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Greywater treatment as an option for effective wastewater management in small communities

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ABSTRACT

This paper presents the results of four different investigations where greywater is treated with low technology as achieved a constructed wetland and a gravel and sand filter as well as with a high-tech option: the membrane bioreactor. The applications are perfectly suited to be operated in remote areas or small communities with tourist depending variation of discharged wastewater flows. The advantage in the general sustainable water management approach of each treatment option will be shown, the technologies will be compared in terms of robustness and effluent quality and first conclusion will be drawn for the field of application in small communities.

Keywords: Greywater; Reuse; Constructed wetland; Gravel filter; MBR

1. Introduction

To improve the current situation of wastewater treatment in most small communities new approaches like water segregation, on-site treatment and internal water reuse are desirable, especially in water scare regions. On a small scale this involves the collection and treatment of greywater [1]. Greywater 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]. Greywater contains impurities and micro-organisms derived from household and personal cleaning activities and it shows a wide range of pathogenic and other liquid waste materials, which people normally want to eliminate from the inside of their homes [3–6]. Those varieties in greywater quality should be taken into consideration when setting appropriate risk-based standards for the reuse.

It is an accepted practice and also a community expectation in sewered areas that there is a supply of tap water and that wastewater is drained to a sewer to promote sanitation and hygiene in the home. However, the demands are contradictory to the limited water supplies and rising cost with increasing population. The expansion of water supply catchments and the adequate central wastewater treatment may become difficult, especially for metropolitan areas. Therefore, domestic greywater from single premises may be considered as a potential resource. It may be reused on-site for irrigation purposes, toilet flushing, and laundry use depending on the type of greywater and its level of treatment. In single house systems, the favourable option for reuse of greywater is the toilet flushing, because the amount of water required equals the amount of greywater produced for hygiene purposes such as washing, shower-

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ing and bathing [7]. It reduces the demand on high quality drinking water of around 35%.

Lately, the greywater treatment and reuse option have been widely studies, especially in Europe, Australia, Japan and California. Still, long term investigations are rare, even though Nolde [2] reported a ten year experience in greywater reuse for a multi storage building. Only a few full-scale plants are in operation to draw enough conclusions out of their operation [4]. Therefore, it is essential to study this topic further and to pay enough attention to protect public health as well as to be consistent with the principles of ecological sustainable development, which does not decrease the amenity of the local community.

Integrated water resources policies should focus on the aspects like demand management, resources development, and environmental protection in order to increase the water availability for all users from various sources, including the viable option of reuse. In addition, the regulations have to save and conserve water quantity and quality, while at the same time protect the environment as well as people from water-related hazards. So, regulation promotes and encourages the reuse of waste- and greywater in terms of the above mentioned manners. New scientific achievements and a broad public discussion have found their way into the legislation, establishing requirements for the reclamation of the different wastewaters, e.g.:

- the World Health Organisation [8];
- the European Commission [9];
- the US Environmental Protection Agency [10];
- the Australian Health Ministers' Conference [11].

These new regulations form set risk based reuse standards on the base of the socio cultural background with variations in the selecting of suitable parameters.

If greywater reuse is practised it goes from simple undertaken approaches, as bucketing wash machine greywater for cleaning stone floors as done in Tunisia in private households up to more advanced technologies, like constructed wetlands for bath greywater in the hotel sector up to high sophisticated systems as membrane bioreactors. Still, reuse is often practiced without a clear understanding of public and private health risks, as well as the environmental degradation that may be caused without properly designed land application systems for dispersal of greywater. This means a necessity to install suitable treatment systems considering the reuse option, including properly addressed cost calculation for installation, operation and maintenance. This paper presents the results of own experiments with lab scale and pilot plants, which then are compared among each other and to literature findings with focus on the differences in greywater treatment.

2. Materials and methods

2.1. Experimental set-up

Four different technical options to treat greywater have been investigated. On the one hand there are the "low-cost", "low-tech" treatments of horizontal flow reed beds, vertical flow reed beds, as well as sand-gravel filters and on the other hand there will be the results from a "high-cost" "high-tech" solution (500 L pilot scale SM-SBR). One is on pilot scale and operated with synthetic greywater, while the other three have been operated under real conditions; set-up B+C are also on pilot scale. Table 1 gives an overview of the four different set-ups.

2.1.1. Set-up A

A 500 L SM-SBR (Fig. 1a) was fed with synthetic GW according to Scheumann and Kraume [12]. It was designed to represent the GW of a 4 person household. Furthermore, it could be shown that the composition is comparable to real GW from shower effluent of a Moroccan sports club [13] and GW of other studies where kitchen effluents were not included [14]. 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.

The SM-SBR cycle, as shown in Fig. 1b, 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

Table 1
Description of the four different technologies in this study

Set-up	Reactor type	Wastewater	Location
Set-up A	Pilot scale 500L submerged membrane sequencing batch reactor (SM-SBR)	Synthetic greywater	TUB in Berlin, Germany
Set-up B	Pilot scale unplanted sand and gravel filter (GSF)	Real greywater (showers effluent)	IAV in Rabat, Morocco
Set-up C	Pilot scale planted sand and gravel filter	Real greywater (showers effluent)	IAV in Rabat, Morocco
Set-up D	Horizontal flow (HF) constructed wetland	Secondary treatment of greywater (80 p.e)	camping site, Tuscany, Italy

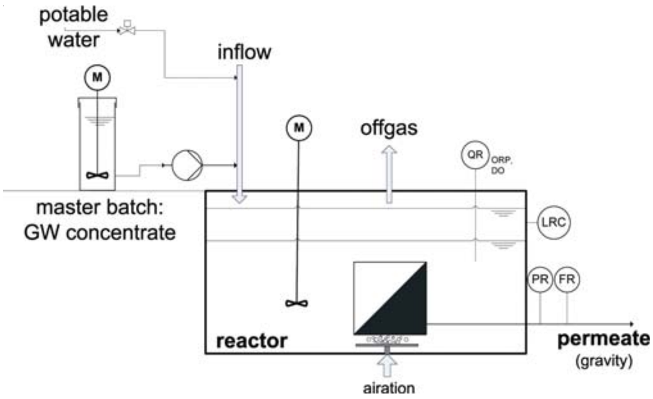

Fig. 1a. Set-up of 500L SM-SBR.

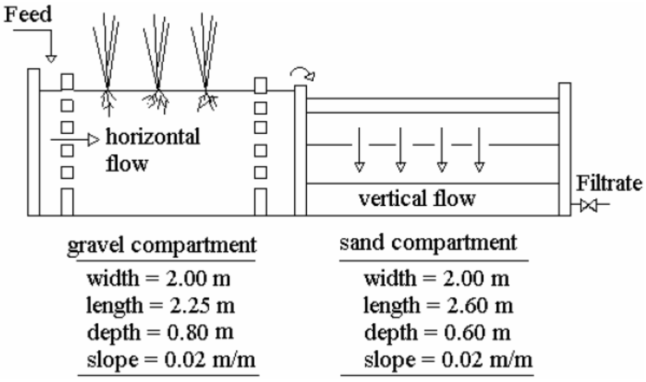

Fig. 2. Set-up of the gravel sand filter; set-up B without plants, set-up C with *Phragmites australis*.

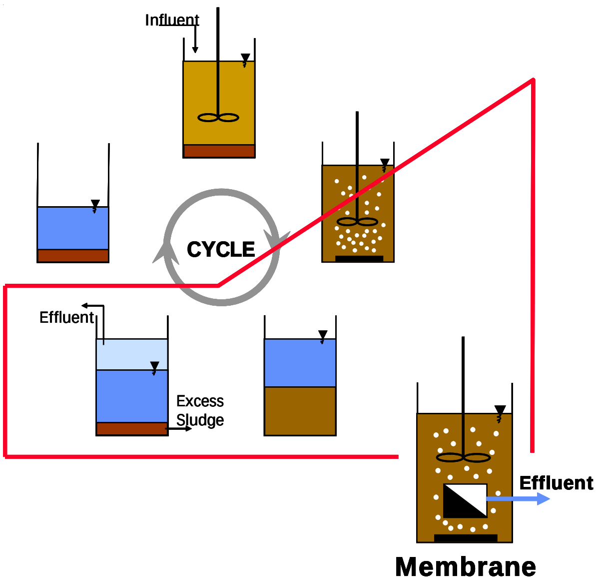

Fig. 1b. SM-SBR principle.

due to the introduction of a membrane. The permeate withdrawal started with begin of the aeration. The cycle ended with the idle phase. The reactor was operated in an SBR mode with a volume exchange ratio of 25% and with cycle lengths of 8, 6, 3, and 2 h. With the latest set-up, the SBR cycle, began with a fill phase of 5 min, which was included in the one hour anoxic phase. The aerated reaction phase consisted then of a period of 60 min, incl. the idle phase.

2.1.2. Set-up B

The gravel and sand filter (GSF, Fig. 2) was taken in operation in June 2005 at the premises of the IAV in Rabat, Morocco to treat greywater coming from a sports club sanitary facility. They comprise ten showers as well as several washing basins which are connected to the greywater collection system. The greywater was screened by a 1 cm × 1 cm-screen and collected in a reservoir made of concrete. At the filter inlet it was passed through a second 1 cm × 1 cm-screen to have reliably removed large particles which might block the filter. The screens were cleaned manually every day. The GSF was constructed as a horizontal and vertical flow filter. It underwent all variations in flow and load, which came in discrete waves during the day according to the activities in the gym. The gravel material was made of limestone. This purification step was followed by vertical filtration through a multi-layer sand (95% silicium) filter, consisted of four layers of differently sized sand. The diameter of the grains increased from top to bottom. The total hollow volume of the gravel and the sand compartment together was 2.78 m^3 and 4.06 m^3 when the receiving ditches at the inlet of each compartment were included. The GSF received an average flow of 8 m^3d^{-1} with $Q_{COD} = 0.8\ kg_{COD}\ d^{-1}$ on workdays and a theoretical HRT at 0.3 Ls^{-1} of 3.8 h.

Complete sets of analyses were performed on samples taken at the beginning of the midday wave, i.e. from the most highly polluted influent. Effluent sampling was immediate, i.e. HRT was not taken into consideration.

2.1.3. Set-up C

One line of the GSF as described in set-up B was planted with *Phragmites australis* in the autumn of 2005, which refers to the operating day 195. 40 shoots were planted in 5 rows of 8 plants each. This resulted in a planting density of 8.9 m^{-2}.

2.1.4. Set-up D

A small camping site “La Cava” in Arezzo, Italy was recently established, and designed according to the Sustainable Water Management principles (water saving, reuse, recycling). As visualised in Fig. 3 the black- and greywater were segregated into two parallel lines for a separate treatment as follows: greywater is treated at a hydraulic loading rate (HLR) of 8.26 cm d^{-1} (equals a flow of 9.5 $m^3\ d^{-1}$ passing through a HF wetland cell with a

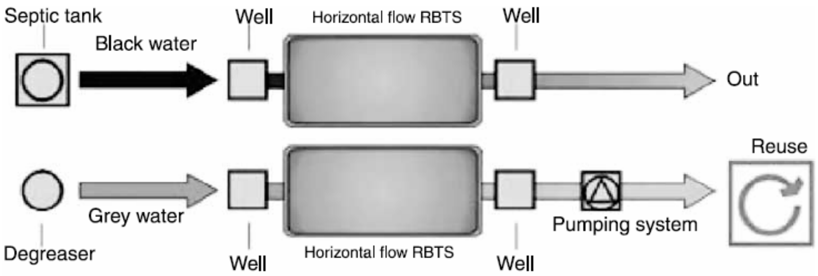

Fig. 3. Scheme of the CW at the camping site "La Cava" (RBTS = reed bed treatment system).

surface area of 115 m^2); blackwater is treated at an HRT of 5.16 cm d^{-1} (equals to an average flow of 6.5 m^3 d^{-1} passing through a HF wetland cell with a surface area 126 m^2). The treated greywater was recycled for toilet flushing whereas the treated black water was reused for drop-irrigation of green areas and landscaping. The camping complex covered a surface area of about 20,000 m^2 with wood, green terraces and parking places for a total of 25 cars. The CW area occupies only 3.5% (700 m^2) of the camp surface area. The wastewater is collected by a gravity system. Water saving measures has been adopted in all buildings (double choice flushing toilets, taps, showers).

2.2. Analytics

For the investigation of the MBR the samples were filtered with a cellulose acetate filter (pore size: 0.2 μm, Sartorius) before measuring NO_2-N, NO_3-N, NH_4-N, PO_4-P according to standardised methods [15,16]. For measuring COD and TN the samples were filtered with a glass fibre filter (pore size: 0.2 μm, Sartorius) and analysed with Dr. Lange kits (LCK 314, 414, 514 and LCK 138, 238, respectively) and spectrophotometry. The analyses for the set-up B and C were performed as defined in Standard Methods [17], except for the determination of nitrate, which was measured according to [18]. For set-up D, inlet grab samples were collected three days before the outlet samples, according to the estimated hydraulic retention time (HRT) and sampling was carried out at least three days after any rainfall event to avoid dilution. All the analyses have been executed by the Regional Environmental Protection Agency of Tuscany (ARPAT). Standard analysis methods IRSA/CNR were used in all cases (IRSA/CNR — Water Research Institute of National Research Centre which is the Governmental Research Institute that provides the analytical standards for Italy: standards methods are almost the same provided by APHA [17]).

3. Results and discussion

3.1. GW characteristics

GW (Table 2) was characterised regarding the proportion of readily biodegradable COD (expressed as the

Table 2
Greywater characteristics

	Average values ± standard deviation			Average literature values	
	Set-up A	Set-up B and C	Set-up D	Jefferson et al. [22]	Nolde [2]
pH	7.5±0.3	7.6±0.4	7.6±0.4		
BOD_5, mgL^{-1}	50±11	53±16	53±16	104±45	50–100*
COD, mgL^{-1}	209±80	122±21	502	207±115	100–200
TN, mgL^{-1}	17.3±6.7			9.6	5–10
TKN, mgL^{-1}		15.2±4.5	2.5	3.91±4.72*	
NH_4-N, mgL^{-1}	7.3±5.4	11.8±4.2	1.7		
$NO_3{-}N$, mgL^{-1}	0.9±0.9		0.32		
TP, mgL^{-1}		1.6±0.53	6.6	3.67±3.88	0.2–0.6
$PO_4^{3-}{-}P$, mgL^{-1}	0.74±1.6	1.0±0.4			
BOD_5/COD	0.25	0.43			
COD/NH_3/TP	121/5.69/1**	127/9.13/1		1030/2.7/1	
Conductivity, μs cm^{-1}		855±191			
Faecal coliform, 100 mL^{-1}		$2.48\times10^5 \pm 1.2\times10^5$			10^{-1}–10^1

* measured as BOD_7 **as COD/NH_3/PO_4-P

ratio BOD_5/COD) and the nutrient fraction (expressed as the ratio COD/NH_4 N/PO_4-P). In the literature the ratio BOD_5/COD varied between 0.25 for GW [19] and 0.44 for domestic low strength wastewater [20]. The high concentrations of detergents in grey water are known to be slowly biodegradable, explaining the difference to the low strength wastewater. The BOD_5/COD ratio of GW in three studies was within this reported range with a value of 0.25 for set-up A, and a value of 0.43 for set-up B and C. The average ratio of COD/NH_3/TP has been reported typically with 100/5/1 for domestic wastewater [20]. Kargi and Uygur [21] calculated an optimum COD/NH_3/PO_4-P for a maximum nutrient removal in the activated sludge process for synthetic wastewater with a five-step SBR of 145/5.87/1, whereas Jefferson et al. [22] measured a COD/NH_3/TP ratio up to 1030/2.7/1 for GW, indicating a macronutrient limitation. The synthetic GW in set-up A had a COD/NH_3/PO_4-P ratio of 121/5.69/1, which is very close to the optimum ratio found by Kargi and Uygur. For the highly diluted GW from set-up B and C the ratio of COD/NH_3/TP was determined at 127/9.13/1 favourable for biological treatment with no limitation concerning the macro nutrients.

3.2. *Experiences from operation of GW treatment plants*

The SM-SBR has been put into operation in January 2006 with a volumetric exchange ratio of 0.25 and started off with an HRT = 33 h. Investigations of COD and nitrogen removal within one cycle, combined with the online measurements of DO, ORP and flux of the membrane module showed possible optimisation potentials in terms of time reduction for the aerated and anoxic phase. After 80 days the HRT was reduced to 24 h and has been since reduced in consecutive steps down to 8 h. With an HRT = 8 h and the last modification to gravity flow the permeability is on average of 360 $L(m^2h\ bar)^{-1}$ (flux = 25 $Lm^{-2}h^{-1}$) for the UF-module and of 660 $L(m^2h\ bar)^{-1}$ (flux = 35 $Lm^{-2}h^{-1}$) for the MF-module. In studies on municipal and domestic wastewater flux values for submerged membrane modules between 5 and 40 $Lm^{-2}h^{-1}$ have been found [23].

The mean organic loading rate for the GSF was low with $L_{org} = 0.29\ kg_{COD}(m^3d)^{-1}$ compared to the value of 1.09 ± 0.73 $kg_{COD}(m^3d)^{-1}$ found by Jefferson et al. [24]. However, it has to be taken into consideration that, especially in the sand filter, only a part of the volume was actually used. If the effectively used reactor volume was taken as a reference, the organic loading rate would be higher.

Due to low temperatures in winter and the fact that plants had to develop firstly their roots for anchoring and water supply, hardly any external development was observed at the beginning. Later, a quick development could be observed during which the first two rows grew significantly faster than the last three rows. This is explained by the gradual decrease of the water level in the gravel due to head loss. The roots of the plants in the first rows reached the water earlier and needed root growth only for anchoring. At the end, the reed had developed to an average height in the first two rows between 150 and 170 cm, but only an average height of 110–120 cm high in the last rows.

The actual HRT was calculated to 122 min according to [25]. This means that the actual HRT was only 54% (51%) of the theoretical one which indicates important short cuts. Especially the sand compartment was not fully used. In the gravel compartment the reduction of the effective volume due to root development may also have been considerable. Roots may help create dead zones.

It appears that planting did not have an overall optimising effect on the GSF. This observation, however, might be due to the fact that results achieved with the unplanted filter were already satisfactory. A negative effect of planting was the decrease of hydraulic conductivity and a subsequent overflowing of the receiving ditch at times with high inflow rates. Phosphorus uptake by the plants may explain the increase in total phosphorus removal with respect to the previous year. However, as total phosphorus concentration in the influent was low, so this was not a critical issue.

The wastewater production at the camping site “La Cava” has a high weekly fluctuation in the range from 0.3 to 7.0 m^3d^{-1}. The inlet COD composition of the segregated greywater is high in comparison to the other greywaters. This is probably due to the concentrating effect obtained with the various water saving measures in operation resulting in an average influent concentrations three times higher then measured at the other places [26].

Table 3 shows the removal efficiencies for COD, TN and NH_4-N for the different set-ups, as well as the average feed and permeate concentrations over the operation period. Each cycle time reduction of the SM-SBR enhanced the removal efficiency and with an HRT of 8 h a first optimised cycle time seems to be reached. The TN removal of 81% achieved under the latest HRT compared to the removal of 73% for the HRT of 33 h illustrated the success of an optimised cycle. Although the microbiological parameters are not measured, it is assumed that the SM-SBR provides effluent of high hygienic quality due to the incorporation of a membrane as it is reported in literature for the operation of MBR by various authors [27–29]. The treatment efficiency of the CW was rather impressive according to the high inlet COD of 503 mgL^{-1} with a removal efficiency of approximately 90%. Winward et al. [30] reported also very good hygienic effluent quality for greywater treatment with CW.

3.3. *Reuse option and its benefit for small communities*

One of the most common solutions for reuse of greywater is garden watering, irrigation of vegetable and crops, as well as the use for toilet flushing. Garden wa-

Table 3
Average concentrations of permeate and the achieved removal efficiencies

	Mandatory values (mg L^{-1})	Set-up A (HRT = 8 h)		Set-up B		Set-up D	
		Permeate (mg L^{-1})	Removal efficiency	Effluent (mg L^{-1})	Removal efficiency	Effluent (mg L^{-1})	Removal efficiency
Turbidity	—	—	—	1.7 NTU	0.93		
COD	30[1]	18.9	0.91	38	0.81	53	0.89
BOD$_5$	25[2]			6	92	—	—
TKN	—	4.1[*]	0.81	9	0.39	1.1	0.56
NH$_4$-N	2.0[3]	0.37	0.97	5.8	0.62	0.13	0.92
NO$_3$-N	—	3.66	—	—	—	0.46	—
Faecal coliforms (cfu/100 mL)	Average: 2.2–20[4] Maximum: 23–75[4]	—[**]	—[**]	After the filter: 8.7×10^3 After UV disinfection: 80	0.97	—	—

[1] Directive (75/440/EEC)
[2] Directive (91/271/EEC)
[3] Italian national law 185/2003
[4] US.EPA/625/R-04/108 (unrestricted urban reuse)
[*] measured as TN
[**] effluent of MBR suitable for reuse [27,28]

tering for example accounts for around 34% of the total household water budget in Melbourne, Australia, with a highly seasonal demand [31]. However, it should be noted that with many of the larger scale schemes, which may include rainwater, the recycled water can be employed for other urban uses such as park irrigation, street cleaning etc. [1]. For small communities the advantages of generating greywater consist in its:

- possibility to use low cost treatment like constructed wetland with ease of operation and maintenance [32]
- reuse in place for toilet flushing or garden watering
- minimising sewage network and wastewater treatment operational cost
- higher public acceptance of greywater reuse compared to the reuse of total municipal wastewater.

The reuse of the treated GW from the SM-SBR is applicable for in-house use, cleaning purposes, like washing cars and irrigation. Its biggest advantages of an effluent with a high hygienic quality and a small footprint of the reactor come in play for tourism attractive centres. The CW and as well as the GSF have their share in the sustainable water management approach due to their low invest and operational costs. The treatment performance is excellent, when correctly designed, but can fail fast, when under designed. Maybe here an additional UV disinfection may be needed.

4. Conclusion

Greywater reuse is next to rainwater harvesting the first decision which should be considered both by individuals and the community when it comes to reuse of water. The results obtained from the CW provide excellent treatment for greywater with variable peak flows. Therefore it can be recommended that this configuration can be used as a benchmark design for other warm climate remote areas or small communities needing to improve and preserve the quality of open water bodies. The SM-SBR is an option where space is limited and high hygienic quality is needed. The unplanted GSF is a very simple technology for low polluted greywater, but needs to be carefully designed to avoid clogging. All described technologies should be considered as solution to gain advantages from a sustainable water management with its many reuse options.

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