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TREATMENT OF CONCENTRATED BLACK-WATER AND KITCHEN ORGANIC-WASTES IN ACCUMULATION SYSTEMS

معالجة مياه الصرف الصحي المنزلي السوداء المركزة والمخلفات العضوية للمطابخ في خزانات تراكمية

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الملخص العربي

معظم الملوثات الموجودة في مياه الصرف الصحي المنزلي مصدرها مياه دورات المياه (المياه السوداء). لذلك ففصل تلك المياه ومعالجتها على انفراد يعتبر احد الوسائل الحديثه للتخلص من ملوثات الصرف الصحي المنزلي ومعالجتها بطريقه اقتصاديه ومستدامه. في هذا البحث تمت دراسة استخدام الخزانات التراكمية لتخزين ومعالجة المياه السوداء بالطريقة اللاهوائية وقد تم تشغيل خزانين تراكميين الاول لمعالجة المياه السوداء كليا بينما الثاني لمعالجة المياه السوداء مفصولا عنها البول وقد تمت اضافة المخلفات العضوية الصلبة للمطابخ مع المياه السوداء الداخلة لكلا الخزانين. واظهرت النتائج ان المياه الداخلة للخزان الثاني ذات تركيز عالي للاوكسجين الكيميائي المستهلك (٥٤ جرام لكل لتر) ويعادل ثلاثة اضعاف تركيزه للمياه الداخلة للخزان الاول. كما ان النتائج اشارت الى ان اداء الخزانان كان مستقرا حيث لم يؤثر تركيز الامونيا على اداء البكتريا. بل اظهرت النتائج انخفاض تركيز المواد الدهنية المتطايرة في المياه الموجودة في الخزانين خلال زمن التشغيل مما يشير الى زيادة تركيز و تحسن كفاءة البكتريا اللاهوائية مع الزمن. وبعد ١٠٥ يوم من التشغيل وعند درجة حرارة ثابتة مقدارها ٢٠ درجة مئوية كانت النسبة المئوية لازالة الاوكسجين الكيميائي المستهلك متساوية في الخزانين ومقدارها ٥٨% ونتيجة لترسب المواد الصلبة الموجودة في المياه الداخلة في قاع الخزان الاول فان تركيز الاوكسجين الكيميائي المستهلك للمياه الموجود اعلى الخزان كان يعادل نسبة مئوية مقدارها ٢٠% من تركيزه للمياه الداخلة (اي يعادل نسبة مئوية لكفاءة ازالة مقدارها ٨٠%) كما لوحظ في الخزان الثاني ان نسبة مئوية مقدارها ٧٤% من الفوسفات الذائب في المياة الداخلة تمت ازالته وتحول الى فوسفات معلق وترسب في قاع الخزان. ولقد تم في هذا البحث عمل نموذج رياضي لمحاكاة تفاعل البكتريا اللاهوائية في الخزانات التراكمية ولقد تم عمل هذا النموذج وفقا لمقترحات منظمة المياه العالميه في الهضم اللاهوائي. ولقد اظهرت نتائج النموذج ان مدة التخزين للخزان التراكمي المعالج للمياه السوداء المضاف اليها المخلفات العضوية الصلبة للمطابخ يجب ان تزيد عن ١٠٠ يوم وذلك للحصول على نسبة مئوية لتحول المواد العضوية تفوق ٥٠% .

ABSTRACT

The feasibility of two accumulation-systems (AC) for anaerobic digestion and storage of concentrated black-water with (AC1) or without (AC2) urine + kitchen organic-wastes were investigated. The wastewater was collected by two vacuum toilet/transport systems. The influent-total chemical oxygen demand (COD_t) of the AC2 system (54000 mg/L) was more concentrated by 3 times than that of the AC1 system. The AC systems demonstrated stable performance. There was no inhibition effect of ammonium (NH_4) and volatile fatty acids (VFA) concentration decreased in time. COD_t removal of 58 % was achieved in both systems, after 105 days at 20°C. Moreover, if the supernatant in the AC1 system is only withdrawn and the settled sludge stays for the next runs, only

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20% of the influent total-COD will be in the supernatant. In the AC2 system, 74 % of influent orthophosphate was removed by precipitation. A mathematical model based on anaerobic digestion model no. 1 showed that the design filling-period for both AC systems should be higher than 100 days at 20°C for obtaining >50% conversion of the wastewater to methane.

KEYWORDS

Anaerobic digestion; black water; domestic wastewater; kitchen organic waste; modeling

INTRODUCTION

The existing paradigm for transport and centralised treatment of municipal wastewater is not a sustainable solution to be applied in the future. Such concept is too costly and complex to be installed, operated and maintained in developing countries, which suffer from a lack of wastewater collection and treatment facilities. The decentralised treatment of municipal wastewater based on separation between grey water and black water, and even between faeces and urine, represents a sustainable and, therefore, future concept for wastewater treatment, especially in rural areas. In the centralised concept, the wastewater is considered as a pollutant, while in the decentralised concept, the wastewater is used as a resource for fertiliser, water and even energy and for closing water and nutrient cycles (Zeeman & Lettinga [1], Elmitwalli *et al.* [2], Otterpohl *et al.* [3], Elmitwalli *et al.* [4]).

Anaerobic digestion represents a sustainable and low-cost technology for wastewater treatment, as no energy is needed for wastewater treatment and, moreover, the produced biogas can be utilised for energy production. In accumulation (AC) systems anaerobic-digestion and storage of wastewater are combined in one reactor (Zeeman [5]). The digested wastewater in the AC system can be applied on the fields, as a fertilizer. For proper operation of an AC system, a sufficient amount of suitable (adapted) inoculum should be added firstly to the system to start the anaerobic digestion process. Thereafter, the system can be started by filling the reactor with the wastewater over the storage period. The total volume of the AC system depends on the amount of provided wastewater and demanded storage-period. The process efficiency depends on the amount and methanogenic activity of inoculum, the temperature, the wastewater composition and storage period (Zeeman *et al.* [6], Elmitwalli *et al.* [4]).

The application potential of the AC system for black water treatment improves at increasing the concentration of the wastewater. This can be achieved by reducing the amount of water used in toilets flushing. In developing countries, the used water for toilets flushing seems limited, as compared to that in the developed countries, because the municipal wastewater of developing countries is more concentrated (Mahmoud [7], Halalsheh [8], Elmitwalli *et al.* [9]). Application of vacuum toilets, which are normally used in aeroplanes and ships, can result in a huge reduction of water used for toilet flushing. Conventional toilets consume 7-9 L/flush, while vacuum toilets only consume 0.7-1.0 L/flush. The vacuum toilets can easily be applied in developed countries, which do not suffer from frequent shut down of electricity, the main drawback of the vacuum toilets. Also, the vacuum toilets can also be applied in some places in the developing countries, where there is a lack of water resources, like the tourist area in Egypt and Gulf countries. In addition to black water, the AC system can also co-digest solids wastes, like organic kitchen-wastes, manure and agricultural wastes. The co-digestion of black water with solid wastes will increase the utilisation of biogas produced from the AC system, as solid wastes have high-organic content. Recently, an integrated sanitation concept with vacuum toilets, vacuum sewers and a bigas plant for black water and kitchen organic-wastes has been implemented for a new settlement (400 inhabitants) within the city of Lübeck, Germany (Otterpohl *et al.* [3]).

The aims of this research are: 1) Study the performance of two AC systems treating concentrated black-water (with and without urine)+ kitchen organic-wastes for a period of 105 days at a temperature of 20°C; 2) Developing a Model for the AC system based on International Water Association (IWA) Anaerobic Digestion Model No. 1, ADM1 (Batstone *et al.* [10]) and predicting the performance of the system at different operational conditions.

MATERIALS AND METHODS

Experimental set-up

Two identical accumulation reactors (AC1 and AC2 system) were connected to two vacuum toilets /transport systems (Roediger, Germany). Each vacuum system consisted of a vacuum toilet, vacuum pump, 10 L equalisation tank and wastewater pump (Figures 1). Each time that the vacuum toilet was used, it was flushed with 1.0 L of water and then the wastewater was transported to the equalisation tank. After the equalisation tank was filled up with 10 L, its content was emptied and brought to the AC systems. Each AC system is a closed tank made of polyethylene with height, diameter and maximum volume of 1.6 m, 0.98 m and 1.22 m^3, respectively. The headspace of each AC system was connected to a gas meter. On the reactor wall at equal distance of 0.2 m, 6 taps were mounted, for obtaining wastewater samples.

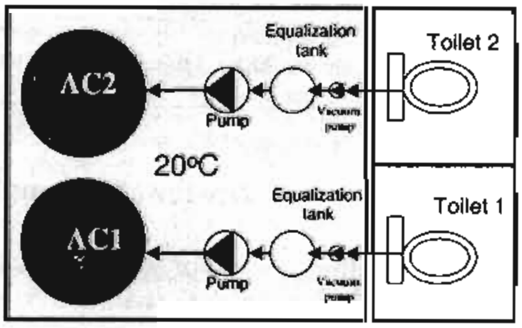

Figure1. Schematic diagram of the pilot AC system for anaerobic digestion of concentrated black water and kitchen organic-wastes.

The AC systems were installed in the Experimental Hall of Bennekom, The Netherlands. The systems were fed with the faeces and urine of the employees in the Hall, while the kitchen organic-wastes were collected from the Ede Hospital, The Netherlands. The AC1 and AC2 systems were fed with a mixture of faeces, urine and kitchen organic-wastes in an amount equivalent to daily production of one individual for each AC system. The difference between the two AC systems is the amount of urine. The AC2 system received less urine (about 0.2 litre per person per day, i.e. only the produced urine during defecation). The daily production of physiological wastes, was assumed based on Van der Wijst and Groot-Marcus [11]. Faeces, is produced once per person per day, while urine is produced 5 times/person/day. The generated kitchen organic-wastes volume produced by one individual was assumed to be 0.2 Kg based on statistical numbers for biowaste produced in the Netherlands (Gaillard [12]). Kitchen organic-wastes were added manually to the reactor via the toilets and flushed. For obtaining the real influent- wastewater quantity and revising the assumed flow, every person using the toilet was requested to fill a special form on the type of the provided wastewater (i.e. faeces, urine, faeces+ urine or extra flushing for more toilet cleaning) for each time of use. Table 1 shows the expected daily-production of concentrated black water + kitchen-wastes in households per individual, when a vacuum toilet (Roediger) is used for wastewater collection.

Anaerobic digestion of the concentrated wastewater is being performed in the AC systems for a period of 15 weeks (105 days). The AC systems were installed at a controlled-temperature room, adjusted at a temperature of 20°C. As there was no available inoculum sludge adapted with the wastewater (black water + kitchen wastes), which has high NH_4 concentration, the two AC systems were operated for a period of 150 days for adaptation of the inoculum sludge (primary digested sludge) with wastewater. Thereafter, the wastewater in both AC systems was stored for a period of 70 days for digestion of the remaining biodegradable organic matters at a temperature of 20°C. Then, for AC1 and AC2 system, respectively, 137 and 167 litres, of sludge settled on the bottom of each AC system were used as inoculum for this research.

Table 1. Expected daily-production of concentrated black water including kitchen-wastes in households per individual, when a vacuum toilet (Roediger) is used for waste collection.

Substrate	Daily production of 1 person	Water used for flushing x frequency of use (b)	Total water consumption by flushing	Total wastewater volume (L)
Faeces	138 gram (a)	1 liter per flush x 1	1 liter	1.138
Urine	1200 ml (a)	1 liter per flush x 5 times	5 liter	6.2
Kitchen organic-wastes	200 gram (a)	1 liter per flush	1 liter	1.2

(a): Gaillard [12]; (b): Van der Wijst and Groot-Marcus [11]

Sludge digestibility experiments

For determination of the remaining anaerobic biodegradable fraction in the wastewater accumulated in the system, anaerobic digestibility tests were performed in closed serum bottles of 0.5 litre at 30°C. The tests were carried out for the inoculum and the sludge from each tap of each reactor at the end of the continuous experiments. The tests were performed for a digestion period of, respectively, 320 and 215 days. The produced CH_4 in all batch experiments was measured by NaOH (5%) displacement.

Wastewater sampling and analysis

For characterisation of the influent black water (without kitchen wastes) of the AC systems, grab samples were taken from the content of the equalization tank, before kitchen organic-wastes addition. The composition of the kitchen organic wastes was measured separately. A mixture of equal-volume grab-samples taken from the taps in each reactor represented the content of each AC system. At the end of the experiment, the characteristics of the sludge from each tap in the AC systems were determined separately.

COD was determined as described by *Standard Methods* (APHA [13]). Raw samples were used for COD_t, 4.4 µm folded paper-filtered (Schleicher & Schuell 5951/2) samples for COD_f and 0.45 µm membrane-filtered (Schleicher & Schuell ME 25) samples for dissolved COD (COD_{dis}). The suspended COD (COD_{ss}) and colloidal COD (COD_{col}) were calculated by the differences between COD_t and COD_f, COD_f and COD_{dis}, respectively. Volatile fatty acids (VFA) were measured from membrane-filtered samples with a gas chromatograph, as described by Lier [14]. The biogas composition CH_4, CO_2, N_2 and O_2 was determined in a 100 µl sample using a gas chromatograph, described by Lier [14]. The Kjeldahl nitrogen (Kj-N) was measured according to the *Dutch Standard Normalized Methods, DSNM*, [15]. Total PO_4–P for wastewater was measured with an auto analyser (Skalar) after treatment according to *DSNM* [15], while NH^+_4-N and dissolved PO_4^{3-}-P were directly measured with the same auto analyser.

Calculations

Percentages of hydrolysis (H), acidification (A) and methanogenesis (M) in each AC system at the end of the experiment were calculated according to equations 1, 2 and 3 respectively.

$$H = 100\left(\frac{(acc.\ CH_4\ as\ COD/V) + COD_{dis}\ in\ the\ system\ at\ the\ end - influent\ COD_{dis}}{influent\ COD_{ss} + influent\ COD_{col}}\right) \tag{1}$$

$$A = 100\left(\frac{(acc.\ CH_4\ as\ COD/V) + VFA\ as\ COD\ in\ the\ system\ at\ the\ end - influent\ VFA\ as\ COD}{influent\ COD_t - influent\ VFA\ as\ COD}\right) \tag{2}$$

$$M\ (\%) = 100\left(\frac{(CH_4\ as\ COD/V)}{influent\ COD_t}\right) \tag{3}$$

Where: V = total volume of the wastewater enters each AC system.

Mathematical Modelling

A mathematical model based on ADM1 (Batstone *et al.* [10]) was developed. The aim of the model is to have more insight on the performance of the AC system and determine the relation between the operation parameters, which can lead to a proper design of the system. The model is based on first-order and Monod kinetics for, respectively, hydrolysis of biodegradable particulate and conversion of dissolved organic matter. Table 2 shows biochemical rate coefficients and kinetic rate equations for particulate and soluble components. As the AC system is characterized by having an influent flow, Q, but no effluent flow, the wastewater volume (V) is variable. Accordingly, the mass balance for any wastewater component, C (soluble or particulate) can be written according to Equation (4). In the model, it was assumed that the AC1 and AC2 systems were fed with wastewater 5 and 1 time/day, respectively, during operation. The model was carried out using the QBASIC program and applying numerical integration at small time interval of a minute for the AC systems.

$$\frac{dVC_i}{dt} = Q_{influent}\ C_{influent,i} + V \sum_{j=1-3} \text{rate coefficient} * \text{kinetic rate equation} \tag{4}$$

RESULTS AND DISCUSSIONS

Reactor feeding

Influent wastewater flow The influent wastewater flow was measured by two methods. The first method was based on the daily wastewater flow for each AC system (calculated based on the daily numbers of faeces, urine, kitchen organic-wastes and flushing added to each AC system) and the volume of each wastewater source based on literatures (as shown in Table 1). The results showed that the average, maximum and minimum influent wastewater volumes per week were, respectively, 33.9, 56.3 and 15.8 liters/week for AC1 system and, respectively, 21.4, 36.1 and 4.4 liters/week for AC2 system. This indicates that both AC systems were exposed to high flow variation. The second method for determination of the wastewater flow was based on the change in the wastewater height (i.e. volume) in time for each AC system. Figure 2 shows the wastewater accumulated in each AC system based on first and second method, respectively. The results indicate that the difference wastewater flow between the two methods is -10% and + 13% for, respectively, AC1 and AC2 systems.

Table 2. Biochemical rate coefficients and kinetic rate equations for particulate and soluble components in the simplified mathematical model.

Component $(i)\rightarrow$ / Process $(j)\downarrow$	X_b	X_i	X_m	S_b	S_{CH4}	S_i	Rate
Hydrolysis	-1			1			$K_h * X_b$
Conversion			Y	-1	(1-Y)		$K_m * S_b * X_m / (K_s + S_b)$
Decay	1		-1				$K_d * X_m$

X_b: biodegradable-particulate concentration (mgCOD/l), X_i: inert-particulate concentration (mgCOD/l), X_m: biomass concentration (mgCOD/l), S_b: biodegradable soluble-substrate concentration (mgCOD/l), S_{CH4}: converted substrate to methane (mg CH_4-COD/l), S_i: soluble-inert concentration (mgCOD/l), K_h: first-order hydrolysis constant (1/d), K_m: Monod maximum specific uptake rate (mg COD_S/mg COD_X.d), K_s: half saturation concentration (mg COD/l), Y: yield of biomass on substrate ((mg COD_S/mg COD_X), K_d: First order decay rate (1/d).

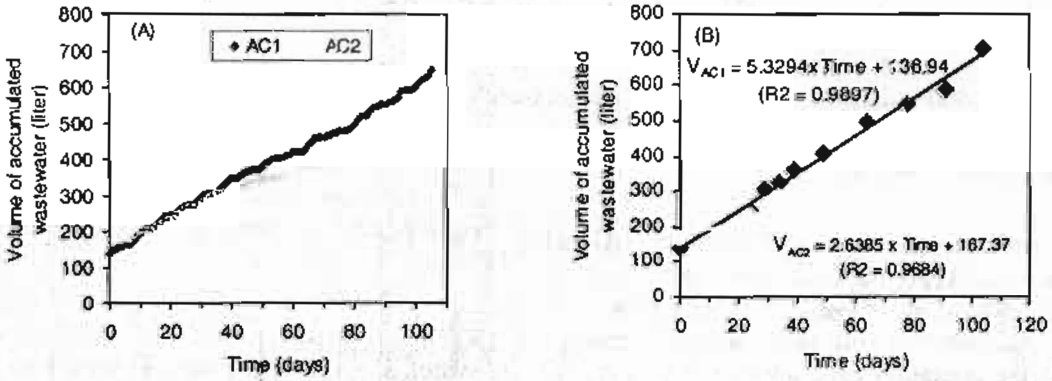

Figure 2. Accumulated influent wastewater volume in the AC systems based on the daily numbers of vacuum toilets usage and assumptions in Table 1 (A) and based on change in the wastewater height in the AC systems in time (B).

Characteristics of the influent wastewater Table 3 presents the characteristics of the influent black water and the influent wastewater (black water + kitchen organic-wastes) for the AC systems. The influent COD_t was more concentrated by 4 times in the AC2 system than that of the AC1 system and the influent Kj-N and total P were higher in the AC2 system by 1.5 and 3 times, respectively. The results showed that the COD_{ss} represented the major part of the influent COD_t in both AC systems (71-73%) and the COD_{col} represented the lowest COD fraction (< 2% of the COD_t) in the influent wastewater of both systems. The percentage of COD_{ss} in the black water (71-73 %) was higher than that in the raw domestic sewage (38-43 %, Elmitwalli *et al.* [16]), while the black water contained a lower fraction of COD_{col}, as compared to that of domestic sewage (25-30%, Elmitwalli *et al.* [16]). The percentage of COD_{dis} seems to be similar in both black water and domestic sewage (about 30% of COD_t).

Characteristics of the wastewater accumulated in the system

Figure 3 shows the course of COD fractions, pH and nutrients (N and P) in the AC systems. The results of both AC systems showed stable performance of the systems, especially after 40 days of operation. There was no inhibition effect of NH_4 and VFA concentration decreased in time in both systems (i.e. no VFA accumulation). Also, the pH values ranged between 7.2 and 7.6, which is in the suitable range for anaerobic digestion. After 105 days of operation, the average COD_t concentration was 7.8 and 22.8 g/L in, respectively, AC1 and AC2 system. This can indicate that the COD_t removal in the AC systems was as high as 58%.

Table 3. Characteristics of the influent black-water for the AC systems.

Waste water	System	pH	COD (mg/l)				Kj-N (mg/l)	NH4-N (mg/l)	Total P (mg/l)	PO4-P (mg/l)	VFA-COD (mg/l)
			Total	Suspended	Colloidal	Dissolved					
a) Measured values: -											
Black water	AC1	8.1	9966	7043	163	2760	1030	586	91	59	1905
		(0.9)*	(8920)	(6926)	(199)	(2023)	(628)	(496)	(10)	(29)	(1518)
	AC2	6.3	38835	28613	74	10148	1498	785	325	311	8887
		(0.7)	(20347)	(21062)	(56)	(1527)	(820)	(636)	(251)	(72)	(2717)
Black water + kitchen wastes	AC1		18668	15745	163	2760	1250	586	111	59	1905
	AC2		53642	43420	74	10148	1887	785	350	311	8887
*b) expected values***											
Black water + kitchen wastes	AC1	-	17900	-	-	5.8	1250	-	170	70	-
	AC2	-	54200	-	-	14.8	2100	-	450	170	-

* Standard deviation in two brackets

** Calculated Based on characteristics of faeces, urine and kitchen-wastes from the measurement of *Gaillard* (2002) and data in Table 1.

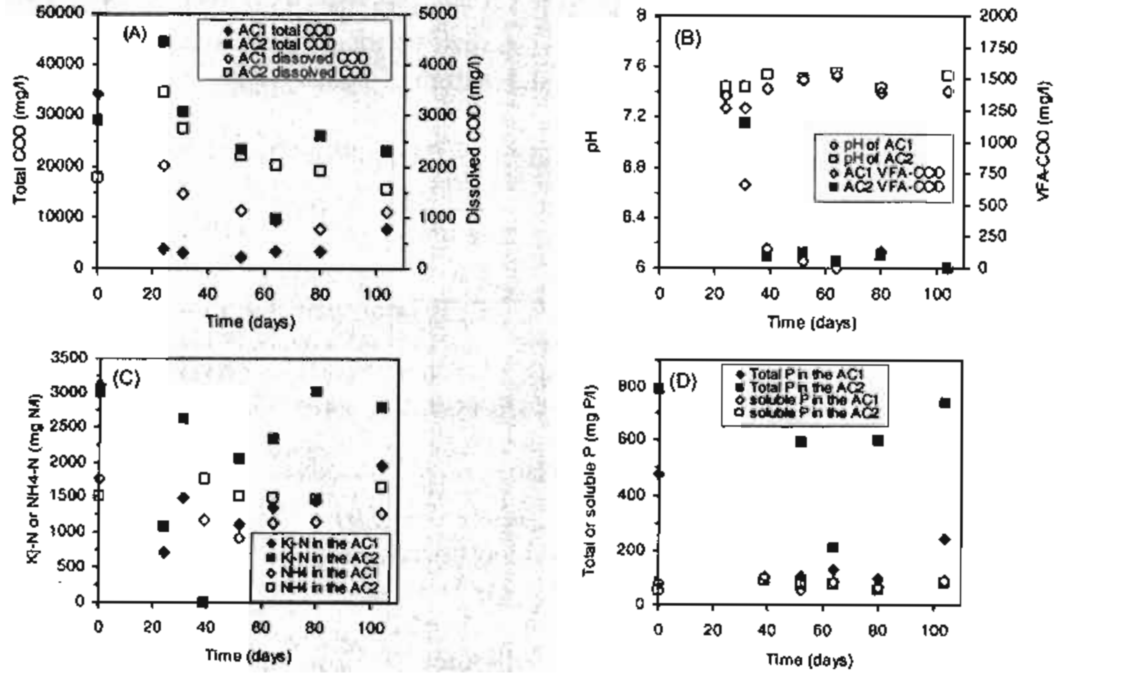

Figure 3. The course of COD fractions, nutrients and pH in the AC systems.

Wastewater profile in the AC systems at the end of the accumulation period

Table 4 shows the wastewater profile in the AC system after the operational period of 105 days. The COD_t profile in the AC1 system indicated that there was poor mixing in the systems (especially in AC1 system), as the sludge occupied only the lowest part of the system. The mixing occurred in the AC systems by the produced biogas and by influent wastewater pumping. The wastewater supernatant of the AC1 and AC2 systems (from tap 2) had only COD_t of, respectively, 3.5 and 4.8 g/L, which results from settling of particulate. Therefore, the bottom sludge of the AC systems had a higher COD_t concentration.

The Kj-N and NH_4-N concentrations of the supernatant and the bottom sludge of the AC system were higher than that of the influent wastewater due to high concentration of nutrients in the inoculum and protein hydrolysis. The soluble P content (80 mg/L) in the supernatant and on the bottom of the AC2 system was significantly lower than that of the influent wastewater (311 mg/L). The high removal of the soluble P (74 %) in AC2 system might be due to the formation of complexes, like struvite ($MgNH_4PO_4$) Loewenthal *et al.*[17], which can precipitate. This can lead to an increase of the total P content of the sludge on the bottom of the reactor. The total-P concentration of the sludge on the bottom of the AC2 system after an operational period of 105 days was 1310 mg/L, while that of the inoculum amounted to 790 mg/L. The inoculum sludge was produced during the first start up of 150 days of AC2 system. The P-total content of the inoculum was also higher than that of the influent (350 mg/L). Such results confirm the precipitation of P-complexes.

The results showed that the COD_t: Kj-N: total P (C: N: P) ratio for the sludge on the bottom of the AC systems changed with operational time. The C: N: P ratios for influent wastewater, inoculum and the sludge on the bottom of the AC system after an operational period of 105 days were, respectively, 170: 11: 1, 72: 6.5: 1 and 35: 4.5: 1 for AC1 system and were, respectively for 153: 5.4: 1, 37: 3.8: 1 and 32: 2.4: 1 for AC2 system. The change in the C: N: P ratio in the both systems demonstrated also that the total P increased for the sludge on the bottom of both systems.

Table 4. The profile of pH, COD fractions, and nutrients (N and P) in the AC system after an operational period of 105 days.

System	Tap	PH	COD (g/L) Total	Suspended +colloidal	Dissolved	Kj-N (g/L)	NH_4-N (g/L)	Total P (g/L)	PO_4-P (g/L)
AC1	1	7.33	20.4	19.2	1.02	2.63	1.31	0.578	0.083
	2	7.37	3.4	2.3	0.96	1.75	1.16	0.136	0.082
	3	7.43	3.5	2.1	1.18	1.76	1.21	0.135	0.087
	4	7.51	3.6	2.0	1.3	1.70	1.44	0.129	0.098
AC2	1	7.58	42.0	40.3	1.6	3.12	1.65	1.31	0.08
	2	7.48	4.8	2.7	1.5	2.44	1.62	0.17	0.083

Wastewater conversion in the AC systems

The results showed that the composition of the produced biogas from both AC systems was similar (70% methane and 30% carbon dioxide). Figure 4 shows the course of the daily biogas production and the accumulated methane production in AC systems. The monitoring of the biogas production started after 31 and 49 days of operation of AC2 and AC1 system, respectively, due to the failure of biogas meters. Moreover, in the AC1 system, the rate of biogas production was very low in the period between day 49 and day 80. The results showed higher values for hydrolysis, acidification and methanogenesis in AC2 system (46, 44 and 53 %, respectively), as compared to those for AC1 system (22, 19 and 28%, respectively). This might be due to the poor wastewater mixing in the AC1 system, which can reduce the contact between wastewater and biomass.

Digestibility of the wastewater in the AC systems and COD_t balance

The digestibility results showed that a relatively high amount of biodegradable particulate remained in the AC1 system (30%), while it was only 8% for AC2 system. However, these values represented only 11 and 4% of the COD_t added to, respectively, AC1 and AC2 system.

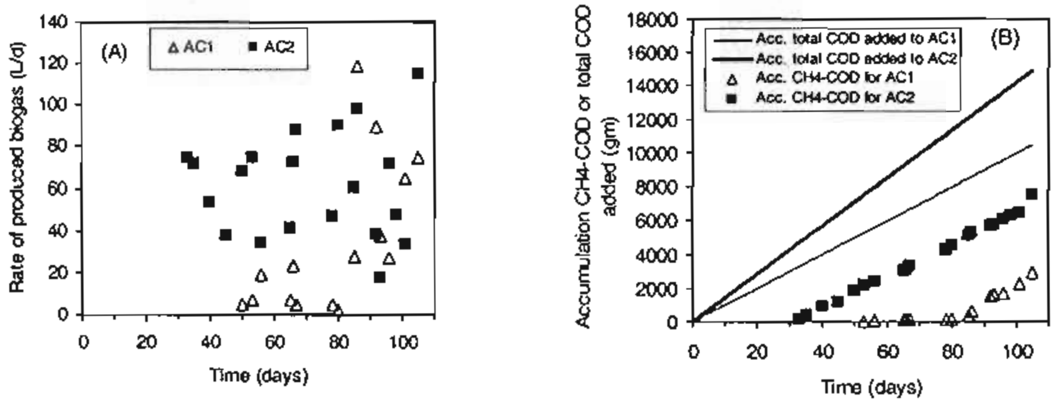

Figure 4. The course of daily biogas production and the accumulated influent total-COD and methane produced in AC systems.

Mathematical Modelling

Table 5 shows the values of the parameters applied in the model. Figures 5 and 6 show the model results and the corresponding experimental results. The model results for total and dissolved COD in AC1 system are higher than the experimental results, except the results at the end of the experiment. This different might be due to the poor mixing in the AC system. The VFA concentration and methane production rate in the AC1 system based on the model results are only similar to that of the experimental results, after 40 and 80 days, respectively.

The model results for the AC2 system are more similar to the experimental results, as compared to that of AC1 system, which indicates that mixing was sufficient in the AC2 system. The better mixing in the AC2 system is due to high-rate of biogas production in the AC2 system, as compared to that in AC1 system, as the influent wastewater concentration of AC2 system is more concentrated, as compared to AC1 system by 2.9 times.

After 105 days of operation, the model results (based on the assumption that the system is completely mixed) demonstrate that 53 and 58% of the COD_t added will be converted to methane in, respectively, AC1 and AC2 system.

Based on the model results, the biodegradable particulate (X_b), biomass (X_m) and inert particulate (X_i) represent, respectively, 16, 20 and 64 % of the particulate COD after an operational period of 105 days for both AC systems. The experimental results for the digestibility of the sludge on the bottom of the AC2 system showed similar results, like that of the model, for the biodegradable particulate (15%), while the digestibility of the sludge on the bottom of the AC1 system was significantly higher (30%), as compared to that of the model due to poor mixing. For an operation period of a year, the model results showed that the suitable filling-period for both AC systems should be higher than 100 days to guarantee sufficient hydrolysis and methanogenesis (>50 %).

Table 5. The values of the parameters applied in the model.

						References
COD Concentration: -	X_b	X_i	X_m	S_b	S_i	
AC1 influent	12980	2080	890	2200	550	
AC1 inoculum	0	20300	8700	0	6000	
AC2 influent	35000	5950	2550	8850	1300	
AC2 inoculum	0	19075	8175	0	1750	
Kinetic parameters: -	Y	K_d	K_s	K_m	K_h	This study, Batstone *et al.* [10]
	0.12	0.015	500	1.0	0.09	

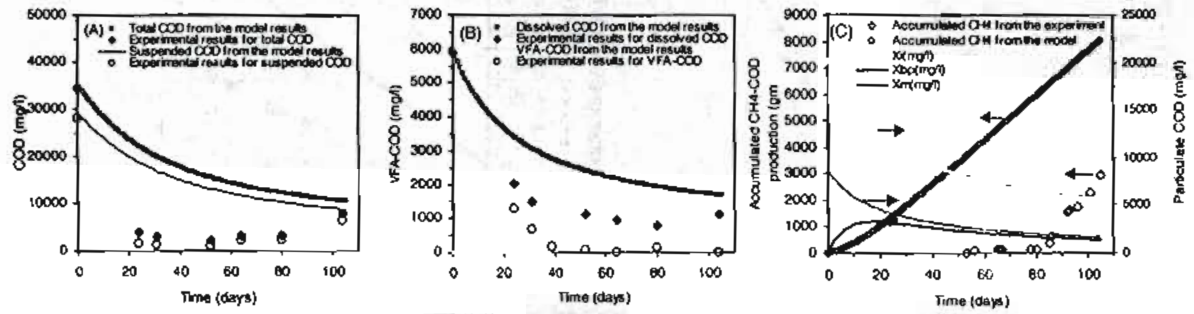

Figure 5. Mathematical model and the corresponding experimental results for the AC1 system operated for 105 days.

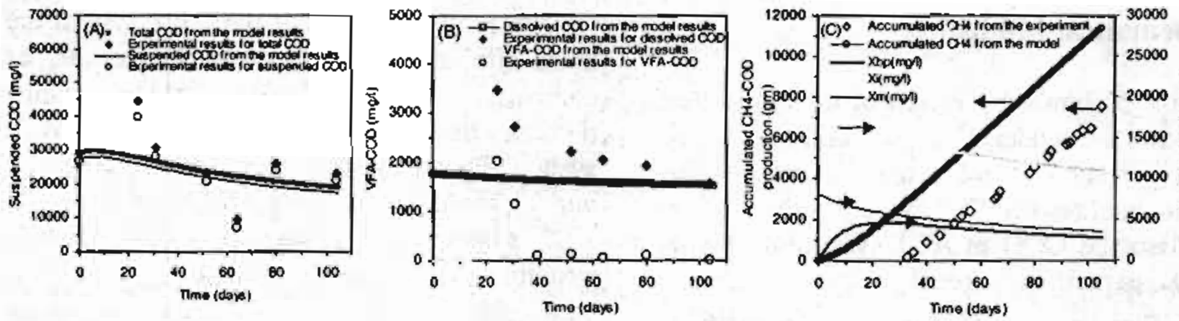

Figure 6. Mathematical model and the corresponding experimental results for the AC2 system operated for 105 days.

Final Discussion

The experimental results proved the great potential of anaerobic digestion for the concentrated black water + kitchen organic-wastes. Moreover, the model results are almost similar for experimental results of the AC2 system. This indicates that there is no need for a mixer in the AC system, when the influent wastewater is concentrated with COD_t as high

55 g/L (influent of AC2 system). Whereas for a dilute influent wastewater, like that of AC1 system (18 g/L), addition of a mixer can significantly increase the methanogenesis in the system (based on the experimental results without mixing and the model results for a completely mixed AC system). The mathematical model showed that the design filling-period for both AC systems should be higher than 100 days at 20°C for obtaining >50% conversion of wastewater to methane.

It was found that settling in the AC system results in a high COD_t removal (81 and 91 % in, respectively, AC1 and AC2 system) and the supernatant had a low COD_t (3.5 - 4.8 g/L). Therefore, for emptying of the AC systems, it is beneficial to remove only the supernatant after settling of the AC systems content. The benefit of that is to keep the non-hydrolysed part of biodegraded particulate (X_b) in the system as long as possible and, accordingly, improving the anaerobic digestion. Additionally, the separation between the supernatant will result in optimising the utilisation of the nutrients in system as agricultural fertliser, depending on plants requirement. The Supernatant has a low P content, while the settled sludge on the bottom of the system has a significantly higher value, as the soluble P is removed and precipitate on the bottom of the system.

CONCLUSIONS

1. The continuous pilot-experiment for AC system demonstrated that 53 % of COD_t added was converted to methane, after an operational period of 105 days at 20°C, when the system (AC2 system) fed with kitchen organic-wastes + faeces + only urine produced during defecation. However, only 28 % of the COD_t added was converted to methane, when the system (AC1 system) fed with kitchen wastes + black water. This was due to the poor contact between wastewater and biomass, as the SS settled on the bottom of the system and occupied only 20% of the total system volume.
2. The results of a mathematical model based on ADM1 demonstrated that a high conversion of 53% can be obtained in the AC1 system, when the system is completely mixed. Moreover, the model results showed that the mixing was sufficient in AC2 system, as the model results were similar to the experimental results.
3. The mathematical model showed that the design filling-period for both AC systems should be higher than 100 days at 20°C for obtaining >50% conversion of wastewater to methane.

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