HRT^{(-1.294)} [kg/d] \quad (2)$$

Equation (2) describes the inverse proportional dependency of the particulate, washed out COD load from HRT which is confirmed by the comparison of the measured COD load in both reactors and the calculated washed out load of COD_{part} (Figure 2).

Disintegration and hydrolysis of COD_{part}

The COD_{part} which remains in the reactor will be partially disintegrated and hydrolysed to $COD_{diss,hydr}$. The size of this fraction depends on the VSS/SS ratio and is mainly influenced by temperature. The HRT does not affect this process because the UASB works as a sedimentation tank and therefore the solid retention time (SRT) is decoupled from HRT. With a VSS/SS-ratio of 0.67 the amount of transformed COD can be calculated on the basis of Dimowski (1981):

$$L_{COD,diss,hydr.} = L_{COD,part,retained} \cdot 0.06 T^{(0.67)} [kg/d] \quad (3)$$

Moreover, the $COD_{diss,hydr}$ and the COD_{diss} from the input are an available source for the conversion into methane.

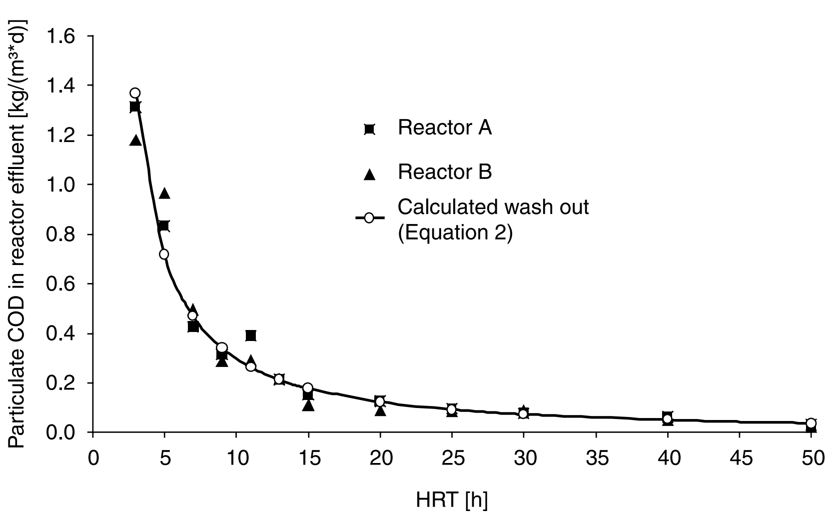

Figure 2 COD_{part} in reactor effluent

Biological degradation of COD_{diss} to CH_4

The specific methanogenic activity (SMA) and the amount of biomass in the reactor, measured as VSS, are the basic parameters which affect the maximum degradation from COD_{diss} to methane. The temperature also influences this process, as shown in the modified Arrhenius-equation by van Haandel and Lettinga (1994).

$$K(t) = K_{30} \cdot 1.11^{(T-30)} \tag{4}$$

Preliminary SMA-batch tests, carried out before the start-up phase, showed that the degradation rate of the inoculum while treating municipal wastewater is affected less than given in Equation (4) (Figure 3). Instead of the empirical factor 1.11 in Equation (4), a factor of 1.08 was calculated from the SMA-batch tests. Figure 3 also indicates the SMA obtained from the pilot plant operation in dependency of SLR.

A comparison of both SMAs has two main interesting aspects.

- Within the temperature range of 21–26°C in the pilot plant operation the observed temperature influence on SMA was very low.
- The SMA determined from the pilot plant is six times higher than the SMA of the batch-test with the inoculum from the digester, which is caused by the adaptation of the inoculum to the municipal wastewater which has a higher contingent of easily degradable dissolved COD than excess sludge in the digester.

On the basis of the data shown in Figure 3 the SMA is set in correlation to the sludge loading rate (SLR). In conjunction with the amount of VSS in the reactor, the biodegraded COD_{diss} per day can be calculated:

$$L_{COD,CH4.} = L_{VSS} \cdot 0.185 \mathrm{SLR}^{(0.59)} [\mathrm{kg/d}] \tag{5}$$

Comparison of measured and calculated COD-removal

Figure 4 shows the measured COD-elimination of each of the seven pilot plant operation phases (black column). For comparison the calculated COD elimination, based on the above defined fractioning, is added (dashed columns). Also, the deviation between these values is also given in Figure 4.

To calculate the COD elimination, only five parameters have to be measured: volumetric load [m^3/d], COD [mg/L] (fractionated in COD_{part} and $COD_{diss,tot}$),

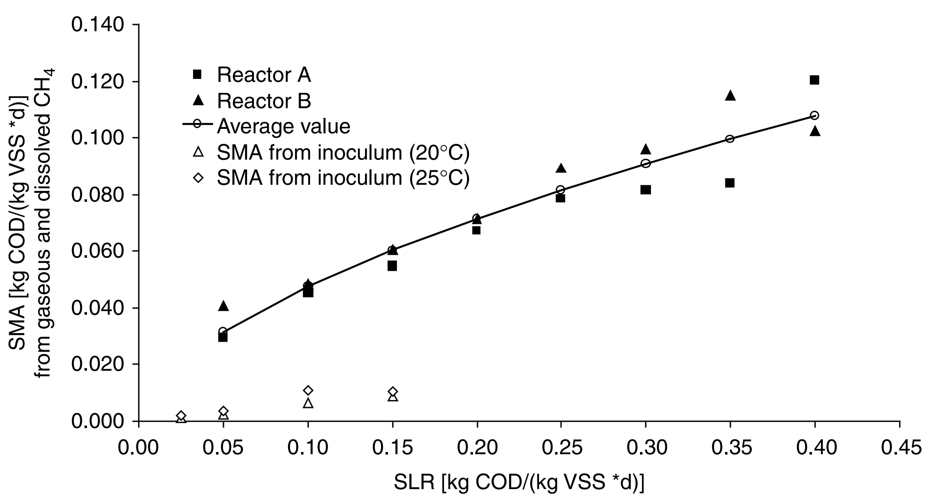

Figure 3 Specific methanogenic activity (SMA) measured with SMA-batch tests and UASB pilot plant

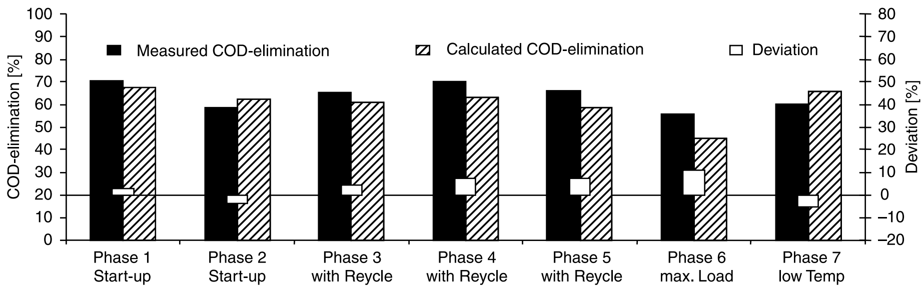

Figure 4 Comparison between measured and calculated COD removal

temperature [°C] and volatile suspended solids [kg VSS]. With these parameters all other values, such as HRT or SLR, could be determined.

For all phases a good correlation between the measured and calculated values is achieved. In phase 6 with the maximum load, and therefore limited degradation efficiency, the deviation rises to 11%. With decreasing HRT the SLR main increases, and the biomass exceeds its maximum SMA. However, based on the necessary contact time between the COD_{Diss} and the biomass, HRT becomes the limiting factor.

Greenhouse effect of the dissolved methane

Besides carbon dioxide, methane is one of the major greenhouse gases with a 21-times higher global warming potential (GWP) (European Commission, 2001), so it is essential to consider the CH_4 emission of the reactors.

The methane in the produced biogas is collected and burned in a combined heat and power plant to gain electricity and heat. Moreover, as municipal wastewater could be labelled as a "renewable" raw material, a "negative" GWP could be attributed to this part of methane.

The situation of the dissolved methane in the liquid phase is totally different. Depending on temperature, Henry's Law and the biogas composition, up to 35 mg/L CH_4 (rsp 140 mg/L COD) could be dissolved. Values between 20 and 25 mg/L CH_4 were reached within the pilot plant operation.

Table 5 Greenhouse gas emission of WWTPs at different treatment scenarios (Process data base: Keller and Hartley (2003); Greenfield and Batstone (2005))

Treatment scenario	kg CO_2/kg (COD resp. N)	kg CO_2/(Person · a)
1: Basic scenario:		
Activated sludge (C-Elimination)	1.44	42.05
Activated sludge (N-Elimination)	6.58	24.02
Mesophilic anaerobic digestion of sludge	− 1.10	− 26.50
Total emission		39.57
2: Anaerobic treatment with ANAMMOX		
Psychrophilic anaerobic digestion	− 1.36	− 44.68
ANAMMOX	2.47	9.02
Aerobic post treatment	1.44	10.51
Total emission		− 25.15*
3: Anaerobic treatment for irrigation, without usage of dissolved biogas		
Psychrophilic anaerobic digestion	− 1.36	− 44.68
Dissolved CH_4 in WWTP Effluent (CO_2-equivalent due to GWP)		38.63
Total emission		− 6.05

*This calculation is based on the supposition that all dissolved CH_4 in the effluent could be used. With no use of the dissolved CH_4 the plant would emit 13.48 kg CO_2/(Person a)

To enhance the amount of "negative" GWP with anaerobic WWT, as much CH_4 as possible has to be collected and used for energy production. Table 5 provides the greenhouse gas emission for three different scenarios. The first scenario is the basic scenario of wastewater treatment in Germany with an emission of nearly 40 kg CO_2/(P·a). If wastewater is treated with a plant comparable to the described pilot plant, a small surplus in the form of "negative" GWP could be gained. If we attempt to use the most energy-efficient strategy to treat the wastewater, a surplus of negative 25 kg CO_2/(P·a) could be reached (as shown in the second scenario).

Conclusions

The SMA-batch tests, as well as the operation of the pilot plant, showed that digested sludge is absolutely adequate as inoculum for UASB-based treatment of municipal wastewater. Though sludge granulation was not achieved in the pilot plant, the SMA of the established sludge was six times higher after the start-up phase and reached over 50% of the activity of granulars (measured in Abdel-Halim, 2005). Although the SMA of the flocculent sludge is lower, the flocculent sludge blanket has a main advantage compared to granulars. The flocculent sludge blanket works as a filter bed, retains solids, prevents the wash-out and hydrolysis of them

After over 400 days of pilot plant operation the basic parameters for the COD balance of anaerobic treated presettled municipal wastewater were evaluated. These static design parameters should now be implemented in a dynamic model of the process. In this case the combination of the biological process with the physical process of the three-phase-separation would be the main challenging point. Until now there is only a narrow range for the temperature from 21 to 26°C. Future operations with the next generation of pilot plant are running with a wider range of reactor temperatures to correctly represent the influence according to the Arrhenius-equation.

With the effluent a relevant part of the produced methane is left dissolved and at present is not used in the reactor. This means not only a loss of energy but also, due to the high GWP of methane, a huge emission of greenhouse gas. The CO_2 balance of the treatment system would be effectively improved by the use of the dissolved methane from the effluent. This could be achieved by stripping the methane from the effluent and reusing it for combustion.

This and other studies show that the anaerobic treatment of municipal wastewater should be considered as an environmentally sound alternative to "standard" aerobic treatment. The development of theses anaerobic treatment should beconsequently implemented, especially regarding the focus on the reduction of greenhouse gases.

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