Influence of hydraulic retention time on the operation of a submerged membrane sequencing batch reactor (SM-SBR) for the treatment of greywater

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Abstract: This study describes the experience received in operating an SM-SBR under different hydraulic retention times for the treatment of synthetic greywater. The pilot scale SM-SBR with a working volume of $V_R = 500L$ is operated with hydraulic retention times of 33h, 24h and 12h, and a volumetric exchange ratio of ~0.25.The removal of COD, ammonia, total nitrogen is investigated for the different set-ups. Despite the low COD in greywater, the treatment performance of the reactor is always sufficient to meet reuse guidelines. The biomass concentration increases slowly, although no excess sludge has been taken out (except sampling). Therefore the sludge age is assumed to be >360d.

Keywords: hydraulic retention time, greywater, membrane bioreactor, SBR

Abbreviations:

GW   greywater
SM-SBR   submerged membrane sequencing batch reactor
VER   volumetric exchange ratio
SRT   sludge retention time
HRT   hydraulic retention time
TMP   transmembrane pressure
PVDF   polyvinylidene fluoride
PES   polyethersulfone

Introduction

Water segregation, onsite treatment and reuse are desirable approaches for water supply and a sustainable water management. Water can be easily stocked but is more costly to transport. Consequently, local water availability must be enhanced. In developed countries water for domestic use is in a range of 100 to 150 L(PE d)$^{-1}$ and greywater (GW) represents 60 to 70% of this amount [1]. GW is generally defined as low polluted wastewater originating from bathtubs, showers, hand washing basins and washing machines excluding wastewater from the kitchen and the toilet flushing system [2]. GW reuse plays an important role in the sustainable water management approach, and is significant, especially for tourism facilities in water stressed regions because of the huge amounts these facilities produce.

Recently membrane bioreactors (MBRs) for GW treatment have been studied more deeply because of their compactness and superior water reuse potential due to the complete disinfection achieved by the micro- or ultrafiltration membranes [3, 4].

A 500L pilot scale bioreactor with a submerged membrane was operated effectively as a sequencing batch reactor for over one year at three different hydraulic retention times. The continuous investigations of the operation of the SM-SBR by online monitoring, together with weekly and cycle analyses gave detailed information about the process and its nutrient removal efficiency. Additionally batch-tests were carried out to validate the obtained results.

Experimental

Analytics

All samples were filtered with a cellulose acetate filter (pore size: 0.2 µm, Sartorius) before measuring NO_2-N, NO_3-N, NH_3-N, PO_4-P according to standard methods, while COD and TN were analysed by Dr. Lange kits (LCK 314, 414, 514 and LCK 138, 238, respectively) and spectrophotometry.

Synthetic greywater (GW)

For this study synthetic GW (Table 1) was used and the recipe was designed according to [5-7]. It represented the GW of a 4-person household with a composition comparable to real GW from the shower effluent of a Moroccan sports club [8] and GW of other studies where kitchen effluents were not included [9]. Urea and ammonia were added to investigate the performance of denitrification with water of low carbon concentration and to make the results transferable to other applications like treatment of surface water.

Table 1: Recipe of synthetic GW and its resulting feed concentration

ingredients	approx. daily amount	feed concentration ($mg\ L^{-1}$) or ($mL\ L^{-1}$)
tooth paste	1.2 g	6.0
shower gel	10 mL	0.05
cleaner	20 mL	0.1
shower oil*	1.0 mL	0.05
shampoo	2.5 mL	0.013
bubble bath	7.0 mL	0.035
urea	4.0 g	20.0
NH_4Cl	2.5 g	12.5
K_2HPO_4	0.5 g	2.5

* with 50% ricinus oil

500L pilot scale reactor

The submerged membrane sequencing batch reactor (SM-SBR) was operated in two different set-ups (Fig. 1). Set-up A consisted of two tanks, the first for storage of the synthetic GW, and the second for the biological treatment, operated with an HRT of 33 and 24h. Two submerged polyphenol resin plate and frame modules were introduced into the biological chamber, each with a membrane area of 3.9 m² and a pores size of 0.4 μm (see Fig. 1A). For set-up B the greywater concentrate and potable water is mixed directly into the biological chamber (see Fig. 1B). The hydraulic retention time (HRT) was reduced to 12h by the introduction of two new membrane modules, all identically in size, but made of different membrane materials (PVDF for the MF module; PES for the UF module).

Permeate was removed using a peristaltic pump and the reactor volume was controlled by a level controller. The data from the probes (dissolved oxygen (DO), and oxidation reduction potential (OPR)) and the pressure transducers for liquid levelt as well as the trans-membrane pressure (TMP) were directly recorded on a computer. The solid retention time (SRT) was >360d for the system, because no biomass was taken out, except for sampling. The volumetric exchange ratio (VER) was kept constant at ~0.25 for all different configurations.

The SM-SBR cycle, as shown in Fig. 1C, began with a fill phase. The reaction phase consisted of an anoxic period and an aerated period. The standard SBR phases: reaction, sludge settling, and withdrawal were combined due to the introduction of a membrane. The permeate withdrawal started with begin of the aeration. The cycle ended with the idle phase. Tab. 2 shows the main operational parameters of the two different pilot SM-SBR set-ups.
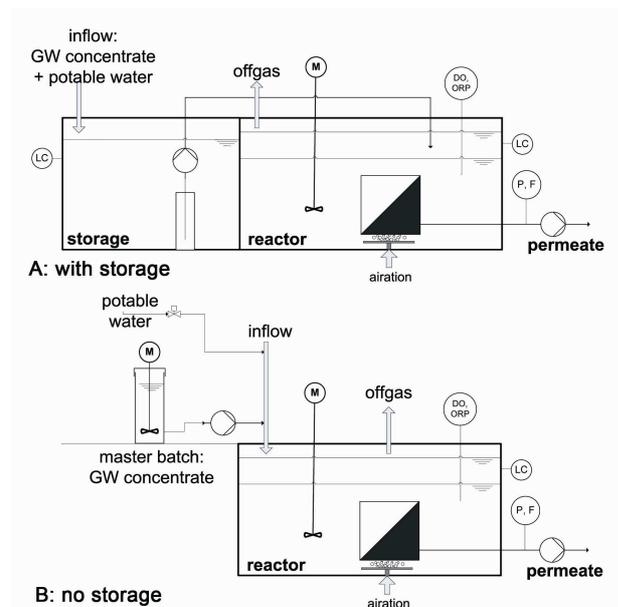
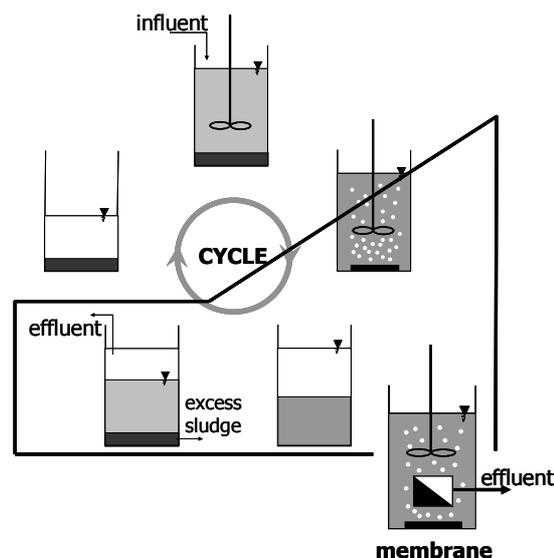**Fig. 1A, B:** Two set-ups of the 500L pilot reactor

Fig. 1C: Scheme of the SM-SBR cycle

Table 2: Operating parameters of the 500L SM-SBR

Operating Parameters		SM-SBR (with storage)	SM-SBR (no storage)
VER		0.24 - 0.25	
feed COD, mg L^{-1}		200-250	
SRT, d		> 360	
HRT, h		33 and 24	12
TS, g L^{-1}		2.5 – 4.5	4.5 – 7.8
average F/M-Ratio, g $_{CODin}$ (g $_{oTS}$ d)$^{-1}$		0.06	0.05
flux, L (hm²)$^{-1}$		5.0-8.0	9.0-12.0
TMP, bar		0.1-0.4	0.1-0.25
cycle times, min:	filling	20-30	5-10
	anoxic phase	170-180 and 120-130	60-65
	aerated phase	300 and 210	110

Determination of AUR and NUR

Experiments in a 1L stirred vessel were undertaken to determine the ammonium utilisation rate (AUR) and the nitrate-N utilisation rate (NUR). For some batch runs, acetate was added as an easily degradable C-source to determine the NUR without substrate limitations. The batch was filled with the sample and left idle for 20 minutes. During the run the temperature was maintained at 20°C by a thermostatic water bath and stirred at 130 rpm all along the experiences. Each run contained two phases, the first started with 90 minutes under aeration with a DO between 8 and 9 mg$_{O2}$L^{-1}, and the second with N$_2$-gas providing anoxic condition with a DO below 0.3 mg$_{O2}$L^{-1}. Samples were taken every 10 to 20 minutes and filtered through a 0.2 μm cellulose acetate filter to be subsequently analysed using ion chromatography.

Results and Discussion

Cycle Analysis

Cycle analyses indicate that the denitrification – nitrification process works under all different HRT and still indicate a small optimisation potential in reduction of the cycle time (t$_c$) down to 2h, meaning a further decrease of the HRT to 8h. Fig. 2 illustrates the results of one cycle for different HRT in terms of the

parameters gained from online measurements (Fig. 2A-C) and the evolution of the nitrogen compounds (Fig. 2D-F). The cycle analyses for nitrogen compounds proved that the cycle length still holds optimisation potential. A complete nitrification was achieved mostly; only for an HRT of 33h complete denitrification was not attained. This might be explained by the still remaining DO of up to 1 mgL^{-1} throughout the anoxic phase together with the long hunger period. In Fig. 2B the oxygen curve shows that after nearly 60min the biological activity (degradation of ammonia) has ended, indicated by oxygen saturation. This is validated by the corresponding nitrogen cycle analysis (Fig. 2E). A similar evolution is recognisable in Fig. 2C, although here the oxygen concentration already starts to increase to saturation after 20min. This observation is contradicted by the cycle analysis, which shows that only 40min after the beginning of aeration the nitrification process was finished.
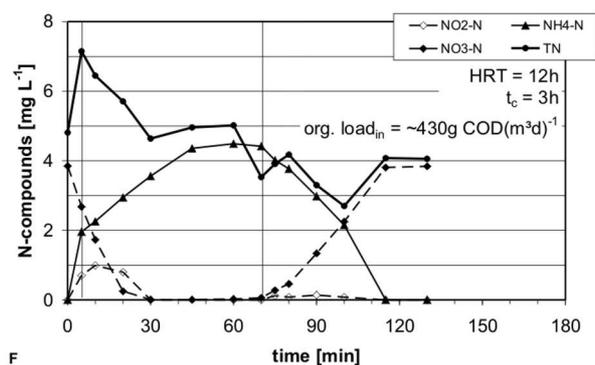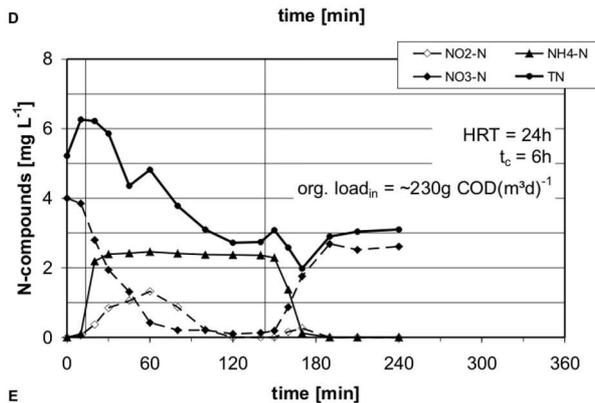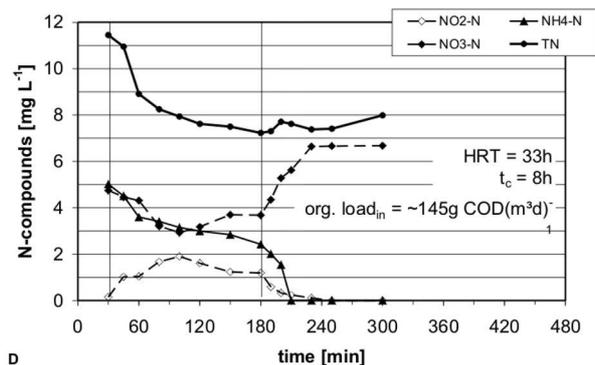

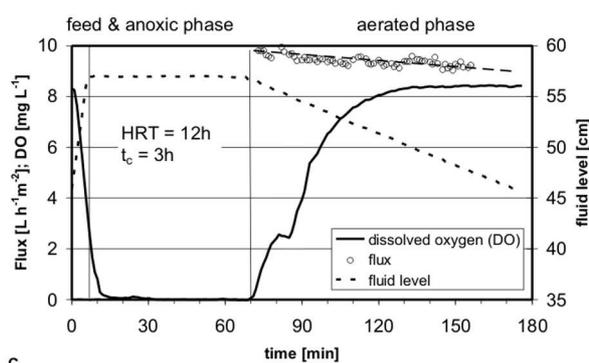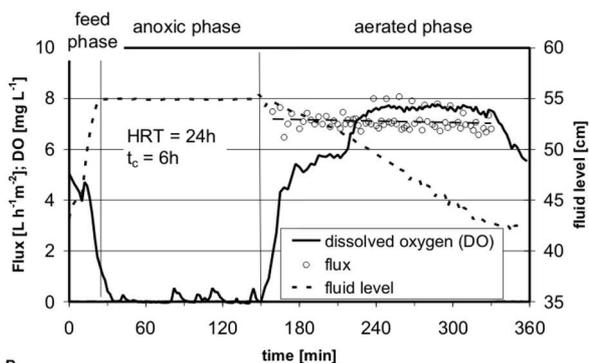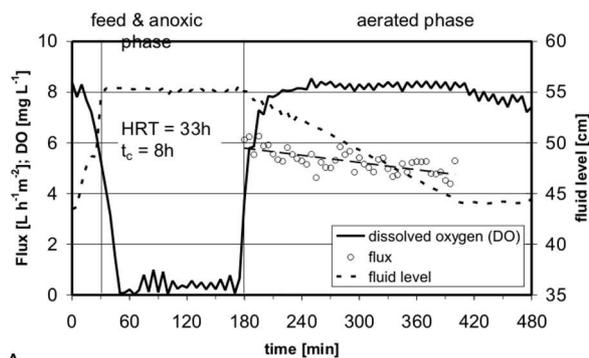**Fig. 2A-C:** Online cycle measurement for HRT = 12-33h   **Fig. 2D-F:** Cycle analysis of nitrogen compounds

During the aerated phase the membrane module was set to 4.5 min of permeation and 0.5 min of relaxation for the HRT of 33h and 24h, while for the HRT of 12h it was set to 9.0 min of permeation and 1.0 min of relaxation. The flux stays more or less constant in one cycle at low values of 5-7 $L(m^2h)^{-1}$. These values lie at the lower end of reported literature data. In studies on municipal and domestic wastewater values for submerged membrane modules between 5 and 40 $L(m^2h)^{-1}$ have been found [10]. The TMP was

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190 mbar on average, corresponding to a permeability of $J = 38$ L(m² h bar)$^{-1}$. To operate the membrane far below the critical flux of 13.5 L(m²h)$^{-1}$ [11] had the advantage that the process could be run over a period of 120d continuously. Due to the mentioned low flux, chemical cleaning outside the reactor was necessary at an interval of 6 month only. Still, a better membrane performance would enhance the SM-SBR performance in terms of cycle reduction. This is desirable because Hu [12] found the optimal HRT for GW treatment to be around 1.5h for carbon removal only. The change of membrane modules led to a reduction of HRT to 12h, by an increase of permeability to 80-100 L(m² h bar)$^{-1}$ and an operating flux of 9-12 L(m²h)$^{-1}$. Still the results concerning the membrane behaviour are not yet sufficient to allow a final statement.

AUR and NUR results

The results of the nitrate-N utilisation rate (NUR) can be used to assess the denitrification potential of the operating system and hence the resulting N removal efficiency. The ammonium utilisation rate (AUR) is measured as the formed nitrite and nitrate concentration during aeration. The rates are presented in Tab. 3 gained from cycle analyses of the pilot scale reactor under the different HRTs. The rates show big changes. It can be seen that for the NUR the rates increase with cycle time reduction. The highest rate is gained from batch experiments with acetate dosing as an easily biodegradable carbon source, undertaken in order to compare the results to literature data and to the performance of the SM-SBR. The value is almost six times the endogenous NUR of 0.52…0.62 mg NO_3-N g^{-1} oTS h^{-1}, but within the same ration found in literature [13].

The data for specific nitrification rates (AUR) in literature range from 0.78…1.81 mg NO_3-N (h g SS)$^{-1}$ for synthetic wastewater (Muller, 1995: quoted in [14]) to 1.7…2.0 mg NO_3-N (h g VSS)$^{-1}$ for municipal wastewater (Fan et al., 2000: quoted in [14]). A steady increase of AUR, similar to the NUR, could not be found during the reduction of HRT for the operation of the SM-SBR. Nevertheless the values are in the range reported in literature under limiting operating conditions for different MBRs. There, values from 1.0 up to 10.8 mg NO_x-N (g MLVSS h)$^{-1}$ are shown [15].

Table 3: Nitrate-N utilisation rate (NUR) and ammonium utilisation rate (AUR)

cycle analyses / batch experiments / literature	NUR [mg NO_3-N g^{-1} oTS h^{-1}]	AUR [mg NO_3-N g^{-1} oTS h^{-1}]
HRT = 33h	0.71…0.79	0.51…0.98
HRT = 24h	0.84…1.53	1.53…3.08
HRT = 12h	1.54	0.96
all HRT, batch, with acetate dosing	3.44…3.55	
Muller, 1995: quoted in [14]		0.78…1.81
Fan et al., 2000: quoted in [14]		1.7…2.0

Biomass evolution

Fig. 3 shows the biomass evolution. Although the HRT was reduced twice, no significant change in the growth rate can be seen. The total solids concentration started at 2.5 gL^{-1} at day 70 and reached a final concentration of 8.0 gL^{-1}. The low growth rate with $\mu = 0.14…0.22$ mg$_{oTS}$ (L d)$^{-1}$ of the activated sludge is the result of the low loading rates of 140…460 mg$_{COD}$ (L d)$^{-1}$.

The almost constant and high organic fraction within the TS concentration of around 90% shows that, although the reactor was operated without excess-sludge removal, no accumulation of inert anorganic substances occurred. Comparing these results with values from a reactor with an HRT of 33h and a low biomass concentration of 2.0…2.5 gL^{-1}, the organic fraction was only around 70%. It can be said that the

continuous reduction of cycle time led to an improvement concerning the biomass structure in favour of a more abundant organic fraction.
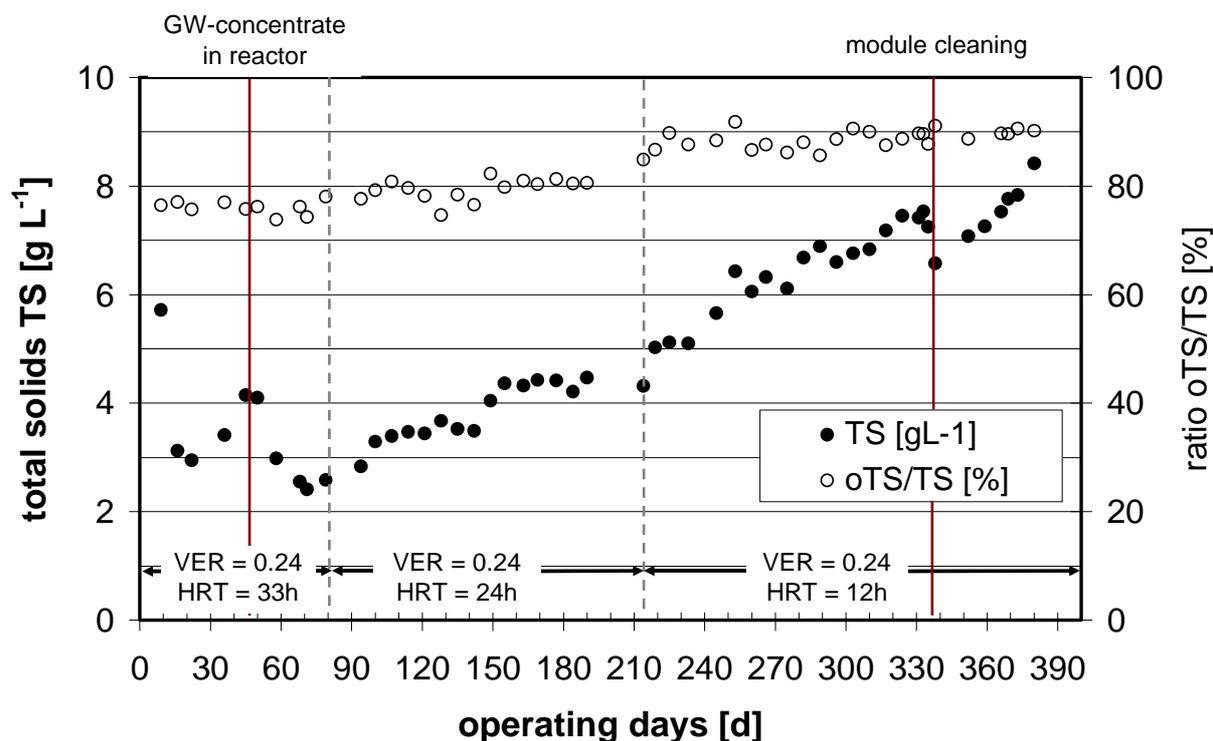

Fig. 3: Biomass development for the operating period

Removal Efficiency

Tab. 4 shows the removal efficiencies for COD, TN and NH_4-N for different HRT, as well as the average feed and permeate concentrations over an operation period of 400 days. The variation in feed concentrations can be explained by the storage tank, where a first biodegradation of COD took place. However, the feed COD variation could still be observed after day 219, where the storage tank was replaced by direct feeding. This might be due to the dead zones in the elbows of the short flexible hose in front and behind the peristaltic feed pump.

Table 4: Average concentrations in feed and permeate and the achieved removal efficiencies

	Feed (mg L^{-1})	Permeate (mg L^{-1})	Mandatory values (mg L^{-1})
COD	230	18.9	30[1]
TN	17.1	4.1	/
NH$_4$-N	11.9	0.37	0.39[2]
NO$_3$-N	0.42	3.66	11.3[2]

[1]Directive (75/440/EEC)   [2]Directive (98/83/EC)

Fig. 4 shows the enhancement of the removal efficiency with each cycle time reduction. It can be concluded that the very long HRT of 33h involved a long starvation phase for the microorganisms. The first reduction to 24h leads already to an improvement, especially for the denitrification process. With the HRT of 12h a first optimised cycle time seems to be reached. The variation of the ratio between feast and hunger favours the storage capacity of microorganism. Figure 2F still reveals the possibility of a further reduction of cycle time in the aerobic phase. There, after approx. 30min the biological activity has ended.
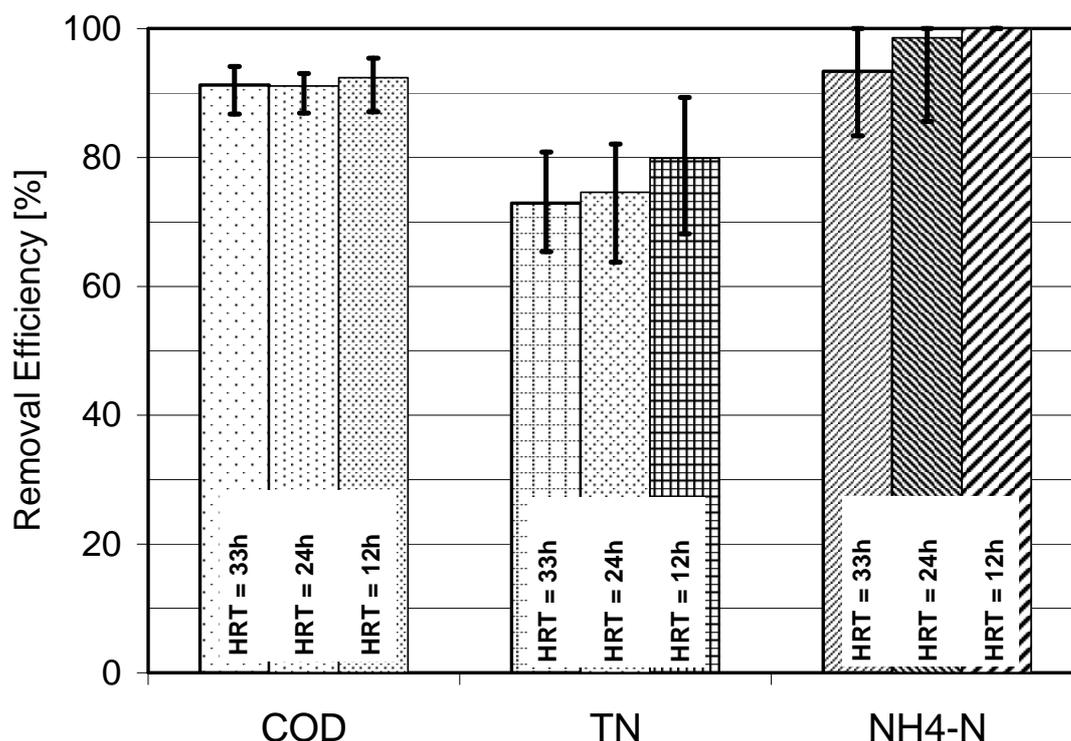
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Fig. 4: Removal efficiency for different HRTs and compounds

Conclusions

Synthetic greywater was treated in an SM-SBR with anoxic and aerobic phases for denitrification and nitrification. Low loading rates resulted in low oTS concentration at the beginning, but increasing loading rates yielded oTS concentrations where an MBR is applicable. NUR and AUR values were comparable to literature data and suggested that nitrogen removal is generally feasible in these systems. The TN removal efficiency achieved under the different HRT illustrated the success of an optimised cycle and phase times as operational parameters. Moreover a further optimisation potential to an HRT of 8h was indicated. The low growth rate must be taken into consideration when designing an SM-SBR for greywater treatment.

References

1. Friedler, E., R. Kovalio, and N.I. Galil, *On-site greywater treatment and reuse in multi-storey buildings.* Water Sci Technol, 2005. **51**(10): p. 187-94.
2. Nolde, E., *Greywater reuse systems for toilet flushing in multi-storey buildings - over ten years experience in Berlin.* Urban Water, 1999. **1**(4): p. 275-284.
3. Melin, T., et al., *Membrane bioreactor technolgy for wastewater treatment and reuse.* Desalination, 2006. **187**(271-282).
4. Lesjean, B. and R. Gnirss, *Grey water treatment with a membrane bioreactor operated at low SRT and low HRT.* Desalination, 2006. **199**: p. 432-434.
5. Komschuvara, K., *UV disinfection in comparison with other small scale technologies for the treatment of domestic greywater.* 2002, Univerity of Hertfordshire.
6. Jefferson, B., et al., *Advanced biological unit processes for domestic water recycling.* Water Science & Technology, 2001. **43**(10): p. 211-218.

7.   Kuhn, R. and N. Mujkic, *Untersuchung zur biologischen Abbaubarkeit von ausgewählten Stoffgemischen in Labor-Belebtschlammanlagen*, in *AG Hygiene, Institut für Umwelttechnik*. 2003, Technische Universität Berlin: Berlin.

8.   Merz, C., et al., *Membrane bioreactor technology for the treatment of greywater from a sports and leisure club.* Desalination, 2007. **215**: p. 37-43.

9.   Jefferson, B., S. Judd, and C. Diaper, *Treatment methods of grey water*, in: *Decentralised Sanitation and Reuse - Concepts, Systems and Implementation*, P. Lens, G. Zeeman, and G. Lettinga, Editors. 2001, IWA publishing: London. p. 334-353.

10.   Stephenson, T., et al., *Membrane bioreactors for wastewater treatment*. 2000, London: IWA Publisching.

11.   McAdam, E., et al., *Critical analysis of submerged membrane sequencing batch reactor operating conditions.* Water Research, 2005. **39**: p. 4011-4019.

12.   Hu, B., *The most optimal retention time for greywater bio-chemical treatment.* Huanjing Wuran Zhili Jishu Yu Shebei, 2002. **3**(7): p. 30-31.

13.   Buckley, C. and V. Naidoo, *Municipal wastewater characterisation: Application of denitrification batch tests*, in *Final Report to the Water Research Commission for Project No. K5/820*. 1999, Pollution Research Group, School of Chemical Engineering, University of Natal: Durban.

14.   Kraume, M., et al., *Nutrients removal in MBRs for municipal wastewater treatment.* Water Science & Technology, 2005. **51**(6-7): p. 391-402.

15.   Soriano, G.A., et al., *A comparative pilot-scale study of the performance of conventional activated sludge and membrane bioreactors under limiting operation conditions.* Water Environment Research, 2003. **75**(3): p. 225-231.