TREATMENT OF DOMESTIC SEWAGE AT LOW TEMPERATURE IN A TWO-ANAEROBIC STEP SYSTEM FOLLOWED BY A TRICKLING FILTER

T. A. Elmitwalli*, J. van Lier**, G. Zeeman** and G. Lettinga**

ABSTRACT

The treatment of domestic sewage at low temperature was studied in a two-anaerobic-step system followed by an aerobic step, consisting of an anaerobic filter (AF) + an anaerobic hybrid (AH) + polyurethane-foam trickling filter (PTF). The AF+AH system was operated at a hydraulic retention time (HRT) of 3+6 h at a controlled temperature of 13^{o}C, while the PTF was operated without wastewater recirculation at different hydraulic loading rates (HLR) of 41, 15.4 and 2.6 $m^3/m^2/d$ at ambient temperature (ca. 15-18^{o}C). The AF reactor removed the major part of the total and suspended COD, viz. 46 and 58% respectively. The AH reactor with granular sludge was efficient in the removal and conversion of the anaerobically biodegradable COD. The AF+AH system removed 63% of total COD and converted 46 % of the influent total COD to methane. At a HLR of 41 $m^3/m^2/d$, the COD removal was limited in the PTF, while at HLR of 15.4 and 2.6 $m^3/m^2/d$, a high total COD removal of 54-57% was achieved without a significant difference between the two HLRs. The PTF was mainly efficient in the removal of particles, which were not removed in the anaerobic two-step. The overall total COD removal in the AF+AH+PTF system was 85%. Decreasing the HLR from 15.4 to 2.6 $m^3/m^2/d$, only increased the nitrification rate efficiency in the PTF from 22% to 60%. Also, at HLR of 15.4 and 2.6 $m^3/m^2/d$, PTF showed a similar removal for *E-coli* by about 2 log. Therefore, the effluent of AF+AH+PTF system can be utilised for restricted irrigation in order to close water and nutrients cycles. Moreover, such a system represents a high-load and a low-cost technology, which is a suitable solution for developing countries.

KEYWORDS

Anaerobic treatment; domestic sewage; low temperature; post treatment; trickling filter

---

* Department of Civil Engineering, Benha High Institute of Technology, P.O. Box 13512, Benha El-Gedida, Benha, Egypt (*E-mail: t_elmitwalli@yahoo.com*)
** Sub-Department of Environmental Technology, Wageningen University, P.O. Box 8129, 6700 EV Wageningen, The Netherlands

1. INTRODUCTION

High-rate anaerobic systems represent low-cost and sustainable technology for domestic sewage treatment, because of its low construction, operation and maintenance costs, small land requirement, low excess sludge production and production of biogas. Although anaerobic treatment plants have been successfully operated in tropical countries, the process up till now did not applied at countries with moderate and low temperatures. At such temperature, the chemical oxygen demand (COD) removal is limited and a long hydraulic retention time (HRT) is needed for one-step system for providing sufficient hydrolysis of particulate organics (Zeeman and Lettinga, [1]). Several investigators (Wang, [2], Elmitwalli *et al.*, [3, 4, 5, 6, 7, 8]) revealed that at low temperatures pre-removal of SS is needed prior to anaerobic treatment in a methanogenic sludge-bed reactor. Wang [2] developed a two-step system, UASB (upflow anaerobic sludge blanket) +EGSB (expanded granular sludge bed) reactor, for the treatment of domestic sewage at low temperatures. The first-step is aimed at removal and partial hydrolysis of suspended COD (COD_{ss}) and the second-step mainly for conversion of dissolved COD (COD_{dis}) to methane gas.

Recently, Elmitwalli *et al.* [7] showed that the AF achieved higher removal efficiency for COD_{ss} as compared to the AH reactor with flocculant sludge and the conventional UASB reactor, as operated by Wang [2]. In the AF reactor, vertical sheets of reticulated polyurethane foam (RPF) with knobs were applied as packing material. A sludge bed was not allowed to develop in the reactor. So, all biomass retained in the reactor was attached to the RPF sheets. Also, Elmitwalli *et al.* [3] compared between a UASB and an AH reactor with a granular sludge-bed both at 8 h HRT for the treatment of pre-treated (pre-settled) sewage at a temperature of 13^oC. At 'steady state', the AH reactor removed higher total COD (COD_t) as compared to the UASB reactor, due to higher removal of colloidal (COD_{col}). Based on these results, the use of an AF reactor with vertical sheets of RPF with knobs followed by an AH reactor with granular sludge, was considered as an appropriate process configuration for the anaerobic treatment of raw domestic sewage at low temperatures.

Despite the advantages of the anaerobic treatment, the anaerobic effluent still needs post treatment for removing the remaining COD, nutrient and pathogen. Table 1 shows a summary of the results of recent researches in the anaerobic+post treatment of domestic sewage. The post treatment system for the anaerobic effluent should be, like the anaerobic pre-treatment, a high-rate, low-cost and sustainable technology. Various high-rate aerobic systems have been proposed for post-treatment, such as submerged aerated biofilter (Collivignarelli *et al.*, [9]), aerobic fluidized bed (Kim *et al.* [10]), rotating biological contactor (RBC) (Castillo *et al.*, [11]), down-flow hanging sponge cubes (Machdar *et al.* [12]), activated sludge (Sperling *et al.*, [13]). The application of such high-rate systems need high-investment, operation and maintenance costs and replacement of mechanical equipment, like aerators, recirculation pumps, and RBC shaft and bearing (Mba *et al.*, [14]). A trickling filter represents a high-rate system with low-cost, when it is operated by gravity without wastewater recirculation (i.e. when the COD_t of the wastewater is rather low, like the anaerobic effluent).

Table 1. Summary of the results of researches in the anaerobic + post treatment of sewage.

System	Anaerobic reactor			Post treatment system			COD	Reference
	HRT h	Influent COD	Effl. COD (% Removal)	HRT	Effl. COD (% Removal)	% NH_4 removal	Removal (%)	
UASB+DHS[1]	7	672	144 (80)	1.3 h	40 (71)	74	94	Machdar *et al*., [12]
UASB+2RBC	3-48	502-625	(22-55)	0.75-4 h	(84-88)	43-86		Castillo *et al*., [11]
UASB+2AF[2]	4–6	413-864	87-142	1.5-24 h	60-90	-	81-93	Chernicharo *et al*., [15]
UASB+UAF[3]	4-16	463	112 (73)	0.11-0.4h	49 (56)	-	88	Goncalves *et al*., [16]
UASB+SP[4]+FP[5]	-	203	-	20 d	121	48	-	Gosh *et al*., [17]
UASB+DHS	7	672	144 (80)	-	40 (71)	78	94	Araki *et al*., [18]
UASB+AS[6]	4-6	386 -958	85-180	3.9-5.2 h	50-128	-	85-93	Sperling *et al*., [13]

[1]; down flow hanging sponge; [2], anaerobic filter; [3], upflow aerobic filter; [4], stabilisation pond; [5], fish pond; [6], activated sludge

From the large variety of available synthetic packing-materials for biofilm, the most suitable are presumed to have a high specific surface, a high porosity and a rough surface, while they also should be oriented in a correct way to avoid clogging. Based on these considerations, vertical sheets of RPF with knobs were selected for this research. RPF media are characterised by a high specific surface area, viz. up to 2400 m^2/m^3 and a high porosity of 97% (Huysman *et al*., [19]). Moreover, the vertical orientation of the RPF sheets with knobs allows the wastewater and biomass to move through the reactors and consequently clogging of the filter medium is prevented (Elmitwalli *et al*., [7]). The objective of the present research is to assess the performance of a two anaerobic-step system (AF+AH) followed by an aerobic-step (PTF) for treatment of domestic sewage at low temperature. The media in the three reactors were vertical sheets of RPF with knobs.

2. MATERIAL AND METHODS

2.1. Experimental set-up

Fig. 1 shows a schematic diagram of the experimental set-up, consisting of an AF reactor (60 L), an AH reactor with granular sludge bed (65 L) and PTF reactor with settler. The diameter of both the AF and the AH reactor was 0.19 m and the heights were 2.1 and 2.3 m respectively. The media of the trickling filter were three vertical sheets of RPF with knobs. Each sheet had a height of 1.7 m and width of 0.06 m. The volume of the PTF settler was 0.27 L. The wastewater temperature in the AF and AH reactors was controlled at 13^{o}C by recirculating thermostated water through a tube placed around the reactors. The trickling filter was operated at ambient temperature and the wastewater temperature ranged between 15-18^{o}C. The AF+AH system was operated for 342 days, 144, 81 and 117 days at HRTs of respectively 4+8, 2+4 and 3+6 h. The trickling filter was operated, when the AF+AH system was operated at an HRT of 3+6 h. The trickling filter was operated for 36, 44 and 37 days at hydraulic loading rates (HLR) of 41, 15.4 and 2.6 $m^3/m^2/d$ respectively, at a corresponding HRT of 1, 2.5 and 15 h respectively and organic loading rates of 5.4, 2.1 and 0.36 $kgCOD_t/m^3/d$ respectively.

2.2. Sewage

The system was fed with domestic sewage originating from the village Bennekom, The Netherlands. The sewage (Table 2) is collected in a combined sewer system.

2.3. Analysis

COD was assessed using the micro-method described by Jirka and Carter [20]. Raw samples were used for COD_t, 4.4 μm folded paper-filtered samples for COD_f and 0.45 μm membrane-filtered samples for COD_{dis}. The COD_{ss} and COD_{col} were calculated by the differences between COD_t and COD_f, COD_f and COD_{dis} respectively. For determining the particles size distribution (PSD) of raw sewage and the effluent of each reactor, the wastewater COD was measured for raw samples and samples after filtration at filters with pore size of 22.5, 8, 4.4, 1.6 and 0.45 μm. The PSD was determined three times for each wastewater, when the PTF reactor was operated at HLR of 15.4 $m^3/m^2/d$. 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 Elmitwalli *et al.* [3]. The total Kjeldahl nitrogen (Kj-N), sludge volume index (SVI), suspended solids (SS) and volatile suspended solids (VSS) were measured according to the *Dutch Standard Normalized Methods,* [21]. *E-coli* (measured for raw and paper-filtered samples) was analysed according to Havelaar and During [22]. Total PO_4–P for wastewater was measured with an auto analyser (Skalar) after treatment according to the *Dutch Standard Normalized Methods* [21], while $NH^+{}_4$-N and dissolved PO_4^{3-}-P were directly measured with the same auto analyser. The amount of dissolved methane in the effluent was calculated according to Henry's Law. Statistical comparison of the performance of the reactors between different HRTs was done as described by Elmitwalli *et al*. [3] and a significant difference is considered at a level higher than 95%.

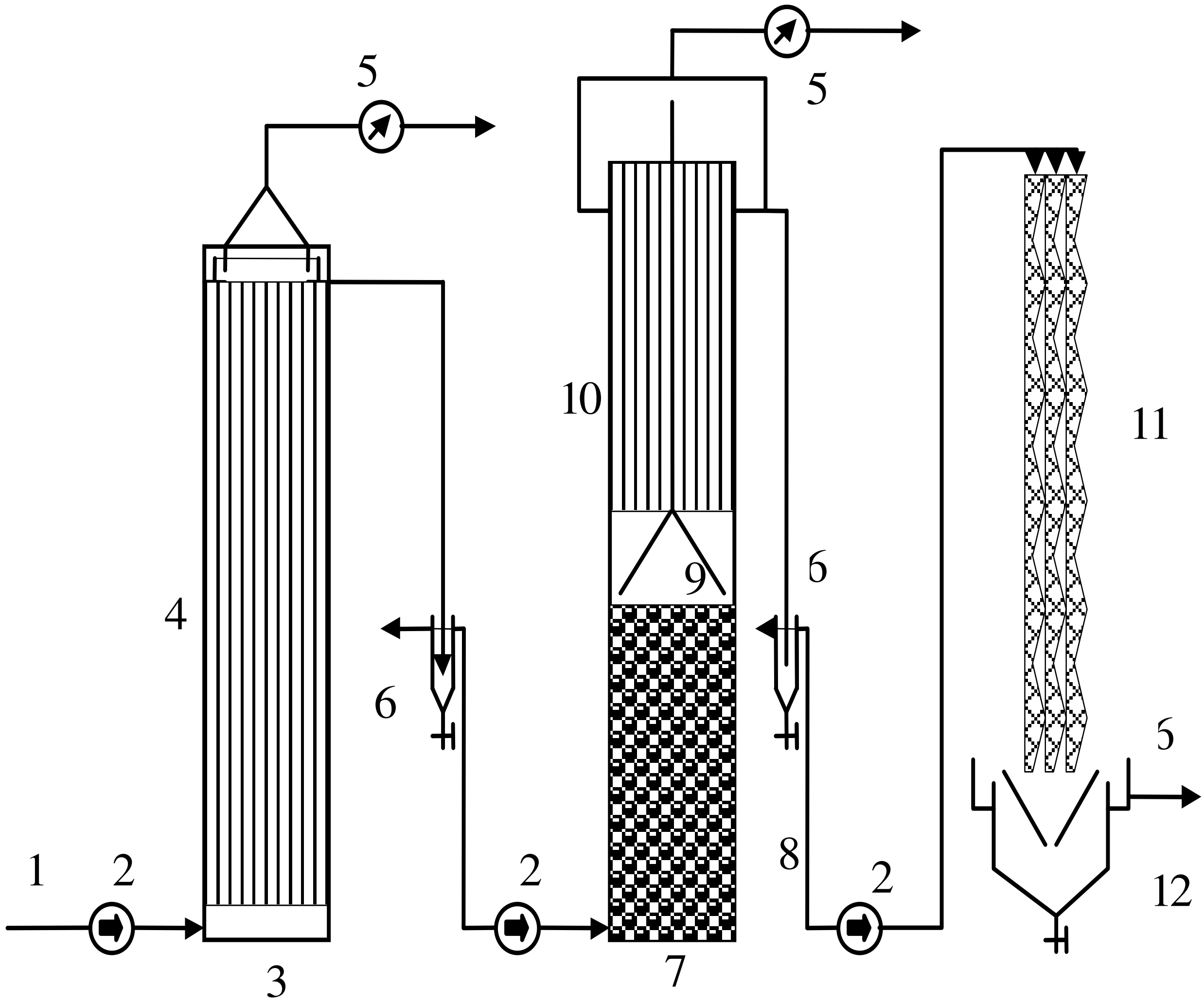

Fig. 1. Schematic diagram of the experimental set-up. 1, influent; 2, peristaltic pump; 3, AF reactor; 4, media of the AF reactor; 5, gasmeter; 6, effluent of the reactor; 7, AH reactor; 8, granular sludge bed; 9, gas-solids separator; 10, media of the AH reactor; 11, trickling filter media; 12 settler of the trickling filter.

Table 2. Characteristics of the domestic sewage used in the experiment. Standard deviation is presented in brackets.

Parameter	Unit	Value	Parameter	Unit	Value
COD_t	Mg/L	533 (86)	Colloidal proteins	Mg/L	56 (15)
COD_{ss}	Mg/L	173 (76)	Dissolved proteins	Mg/L	26 (17)
COD_{col}	Mg/L	191 (123)	N-Kj	Mg/L	70 (3)
COD_{dis}	Mg/L	169 (68)	NH^+_4-N	Mg/L	48 (10)
COD-VFA	Mg/L	53 (11)	Total PO_4-P	Mg/L	9.4 (1.3)
Total carbohydrates	Mg/L	55 (11)	Dissolved PO_4^{-3}-P	Mg/L	5.9 (0.7)
Suspended carbohydrates	Mg/L	36 (9)	Suspended PO_4	Mg/L	3.6 (0.7)
Colloidal carbohydrates	Mg/L	10 (3)	Total *E-coli*	*E-coli*/100 mL	7.3×10^6 (2.3×10^6)
Dissolved carbohydrates	Mg/L	9 (4)	Suspended *E-coli*	*E-coli*/100 mL	2.5×10^6 (1.4×10^6)
Total proteins	Mg/L	110 (16)	Paper-filtered *E-coli*	*E-coli*/100 mL	4.8×10^6 (2.2×10^6)
Suspended proteins	mg/L	28 (11)			

3. RESULTS AND DISCUSSION

3.1. COD removal and conversion

The results in Table 3 show the concentration of different COD fractions and removal efficiencies at the treatment of domestic sewage in the system. Most of the COD_t was mainly removed in the two-anaerobic steps, which led to a substantial decrease of the organic loading on the aerobic step (PTF reactor). Although the AF reactor was operated at a short HRT of 3 h at a low temperature of 13^{o}C, the reactor removed the major part of the COD_t (41-57%) and COD_{ss} (58%). Therefore, the AH reactor effectively converted the anaerobically biodegradable COD to biogas. The removal of COD_{dis} in the AF+AH reactor was almost equal to the maximum removal for COD_{dis} (54%) as reported by Last and Lettinga [23] for the same wastewater. Moreover, the two-step, AF+AH, system converted 46 % of the influent COD to methane, which represented 72-82% of the biogas content. Unlike the low temperature and the short HRT, the average effluent COD_t concentration was only 182 mg/L, which is similar to that found in tropical countries at higher wastewater temperatures > 20^{o}C (Draaijer *et al*., [24]).

The COD_t removal efficiency was limited in the PTF when a HLR of 41 $m^3/m^2/d$ was applied. However, significantly higher removal efficiencies for COD_t, COD_{ss} and COD_{col} were achieved at both HLRs of 15.4 and 2.6 $m^3/m^2/d$, without a significant difference between both HLRs. The AF+AH system removed 71-80% and 44-68% for respectively COD_{ss} and COD_{col} and the addition of the PTF at HLRs of 15.4 and 2.6 $m^3/m^2/d$ increased the overall removal for these two fractions in the system to 95-97% and 86-95% respectively. Therefore, the aerobic post treatment step (PTF) is highly efficient in the removal of particles (COD_{ss} and COD_{col}), which were not removed in the anaerobic system. The PTF removed 12-21% of COD_{dis} at HLR between 2.6 and 15.4 $m^3/m^2/d$. The PTF only decreased COD_{dis} from 64-69 mg/L to 49-60 mg/L. This observed COD_{dis} removal in the aerobic-step might be even due to the removal of very fine particles <0.45 μm (the pore size of membrane COD; i.e. COD_{dis}).

Table 3. COD fraction concentration (mg/L) and removal efficiency (%) in the treatment of domestic sewage in the AF+AH+PTF system. Standard deviation is presented in brackets.

Wastewater (Reactor)	Period*	Wastewater concentration (mg/L)				Reactor removal efficiency (%)			
		COD_t	COD_{ss}	COD_{col}	COD_{dis}	COD_t	COD_{ss}	COD_{col}	COD_{dis}
Raw	1	482(97)	171(43)	150(16)	162(43)				
	2	501(96)	219(31)	142(35)	140(32)				
	3	487(51)	139(10)	148(37)	200(10)				
AF effluent	1	285(77)	72(25)	105(21)	108(31)	41(4)	58(5)	30(7)	33(2)
(AF)	2	286(40)	91(20)	106(34)	89(16)	43(7)	58(15)	25(15)	36(13)
	3	208(30)	60(19)	72(29)	76(16)	57(8)	57(24)	51(16)	62(7)
AH effluent	1	225(38)	48(26)	84(10)	94(10)	21(8)	36(15)	19(15)	11(16)
(AH)	2	188(23)	44(14)	79(16)	64(16)	34(8)	50(14)	18(27)	27(15)
	3	156(27)	40(24)	47(16)	69(14)	23(19)	31(31)	29(23)	9(8)
PTF effluent	1	193(38)	11(7)	96(25)	86(7)	14(3)	77(2)	-14(29)	9(3)

(PTF)	2	80(15)	11(11)	20(10)	49(7)	57(14)	75(29)	75(14)	23(23)
	3	72(4)	4(3)	8(7)	60(10)	54(7)	90(12)	83(15)	13(13)
(AF+AH)	1					53(2)	72(10)	44(6)	42(9)
	2					62(8)	80(13)	44(18)	54(8)
	3					68(4)	71(13)	68(9)	66(6)
(AF+AH+ PTF)	1					60(1)	94(3)	36(10)	47(10)
	2					84(6)	95(11)	86(11)	65(10)
	3					85(1)	97(2)	95(4)	70(5)

* Period 1, 2 and 3 for the HLR of 41, 15.4 and 2.6 $m^3/m^2/d$ respectively for the PTF.

Fig. 2 shows the PSD for the raw sewage and the effluent of each reactor, when the PTF was operated at HLR of 15.4 $m^3/m^2/d$. The particles in the range >22.5, 1.6-0.45 µm and < 0.1 µm represented the major part in raw sewage and the anaerobic effluent, 80 and 70% respectively, while the particles <1.6 µm represented the major part of the PTF effluent (85%), Fig. (2.A). The results showed that the anaerobic treatment resulted in a removal of the large particles and the effluent mainly contained colloidal and dissolved organics. The aerobic (PTF) process removed mainly the colloidal particles from the aerobic effluent and the removal dissolved COD was limited (Fig. 2.B). The average effluent COD for the AH and PTF reactor after filtration at filter with pore size of 0.1 µm was 41 and 35 mg/l respectively, which indicates that the removal of domestic-sewage COD_{dis} can be considered the same under anaerobic and aerobic conditions.

The excess sludge produced in the AF+AH system mainly originated from the AF reactor. The excess sludge in the AF reactor had a concentration of 8 gVSS/L and amounted to 20-30% of the removed COD_t in the AF+AH system, while the excess sludge production in the AH reactor only amounted to 0.5-1.5 %. SVI of the excess sludge produced in the AF reactor was 39 mL/gSS, which indicates good settlability. The amount of excess sludge produced per removed COD in the PTF was similar for both applied HLR of 15.4 and 2.6 $m^3/m^2/d$ and reached 0.61-0.69 gVSS/gCOD removed. The excess sludge production in PTF reactor had a concentration of 1.6-3.9 gVSS/L with a SVI of 46 mL/gSS.

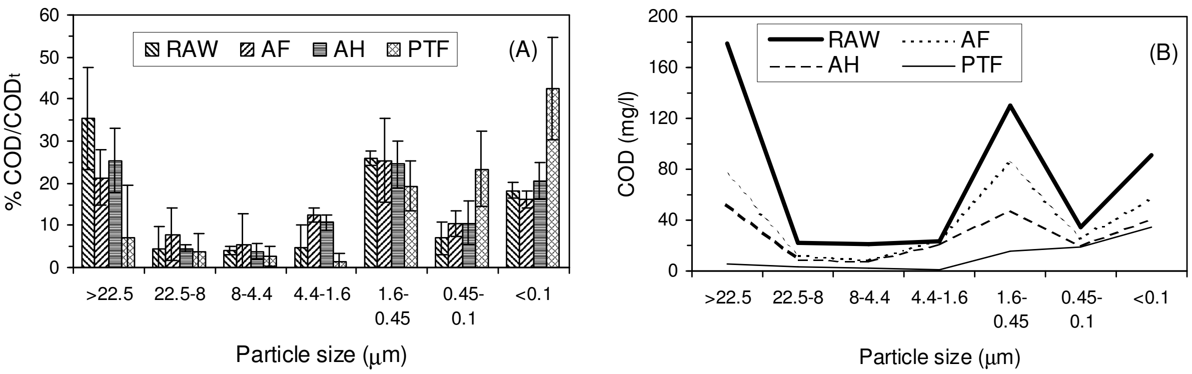

Fig. 2. Particles size distribution for the raw sewage and the effluent of each reactor, when the PTF was operated at HLR of 15.4 $m^3/m^2/d$.

3.2. Nutrients (N and P) removal

Table 4 shows the concentration of the nutrients at the treatment of domestic sewage in the system. Due to the poor performance of the PTF at HLR of 41 $m^3/m^2/d$, only the results at HLR of 15.4 and 2.6 $m^3/m^2/d$ are presented. The removal of Kj-N was limited and not significant in the anaerobic system (6-10 %) and mainly due to the removal of particulate Kj-N. At a HLR of 41 $m^3/m^2/d$, no ammonia removal was achieved in the PTF, while at HLRs of 15.4 and 2.6 $m^3/m^2/d$, it was 22 % and 60 % respectively. The decrease of the HLR from 15.4 to 2.6 $m^3/m^2/d$ resulted in an increase of NO_3 production from 3.5 to 13.6 NO_3-N mg/L. The removal of total phosphate in the whole system was limited (23-25%) and was mostly due to the removal of particulate phosphate.

Table 4. The concentration of the nutrients (N and P) in the treatment of domestic sewage in the AF+AH+PTF system at HLR of 15.4 and 2.6 $m^3/m^2/d$. Standard deviation is presented in brackets.

Parameter	Unit	HLR = 15.4 $m^3/m^2/d$				HLR = 2.6 $m^3/m^2/d$			
		Raw	AF	AH	PTF	Raw	AF	AH	PTF
NKj-N	(mg/L)	70.4	67.1	66.2	43.4	73.1	71.3	65.5	31.7
		(1.9)	(5.9)	(6.8)	(13.9)	(7.5)	(6.5)	(4.7)	(7.2)
NH_4-N	(mg/L)	52.1	52.5	53.9	41.9	55.8	56.3	56.5	22.4
		(11.1)	(13.9)	(10.9)	(7.4)	(8.4)	(8.6)	(10.4)	(8.9)
NO_2-N	(mg/L)	0	0	0	8.4	0	0	0	9.8
					(8.3)				(5.5)
NO_3-N	(mg/L)	0	0	0	3.5	0	0	0	13.6
					(2)				(8.4)
Total PO_4-P	(mg/L)	9.5	7.3	7.1	7.1	9.1	7.7	7.6	7.4
		(1.3)	(1.5)	(1.6)	(0.9)	(1.4)	(1.1)	(0.7)	(1.2)
Ortho PO_4-P	(mg/L)	5.7	5.6	6.1	6.2	6.3	6.8	6.4	6.5
		(0.7)	(0.6)	(0.7)	(0.6)	(0.9)	(0.9)	(1.5)	(1.5)

3.3. E-coli removal

Table 5 presents the *E-coli* concentration at the treatment of domestic sewage in the system at HLR of 15.4 and 2.6 $m^3/m^2/d$. The results showed that *E-coli* present in domestic sewage is mainly associated with colloidal particles. The removal of *E-coli* was limited in the anaerobic system (less than 1 log) and mainly associated with the removal of suspended particles. The removal of *E-coli* mostly occurred in the PTF without effect of HLR decreasing from 15.4 to 2.6 $m^3/m^2/d$. The PTF removed *E-coli* by about 2 log. Therefore, the whole system reduced *E-coli* in domestic sewage from 8-4.2 x 10^6 to 2.4-3.5 x 10^4 *E-coli*/100 mL.

Table 5. The concentration of *E-coli*/100 ml in the treatment of domestic sewage in the AF+AH+PTF system at HLR of 15.4 and 2.6 $m^3/m^2/d$. Standard deviation is presented in brackets.

Period	Raw		AF		AH		PTF	
	Total	Paper-filter	Total	Paper-filter	Raw	Paper-filter	Raw	Paper-filter
HLR = 15.4 $m^3/m^2/d$	$8x10^6$ ($1.9x10^6$)	$5.4x10^6$ ($2.1x10^6$)	$2.3x10^6$ ($0.8x10^6$)	1.8x106 ($0.7x10^6$)	$1.4x10^6$ ($0.4x10^6$)	$1.2x10^6$ ($0.8x10^6$)	$2.4x10^4$ ($1x10^4$)	$2x10^4$ ($1x10^4$)
HLR = 2.6 $m^3/m^2/d$	$4.4x10^6$ ($1x10^6$)	$3.2x10^6$ ($1x10^6$)	$1.1x10^6$ ($0.5x10^6$)	$1x10^6$ ($0.5x10^6$)	$1.2x10^6$ ($1x10^6$)	$0.9x10^6$ ($0.7x10^6$)	$3.5x10^4$ ($2.6x10^4$)	3x104 ($2.4x10^4$)

3.4. General discussion

The results of this research revealed that the AF+AH+PTF system was highly efficient in removing COD_t, viz. 84%, when the AF+AH system was operated at HRT of 3+6 h and the HLR of PTF was 15.4 $m^3/m^2/d$, i.e. overall HRT for the system was 12.25 h. Removal of COD fractions in the system by different processes (biophysical, anaerobic conversion and aerobic degradation in, respectively, AF, AH and PTF reactor) results in a high COD removal and stable performance at short HRT and at low temperature. The AF reactor removed the big particles (58% of COD_{ss} was removed), which can reduce the methanogenic activity in the second anaerobic-step, as found by Elmitwalli *et al.* [8]. Therefore, the AH reactor (methanogenic reactor with granular sludge) efficiently removed and converted at 13^{o}C the anaerobically biodegradable COD. In the AF+AH system, 46% of the influent COD_t was converted to methane gas (energy source). The PTF removed the fine particles, which have limited removal in the anaerobic treatment (Wang, [2], Elmitwalli *et al.*, [3]). Also, the PTF worked as a polishing-step that guaranteed a stable effluent quality. In addition to COD removal, a partial nitrification efficiency (22%) and removal of *E-coli* (about 2 log) were achieved in PTF. Decreasing the HLR of the PTF to 2.6 $m^3/m^2/d$ only increased the nitrification efficiency to 60 %.

The AF+AH+PTF system is a high-rate and low-cost technology, as no mechanical equipment and energy are required for aeration and sludge or wastewater recirculation and, moreover, small land requirement. Therefore, the AF+AH+PTF system represents a suitable solution for on and off site treatment of domestic sewage in developing countries at low temperatures. Moreover, the effluent of such system is a valuable product for restricted irrigation (WHO, [25]) and fertilisation, especially for regions suffering from the lack of water resources, like Middle East and for closing water and nutrients cycle.

4. CONCLUSIONS

- The AF reactor removed the major part of the total and suspended COD in the system, viz. 46 and 58% respectively.
- The AF+AH system removed 63 % of total COD and converted 46 % of the influent total COD to methane gas, which can be used as an energy source.

- At a HLR of 41 $m^3/m^2/d$, the COD removal was limited in the PTF, while at HLR of 15.4 and 2.6 $m^3/m^2/d$, PTF showed a high total COD removal of 54-57% without significant difference between the two HLRs. Accordingly, the overall total COD removal in the AF+AH+PTF system was 85 %.
- The aerobic step (PTF) was mainly efficient in the removal of particles (COD_{ss} and COD_{col} removal were 75-90 % and 75-83 % respectively), which were not removed in the anaerobic system.
- Decreasing the HLR from 15.4 to 2.6 $m^3/m^2/d$, increased the nitrification efficiency in the PTF from 22 % to 60 %. At HLR of 15.4 and 2.6 $m^3/m^2/d$, *E. coli* was removed by ca. 2 log.
- The AF+AH+PTF system represents high-loading and low-cost technology, which is suitable for on and off site treatment of domestic sewage in developing countries at low temperatures.

ACKNOWLEGEMENTS

This work has been financially supported by European Commission in the framework of the INCO-MED project CORETECH, contract nr. ICA3-1999-10009.

REFERENCES

1. Zeeman G. and Lettinga G. (1999). The Role of anaerobic digestion of domestic sewage in closing the water and nutrients cycle at community level. *Water Science & Technology,* **39**(5), 187-194.

2. Wang K. (1994). *Integrated anaerobic and aerobic treatment of sewage*. Ph. D. thesis, Sub-department of Environmental Technology. Wageningen University. The Netherlands.

3. Elmitwalli T. A., Zandvoort M., Zeeman G., Bruning H. and Lettinga G. (1999). Low temperature treatment of domestic sewage in upflow anaerobic sludge blanket and anaerobic hybrid reactors. *Water Science & Technology,* **39**(5), 177-185.

4. Elmitwalli T. A., van Dun M. , Bruning H., Zeeman G. and Lettinga G.(2000). The role of filter media in removing suspended and colloidal particles in anaerobic reactor treating domestic sewage. *Bioresource Technology* **72**(3), 235-242, (2000).

5. Elmitwalli T. A., Zeeman G.and Lettinga G.(2001). Anaerobic treatment of domestic sewage at low temperature. *Water Science & Technology*, **44**(4), 33-40.

6. Elmitwalli T. A., Soellner J., Keizer A. de, Zeeman G., Bruning H. and Lettinga G. (2001). Biodegradability and change of physical characteristics of particles during anaerobic digestion of domestic sewage. *Water Research,* **35**(5), 1311-1317.

7. Elmitwalli T.A., Sklyar V., Zeeman G. and Lettinga G. (2002b). Low temperature pre-

treatment of domestic sewage in anaerobic hybrid and anaerobic filter reactor. *Bioresource Technology,* **82**, 233-239.

8. Elmitwalli T.A., Zeeman G., Oahn K.L.T. and Lettinga G. (2002a). Treatment of domestic sewage in a two-step system anaerobic filter/anaerobic hybrid reactor at low temperature. *Water Research,* **36**(9), 2225-2232.

9. Collivignarelli C., Urbini G., Farneti A., Bassetti A. and Barbaresi U. (1990). Anaerobic-aerobic treatment of municipal wastewater with full scale up-flow anaerobic sludge blanket and attached biofilm reactors. *Water Science & Technology,* **22** (1/2), 475-482.

10. Kim Y., Mikawa K., Saito T., Tanaka K. and Emori H. (1997). Development of novel anaerobic/aerobic filter process for nitrogen removal using immobilized nitrifiers pellets. *Water Science & Technology,* **36**(12), 151-158.

11. Castillo A., Cecchi F. and Mata-Alvarez J. (1997). A combined anaerobic – aerobic system to treat domestic sewage. *Water Research*, **31**(12), 3057-3063.

12. Machdar I., Harada H., Ohashi A., Sekiguchi Y., Okui H. and Ueki K. (1997). A novel and cost-effective sewage treatment system consisting of UASB pre-treatment and post-treatment units for developing countries. *Water Science & Technology*, **36**(12), 189-197.

13. Sperling M.V., Freire V.H. and Chernicharo C.A.L. (2001). Performance evaluation of a UASB-activated sludge system treating municipal wastewater. *Water Science & Technology,* **43**(11), 323-328.

14. Mba D., Bannister R.H. and Findlay G.E. (1999). Mechanical redesign of the rotating biological contactor. *Water Research,* **33**(18), 3679-3688.

15. Chernicharo C.A.L. and Machado M.G.R. (1998). Feasibility of the UASB/AF system for domestic sewage treatment in developing countries. *Water Science & Technology,* **38**(8/9) 325-332.

16. Goncalves R., Araujo V. and Chernicharo C. (1998). Association of a UASB and a submerged aerated biofilter for domestic sewage treatment. *Water Science & Technology,* **38**(8/9), 189-195.

17. Gosh C., Frijns J. and Lettinga G. (1999). Performance of silver carp (*Hypophthalmicthys molitrix*) dominated integrated post treatment system for purification of municipal wastewater in a temperature climate. *Biores. Tech.,* **69**, 255-262.

18. Araki N., Ohashi A., Machdar I. and Harada G. (1999). Behaviors of nitrifiers in a novel biofilm reactor employing hanging sponge-cubes as attachement site. *Water Science & Technology,* **39**(7), 23-31.

19. Huysman P., van Meenen P., van Assche P. and Verstraete W. (1983). Factors affecting the colonization of non porous and porous packing materials in model upflow methane reactors. *Biotechnology Letter,* **5**(9), 643-648.

20. Irka A. and Carter M.J. (1975). Micro semi-automated analysis of surface and waste waters for chemical oxygen demand. *Analytical Chemistry,* **47**, 1397-1401.

21. Dutch Standard Normalized Methods. (1969). Normalisation Institute, Delft, The Netherlands.

22. Havelaar A. H. and During M. (1988). Evaluation of Anderson Baired-Parker direct plating method for enumerating Escherichia coli in water. *Journal of Applied Bacteriology,* **64**, 89-98.

23. van der Last A. R. M. and Lettinga G. (1992). Anaerobic treatment domestic sewage under moderate climatic (Dutch) conditions using upflow reactors at increased superficial velocities. *Water Science & Technology,* **25**(7), 167-178.

24. Draaijer H., Maas J. A. W., Schaapman J. E. and Khan A. (1992). Performance of the 5 mild UASB reactors for sewage treatment at Kanpur, India. *Water Science & Technology,* **25**(7), 123-133.

25. World Health Organisation (WHO). (1989). *Health guidelines for the use of wastewater in agriculture and aquaculture*. WHO technical report series 778, WHO, Geneva, pp. 36-44.