Organic matter degradation in a greywater recycling system using a multistage moving bed biofilm reactor (MBBR)

Assia Saidi, Khaoula Masmoudi, Erwin Nolde, Btissam El Amrani and Fouad Amraoui

ABSTRACT

Greywater is an important non-conventional water resource which can be treated and recycled in buildings. A decentralized greywater recycling system for 223 inhabitants started operating in 2006 in Berlin, Germany. High load greywater undergoes advanced treatment in a multistage moving bed biofilm reactor (MBBR) followed by sand filtration and UV disinfection. The treated water is used safely as service water for toilet flushing. Monitoring of the organic matter degradation was pursued to describe the degradation processes in each stage and optimize the system. Results showed that organic matter reduction was achieved for the most part in the first three reactors, whereas the highest reduction rate was observed in the third reactor in terms of COD (chemical oxygen demand), dissolved organic carbon and BOD$_7$ (biological oxygen demand). The results also showed that the average loading rate entering the system was 3.7 kg COD/d, while the removal rate was 3.4 kg COD/d in a total bioreactor volume of 11.7 m$^3$. In terms of BOD, the loading rate was 2.8 kg BOD/d and it was almost totally removed. This system requires little space (0.15 m$^2$/person) and maintenance work of less than one hour per month and it shows operational stability under peak loads.

Key words | biological treatment, greywater recycling, MBBR, organic pollution load

INTRODUCTION

Although Germany is considered rich in water resources, high water costs play an important role in the increase in decentralized wastewater treatment plants (WWTPs) installed in buildings (Nolde 2005). According to the German Federal Statistical Office, water consumption in Germany amounts to 129 L/(person-d), whereas only 52 L/(person-d) are needed for potable use (IWR Regulatory Guide H 201 2005).

High quality water is becoming very scarce. Water saving and recycling combined with energy and nutrients recovery are a key for a sustainable sanitation, which can be implemented in a decentralized way. Water reuse may raise awareness about water conservation and wastewater management. Decentralized source separation is not new and it has long been propagated as an inexpensive and environmentally safe technology, especially for rural areas.

Greywater is part of the household wastewater excluding blackwater. It is the drain from bathtubs and shower trays, washbasins and washing machines (low load) and may also contain high-strength kitchen wastewater (high load) (IWR Regulatory Guide H 201 2005). Greywater constitutes 50–80% of the total household wastewater and can be recycled and reused as service water for different applications such as toilet flushing, laundry, cleaning, and irrigation (Eriksson et al. 2002).

In Germany, the concept of decentralized greywater treatment is included within the approach ‘Neuartige Sanitärsysteme (NASS)’ which is based on the separate collection, derivation, treatment and reuse of useful parts of the wastewater streams. These concepts are embraced in English by the terms ‘ecological sanitation’, ‘resources oriented sanitation’, ‘sustainable sanitation’ and ‘decentralized sanitation and reuse’ (DWA 2008).

A wide variety of technologies have been used or are being developed for greywater treatment and reuse, including natural treatment systems, basic coarse filtration and chemical, physical, physiochemical and biological processes (Jefferson et al. 2004).

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Jefferson et al. (2004) suggested that advanced biological processes which combine a bioreactor with an efficient solid separation process are likely to be the most suitable technology for greywater recycling.

The moving bed biofilm reactor (MBBR) is an attractive treatment system for greywater at the household level and this is thanks to its high performance, stability, robustness and compactness. It was developed to adopt the best features of the activated sludge and biofilter processes (Rusten et al. 2006). In order to make this technology more efficient, several studies investigated the optimization of the treatment process by using different types of bed carriers (Chu & Wang 2014) or filling ratios (Gu et al. 2014).

Numerous studies have shown that MBBR processes have excellent traits such as a high biomass, high chemical oxygen demand (COD) loading, strong tolerance to loading impact, relatively small reactor requirement and no sludge bulking issues (Leyva-Díaz et al. 2015).

Ødegaard (1999) recommended a design value for an MBBR system with 67% filling ratio using the Kaldnes bi-media K1 of 8 kg/m³·d at a high loading rate of biological oxygen demand (BOD₇) and with a treatment goal that goes up to 75–80%.

An MBBR system for greywater treatment, which started operating in 2006 and serves a multi-storey complex in Berlin, has been investigated for kinetics of organic matter degradation. In this regard, the removal of soluble organic compounds depends on the biodegradation process in the biofilm reactor (Sun et al. 2009). Presented in this paper are the kinetics of organic matter degradation according to two types of sampling. Thus, the objective of this research work is to understand the role of each processing stage, particularly in the removal of organic matter, in order to optimize the system for future implementations.

MATERIAL AND METHODS

Plant setup

The study area (Block 6) is a community-based dwelling in the centre of Berlin consisting of three residential buildings accommodating 71 families (approx. 223 tenants). The existing infrastructure from a past demonstration project included water saving measures and a dual-piping system (Berlin Senate Department for Urban Development 2008).

Greywater from showers, bathtubs, washbasins, kitchens and washing machines undergoes an advanced physical–biological treatment in an MBBR followed by sand filtration and UV disinfection (Figure 1). After an initial screening of the solid matter and grease, greywater enters the recycling system consisting of 10 MBBR reactors (R1–R10) (polyethylene), each having a capacity of 1.3 m³. The first eight reactors are MBBR reactors while the ninth serves only as a sedimentation stage followed by the final MBBR reactor. The system treats between 8 and 11 m³ greywater per day.

Figure 1 | Greywater treatment system design in Block 6 in Berlin, Germany.
depending on the daily service water demand (Figure 1), which is reused to flush 90 toilets and irrigate home gardens. In a further research project (Roof Water-Farm; http://www.roofwaterfarm.com), the treated greywater (service water with <2 mg/L BOD and 2–4 Escherichia coli/100 mL) is safely used for food production (aquaponics). The hydraulic retention time (HRT) varies between 1.2 and 1.6 days.

The moving bed carrier is made of polyurethane foam on polyether basis with open pore size structure (EMW, Filter-technik). The bio-carrier has a net density of 20–30 kg/m³ with the number of pores between 40 and 50 ppi (pores per inch) and a specific surface area of about 1,000 m²/m³ (Figure 2). The filling ratio for the first two reactors is 11.5% (ideal ratio), due to the limited oxygen concentration in the reactors. The filling ratio for the remaining reactors is 15%.

Aeration is accomplished by different air blowers (45–120 L/min) placed in each reactor. The airflow rate decreases from 60 L/min in the first reactors to 30 L/min in the final reactors.

**Analytical methods**

Conductivity, dissolved oxygen (DO) and pH were measured using an ECM Multi type LXG090 spectrophotometer (Dr. Lange). Turbidity was measured for fresh samples and settled samples (2 h) using a WTW Turb 450 IR turbidity meter.

UV transmission was determined in the settled samples using a Shimadzu UV-1201 spectrophotometer. Samples were run through a glass fibre filter and measured at 254 nm in 1 cm cuvettes against Millipore water.

COD and measurements of settled samples (2 h) were carried out photometrically using a Lange LTG061 and quick test cuvettes (ISO 6060-1989; DIN 38409-H41-H44). Dissolved organic carbon (DOC) for filtered samples (glass fibre filter) was measured using a Multi N/C 3100, Analytik Jena (DIN EN 1484). BOD was determined in fresh settled samples on the seventh day using a WTW OxiTop®Control OC 110 (DIN EN 1899-2). Settled sludge (mL/L) was measured after 2 hours decantation in a sedimentation cone.

**Experimental procedure**

The aforedescribed greywater recycling system has been operating since 2006 and no study has been previously carried out to explain the mechanisms of organic matter degradation. The only available information is that the system is continuously stable even under fluctuating and high pollutant loads (paints, disinfectants, bleaching products, etc.). The quality of
the treated water is high and complies with European standards for bathing water quality (EU Directive for Bathing Water 2006).

All analyses series were carried out from March 2014 to June 2015. Measurement of raw greywater was done to determine the appropriate time of sampling corresponding to the highest organic load. Greywater was taken on an hourly basis proportional to the inflow over a period of 24 hours from 14/10/2014 at 12 noon to 15/10/2014 at 12 noon.

Twenty-four-hour composite samples were taken over 10 days (from 05/06/2015 to 15/06/2015) from the influent and effluent of the greywater recycling system.

Kinetics studies on organic matter removal are often done according to the respirometry method (Ferrai et al. 2010; Leyva-Díaz et al. 2015). However, in this study the removal of organic matter was investigated by analysing the COD, DOC and BOD\(_7\) at the effluent of each reactor using two types of sampling.

(a) Twenty-four-hour composite samples were taken over 10 days (from 05/06/2015 to 15/06/2015) to determine the average removal of COD, DOC and BOD\(_7\) in each reactor.

(b) Grab samples were used for the first order kinetics study, during which the reactors were operated separately as batch reactors on different days. Fresh greywater was pumped into the system to obtain high initial COD and BOD concentrations. During sampling, no greywater was pumped into the system, in such a way that the individual reactors were operated as batch reactors for a period of 6 hours. Hourly samples were taken and analysed directly.

(Note: reactor 9 was not analysed during the kinetics study as it only served as a sedimentation tank and not as an MBBR.)

RESULTS AND DISCUSSION

Estimation of wastewater flow and pollution load

To determine the peak of pollutant load during the day, automatic sampling was performed hourly over a period of 24 hours. The typical graph shown in Figure 3 presents the variation in the inflow, DOC (in mg/L) and DOC (in g/h) during the whole day.

Figure 3 shows that the peak pollutant load was at 19:00 (DOC = 112 g/h), which could be related to the type of activities conducted by the inhabitants once they return home from work such as cooking, washing dishes, and bathing, etc. At about 08:00 a volume peak (1,016 L) was recorded during which the DOC concentration was low (61 mg/L). The fact that people mostly take a shower in the morning may explain the high water inflow and low (diluted) organic load.

In this study, greywater was taken after the first pre-treatment stage (Figure 1, sampling point 2). In order to obtain information on the raw greywater quality, results from another study (Sievers et al. 2014), which also investigated the aforementioned greywater system, are presented and compared with results from this study.

In an independent sampling campaign, greywater from one of the connected residential buildings was analysed over a period of 7 days by Sievers et al. (2014). The results for homogenized samples showed an average COD concentration of 858 mg/L with daily maxima in the peak ranging from 560 to 1,327 mg/L, while BOD\(_5\) values varied between 260 and 766 mg/L with a mean value of 470 mg/L.

Based on the data from Sievers et al. (2014), the average loading rates for homogenized samples are about 8.5 kg COD/d and 4.7 kg BOD\(_5\)/d. The average reduction in the first mechanical stage (screen, 1 mm, Figure 1), which is
not the objective of the present study, is about 43% (average total COD after screening 490 mg/L). The pollutant load removed in this stage is mainly in the form of grease. Theoretically, the removed sludge can be reused to produce energy in a biogas plant.

Organic load variation and nutrient removal

The main goal of the treatment is the degradation of the organic matter, which is the main pollutant load of greywater. Table 1 shows average values of organic matter, nitrogen and phosphorus in the influent and effluent of the greywater treatment system.

The system achieved an average organic removal rate of 94.5% in terms of COD, 99.4% for BOD, and 91% in terms of DOC, which are higher compared to other studies (64% by Jabornig & Favero (2013); 87% by Melin et al. (2005)).

Sievers et al. (2014) measured relatively higher COD and BOD concentrations at the influent, which can be explained by the fact that in this study settled samples were measured, while Sievers et al. used homogenized samples.

A typical COD:N:P ratio for greywater is 100:2:1 (Larsen et al. 2013). In this study, the ratio was 100:3.1:0.63. The ratio of COD/BOD was 1.5, which is within the same range compared to that from Sievers et al. (2014) (1.4–2.1). These ratios indicate a high biodegradability of the greywater.

The concentration of total nitrogen (TN) in greywater is lower compared to municipal wastewater due to the absence of urine in greywater, where it could reach up to 100 mg N/L (Leyva-Díaz et al. 2013). Nitrogen in greywater originates mainly from protein contained in food residues, household cleaning products and personal care products. In this study, TN was reduced by 63% with the removed sludge and due to the nitrification process.

Average phosphorus concentrations in greywater are typically found within the range of 4–14 mg/L in areas where non-phosphorus detergents are used (Eriksson et al. 2002). The average of total phosphorus (TP) concentration in the influent was 2.8 mg/L and it achieved a 14% reduction. This value lies within the range (2.7–7.4 mg/L) measured by Sievers et al. (2014). The source of phosphorus in greywater is mainly food but it can also originate from dishwashing detergents, which may contain up to 50% phosphates (DWA 2008). In the literature, phosphorus removal is achieved by chemical precipitation in most tested MBBR treatment systems (Wang et al. 2006) or it requires the existence of an anaerobic zone, or specific bacteria and operating conditions for its removal (Kermani et al. 2009).

From Table 1, it can be seen that the phosphate concentration increased in the effluent. This can be explained by the fact that the sedimentation stage, taking place in reactor 9, is an anaerobic stage, which leads to the release of phosphates.

Organic removal activity

In order to get an idea about the general conditions in the treatment system, the analyses of the major parameters, including turbidity, settled sludge and DO, in each reactor are summarized in Figure 4. Generally, pH varied between 7.6 and 8.2 in the different reactors. The conductivity was about 1 mS/cm and remained stable around this value.

Turbidity of fresh greywater samples was 291 NTU in R1, which increased to 385 NTU in R2 and then decreased to 4.5 NTU in R10. Following sand filtration as a final treatment step, the measured turbidity was below 0.5 NTU (Figure 4). In the first reactors, the high turbidity is due to the high pollution of the greywater. In fact, the COD concentration is above 200 mg/L in the three first reactors while it decreases to reach a concentration under 50 mg/L for the two last reactors. Among the COD fractions, the colloidal COD represents 55% of the total COD (Leal et al. 2010), (Ghunmi et al. 2010) and is also responsible for the turbid aspect of the water. After R2, a continuous reduction in the turbidity is observed due to the continuous removal of soluble dissolved matter by the microbial biofilm and sludge formation.

The sludge settleability remains as one of the most important parameters that can affect system stability, removal efficiency of organics present in the wastewater,

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Table 1 | Average treatment performance for settled samples (n = 10)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>COD (mg/L)</th>
<th>BOD (mg/L)</th>
<th>DOC (mg/L)</th>
<th>NH₄-N (mg/L)</th>
<th>NO₂-N (mg/L)</th>
<th>TN (mg/L)</th>
<th>PO₄-P (mg/L)</th>
<th>TP (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>413.3</td>
<td>293</td>
<td>77.8</td>
<td>7.15</td>
<td>0.34</td>
<td>13</td>
<td>1.9</td>
<td>2.81</td>
</tr>
<tr>
<td>Effluent</td>
<td>22.6</td>
<td>1.6</td>
<td>7</td>
<td>0.02</td>
<td>3.27</td>
<td>4.8</td>
<td>2.4</td>
<td>2.42</td>
</tr>
<tr>
<td>% Reduction</td>
<td>94.5</td>
<td>99.4</td>
<td>91</td>
<td>99.7</td>
<td>–</td>
<td>63</td>
<td>–</td>
<td>14</td>
</tr>
</tbody>
</table>

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and ability to withstand shock loads. It has also an impact on dimensioning of the treatment units and HRT. In order to confirm the advantage of the MBBR of producing less sludge comparing to the activated sludge systems, the parameter settled sludge volume is here presented to give an idea about the volume of the produced sludge in each reactor (Aygun et al. 2008).

The settled sludge volume, which indicates the settled particulate matter, increased from 1.5 mL/L in R1 to 6.9 mL/L in R3. In R1, the degradation rate was high (COD reduction 0.61 kg/(m³·d)), which resulted in high sludge formation in comparison with the other reactors. In the following reactors with lower pollutant load, less particulate matter is present and more sludge oxidization takes place. Following R3, the sludge volume decreased continuously to 1.2 mL/L.

The DO concentrations represent the average quantity of DO during a whole day in each reactor. Figure 4 shows that the concentration of DO in reactors 1, 2, 3 and 4 did not exceed 1 mg/L, while in R5 the DO concentration reached 5.1 mg/L and increased to 8.4 mg/L in R10. In the first reactors, DO is consumed all the time due to the high pollution load and high biodegradation rate, while in the remaining reactors there is a lower oxygen consumption due to the lower pollution load. Water temperatures ranged between 20 and 25 °C.

**Results of 24-hour composite samples**

In order to evaluate the contribution of each reactor to the degradation of organic matter, the performance of each reactor was tested by measuring the average concentrations of COD, DOC and BOD₇ (g/m³) for 24-hour composite samples and the average reduction of each component in g/(m³·d) (Figure 5). The reduction of the three parameters is calculated as follows (Equation (1)):

\[
\Delta \text{COD}(\text{g}/(\text{m}^3 \cdot \text{d})) = (\text{COD}_{\text{output}} R_i/\text{g}/\text{m}^3) - (\text{COD}_{\text{input}} R_i - 1/\text{g}/\text{m}^3) \times \frac{Q}{V} \tag{1}
\]

Rᵢ: reactor
Rᵢ₋₁: previous reactor
Q = inflow (m³/d)
V = reactor volume (m³)

The COD average loading rate entering the system was 3.7 kg COD/d and the removal rate was 2.6 kg COD/(m³·d). Comparing COD reduction (kg/(m³·d)) in each reactor calculated as described above (Equation (1)), the removal peak was found in R3 (0.61 kg/(m³·d)) followed by R1 (0.5 kg/(m³·d)), R2 (0.4 kg/(m³·d)) and R4–R5 with approximately 0.3 kg/(m³·d). In R7, COD removal was low (0.18 kg/(m³·d)) and decreased to 0.07 kg/(m³·d) in the last two reactors.

In terms of BOD₇, the average loading rate was 2.8 kg BOD₇/d, which was almost totally removed during the treatment process. Comparing the different reactors, a similar fluctuation was observed in the variation of BOD₇. BOD₇ reduction mainly took place in the first and the third reactors with 0.47 kg/(m³·d) and 0.42 kg/(m³·d) in R2 and then to approx. 0.22 kg/(m³·d) in the following two reactors. In R6, BOD₇ reduction achieved 0.16 kg/(m³·d) and in R7 and R8 0.05 kg/(m³·d). In the final reactor, BOD₇ reduction did not exceed 0.02 kg/(m³·d).

The average reduction of DOC in the whole system was about 91%. The loading rate was 0.7 kg DOC/d and the average removal rate was 0.4 kg DOC/(m³·d).
Comparing the different treatment stages of the greywater treatment plant, most of the DOC was removed in the first reactor (0.18 kg/(m$^3$·d)) followed by the third reactor (0.1 kg/(m$^3$·d)). DOC reduction in R2 and the following four reactors was between 0.06 kg/(m$^3$·d) and 0.04 kg/(m$^3$·d), while it did not exceed 0.01 kg/(m$^3$·d) in the last two reactors.

The fluctuation in the organic matter reduction in the first two reactors can be explained by the fact that the water level in R1 and R2 fluctuates between 50 and 100%, since both reactors serve not only as MBBR reactors but also as a buffer. Figure 1 demonstrates that these two reactors are interconnected at the bottom. In contrast, in the other reactors the degradation rates are in accordance with the pollution level; the lower the pollution the lower is the degradation rate. There is a negligible difference between R4 and R5. Thus, we can say that the readily biodegradable soluble compounds are removed first. Then with less pollution load, the compounds with higher refractoriness are slowly degraded.

A study which investigated the treatment of raw wastewater from a municipal WWTP in a pilot scale MBBR showed a removal rate of soluble COD of about 0.62 kg/(m$^3$·d) with a loading rate of 0.94 kg/(m$^3$·d) (Plattes et al. 2006). This is comparable to the value measured in R3 in this study.

In terms of BOD, Plattes et al. (2006) achieved in a pilot scale MBBR a removal rate of 0.5 kg/(m$^3$·d) for soluble BOD$_5$ with an organic loading of 0.57 kg/(m$^3$·d). These values are also comparable to the values measured in the first three reactors in this study (0.47–0.42 kg/(m$^3$·d)).

The average total COD removal efficiency for the whole system was 94.5%, which is significantly higher compared to 64% (average COD$_{inflow}$ 240 mg/L) achieved by a moving bed biofilm membrane reactor used to treat greywater for a single household (200 L, HRT 24 h) (Jahornig & Favero 2013). This low removal efficiency (64%) was explained by the poor nutrient ratio in the feed greywater, which was only in the range of 100:2.28:0.24 (COD:N:P).

Friedler et al. (2005) investigated greywater treatment in a rotating biological contactor followed by sand filtration and disinfection in a multi-storey building (max. mean retention time 17.2 h). Their system achieved a 64% removal rate for dissolved COD and 75% for total COD, at an overall COD inflow of 150 mg/L. They also found that COD removal was significantly lower than that of BOD implying that the greywater contains slowly/non-biodegradable organic matter, especially in soluble form.

The COD removal efficiency (64%) obtained in the two aforementioned studies was achieved in the present study after the fourth reactor. This might confirm that the presence of a multistage treatment system can enhance the
degradation of the slowly/non-biodegradable organic matter in greywater.

Figure 6 shows the variation of the average COD/BOD$_7$ ratio in the different reactors. The ratio increases from 1.5 in the influent to 6.2 in R7. Overall, it may be concluded from these results that bacteria first start with the degradation of the easily biodegradable part of the organic matter, while the slowly/non-biodegradable part is degraded at a later stage in the system.

Results of grab samples

For a better understanding of the organic matter degradation in each reactor, the removal of organic substrate in each reactor was demonstrated in the form of correlation between COD (mg/L) measured hourly during the operational HRT (5 h) and calculated as $\Delta$COD = $(\text{COD}_{t1} - \text{COD}_{t2})/\left(t_2 - t_1\right)$ (g/(m$^3$·d)); a similar correlation for BOD$_7$ was also studied (Figures 7 and 8, respectively).

Figure 7 shows the COD degradation rates in the different reactors dependent on COD concentration. Taking as an example R1, it can be seen that during the first hour at COD concentration of 350 mg/L, a degradation rate of 0.95 kg/(m$^3$·d) was achieved. After 2 hours and COD concentration of 325 mg/L, a reduction of 0.72 kg/(m$^3$·d) was achieved. After 5 hours, a reduction of 0.38 kg/(m$^3$·d) was achieved at COD concentration of 260 mg/L. The same is presented in Figure 8 in terms of BOD.

Given the above results, it is obvious that there is a high positive correlation between COD as well as BOD concentrations and the achieved degradation rates. In the third reactor, a higher organic matter removal rate takes place. The fluctuation of the water volume in the first two reactors, as explained previously, and the lower filling ratio of the...
foam cubes are the reasons for the lower removal rates in these reactors comparing to R3.

In R3 with 1.9 kg/(m$^3$·d), the highest COD reduction was observed followed by R1, R2, R4 and R5, with approximately 1 kg/(m$^3$·d). In R6, COD reduction decreased to 0.4 kg/(m$^3$·d), while in the final reactors it did not exceed 0.14 kg/(m$^3$·d). The correlation between COD (mg/L) and $\Delta$COD (g/(m$^3$·d)) in each reactor is high. The coefficient of correlation varied between 0.88 and 0.99 (Figure 7). Reactor 3 exhibited the highest values in terms of COD reduction, thus confirming the results in Figure 5.

In terms of BOD$_7$, higher reduction was observed in R1 and R3 with approximately 1 kg/(m$^3$·d) followed by R2 with 0.72 kg/(m$^3$·d) and R4 and R5 with nearly 0.4 kg/(m$^3$·d) each. BOD reduction in the final reactors was between 0.15 and 0.04 kg/(m$^3$·d). The correlation between BOD$_7$ (mg/L) and $\Delta$BOD$_7$ (g/(m$^3$·d)) in each reactor was also high and the coefficient of correlation varied between 0.91 and 0.97 (Figure 8).

The COD and BOD$_7$ reduction rates aforesaid were observed during the first hour of the treatment process. At the end of the treatment process COD reduction was between 0.3 and 0.05 kg/(m$^3$·d), while BOD reduction was between 0.2 and 0.006 kg/(m$^3$·d) in the different reactors.

The COD and BOD removal rates show different slopes for the different reactors. One explanation could be the different pollution loading rates in the reactors on different days.

In one study with three MBBRs using three different carriers, the removal rate for filtered COD was between 0.1 and 3.5 kg/(m$^3$·d) and the volumetric loading varied between 0.5 and 5 kg/(m$^3$·d) (Ødegaard et al. 2000).

A study on the influence of high organic load in an MBBR with Kaldnes biomedia K1, which is used in the patented Kaldnes moving bed process, showed the removal efficiency versus volumetric and surface loads. With an HRT of 12 hours and a volumetric organic loading rate between 1.5 and 6 kg total COD/(m$^3$·d) (corresponding to 500–8,000 mg/L influent total COD and average effluent COD between 24.5 and 4,576 mg/L), it was possible to obtain the highest removal efficiency for total COD in the MBBR. However, the removal efficiency of total COD decreased to 45.2% when 6 kg total COD/(m$^3$·d) volumetric organic loading rate was applied (Aygun et al. 2008).

A comparative study between a UASB (up-flow anaerobic sludge blanket) reactor and an aerobic fed-batch reactor treating greywater showed that the aerobic treatment is more efficient in the removal of COD than the anaerobic treatment, reaching 90% at loading rates ranging from 0.15 to 8 kg COD/(m$^3$·d) (average total COD 1,583 mg/L) (Leal et al. 2007). A comparison of data from the three studies mentioned above is revealed in Table 2.
Based on these results, it can be concluded that by optimizing the operation of the first reactors (DO concentration and filling ratio of foam material) higher degradation rates can be achieved with fewer bioreactors.

**COD, A<sub>254</sub> and turbidity correlations**

For many years, UV-visible spectroscopy has been proposed as an alternative and rapid way to estimate the level of pollution in wastewater and surface water and the 200–300 nm range is of particular interest. The 254 nm wavelength has been selected and correlations between absorbance at 254 nm (A<sub>254</sub>) and COD or total organic carbon have been established (Wu et al. 2006).

In this study, a good correlation was obtained between A<sub>254</sub> and COD (filtered samples) with a coefficient ranging from 0.91 to 0.97 (Figure 9), which confirms that A<sub>254</sub> can be used as a surrogate parameter for COD (Thomas et al. 1993). Likewise, a good correlation was obtained between turbidity (NTU) and COD (settled samples) and the coefficient of correlation varied between 0.97 and 0.99 (Figure 10).

The good correlation between the different settled samples in terms of turbidity and COD in each reactor can be explained by the fact that during the degradation process samples were taken from batch-operated reactors (i.e. samples originate from the same wastewater). In the case of unknown samples, turbidity and absorption do not replace COD measurements but are appropriate to control the results. However, a long-term online monitoring of COD in a system is often not possible or can be expensive. In such a case, turbidity and absorbance measurements could help verify the water quality.

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**Table 2 | Design, operating conditions and results of the three mentioned studies**

<table>
<thead>
<tr>
<th>Study</th>
<th>Design</th>
<th>Operating conditions</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ødegaard et al. (2000)</td>
<td>- MBBR (20 L) and a settling tank</td>
<td>- Organic loads (10–120 g COD/(m&lt;sup&gt;2&lt;/sup&gt;·d))</td>
<td>COD removal rate: between 0.1 and 3.5 kg/(m&lt;sup&gt;3&lt;/sup&gt;·d)</td>
</tr>
<tr>
<td></td>
<td>- Three different types of carriers (60% filling ratio)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aygun et al. (2008)</td>
<td>- A reactor (2 L) and a settler (1.2 L)</td>
<td>- HRT: reactor (8 h) and settler (4 h)</td>
<td>COD influent (mg/L): 500–8,000 Average COD effluent (mg/L): 24.5–4,576</td>
</tr>
<tr>
<td></td>
<td>- Kaldnes biomedia K1 with a filling ratio of 50%</td>
<td>- Continuously fed</td>
<td></td>
</tr>
<tr>
<td>Leal et al. (2007)</td>
<td>Anaerobic treatment</td>
<td>- HRT from 12 to 24 h</td>
<td>40% COD removal</td>
</tr>
<tr>
<td></td>
<td>- UASB reactor with a capacity of 3.6 and 5 L</td>
<td>- Loading rates ranging from 0.15 to 8 kg COD/(m&lt;sup&gt;3&lt;/sup&gt;·d)</td>
<td></td>
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<td></td>
<td>- Inoculum: flocculent anaerobic sludge (mixed primary and secondary sludge) from the municipal WWTP</td>
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<tr>
<td></td>
<td>Aerobic treatment</td>
<td>- A reactor of 3.6 L</td>
<td>90% COD removal</td>
</tr>
<tr>
<td></td>
<td>- Inoculum: activated sludge from WWTP</td>
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</tbody>
</table>

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**Figure 9 | Correlations in reactors 1, 3 and 4 between absorbance at 254 nm and COD (filtered samples).**
CONCLUSION

The multistage greywater treatment system showed a good performance for the organic substrate removal, with 94%, 99% and 91% for COD, BOD and DOC reductions, respectively (COD effluent 22 mg/L; BOD < 2 mg/L). The system verifies the objective of design in series, in which each reactor is designated for a specific treatment function within the greater treatment scheme. The reactors enhance the development of a specialized biofilm dependent on the prevailing conditions within the reactor, which also promotes the degradation of the less biodegradable organic matter (the ratio COD/BOD$_7$ increases from 1.5 in the influent to 6.2 in R7).

The organic matter reduction was achieved for the most part by the first three reactors (reduction of more than 50% in COD and 65% in BOD). R5 showed the highest performance for organic matter degradation within a wide load range (0.61–1.9 kg COD/(m$^3$·d)). It results from the above that the final reactors present more of a safety factor in the presence of high load greywater, which guarantees higher stability and system performance against high organic load fluctuations. In addition, the optimization of process parameters, such as carrier filling ratio and aeration efficiency, can increase the system performance at early stages of the treatment.

It can be concluded also that decentralized recycling systems can be so effective that they could achieve high water quality (2 mg/L BOD and 2–4 E. coli/100 mL) and save water by reducing the water consumption as well as the amounts of generated wastewater (between 9 to 11 m$^3$ of service water per day).

According to the Berlin Water Works (BWB 2014), 99.9% of Berlin's households are connected to the central sewage system. Compared to Berlin, Casablanca faces massive problems in sanitation and wastewater treatment, although potable water there is cheaper (water and sanitation costs for a four-person household in Germany are approximately five times more than those in Morocco). Therefore, the need for solutions and investments is urgent. In case of the aforementioned cities, source separation is a highly sustainable solution, which can reduce the water costs in Berlin and contribute to solving some of the sanitation problems in Casablanca.

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