Performance study of biofilter system for onsite greywater treatment at cottages and small households

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Abstract

The performance of a source separating wastewater management system for the removal of organic matter, total P, total suspended particles and *E. coli* was assessed. The system is a multi-barrier approach encompassing a separate collection of blackwater and on-site treatment of greywater in a fixed-film biofilter with soil infiltration as final polishing and discharge. For BOD, COD, TSS and phosphorous, a removal efficiency of >90% was reached at the effluent of the biofilter and >95% at the bottom of the constructed infiltration columns. For coliform bacteria, the overall system reached a reduction of 4-5 log_{10} units of which the major reduction was observed in the infiltration columns.

Keywords: Source separation, greywater treatment, biofilter, effluent polishing, infiltration trench.

Introduction

In rural areas without common infrastructure for water supply and sewerage, wastewater has to be treated on site according to national or local discharge regulations. In European countries, discharge regulations are dependent on the local recipient status i.e. the sensitivity to eutrophication. Based on statistics from 2015 (Berge and Chaudhary, 2015)(Berge and Chaudhary 2015) 16 % of the Norwegian population are not connected to central sewerage systems and wastewater discharges from this fraction represents 24 % of the wastewater-generated from the Norwegian population. Like many other European countries, Norway is lagging behind in the efforts to fulfill the water quality goals defined by the European water directive. In addition to eutrophication effects, on-site wastewater systems may pose a health risk to consumers of drinking water by spreading of pathogens to raw water catchments or by direct contamination of local wells. Hence rural wastewater management needs to be improved in order to sustain or improve the environmental quality and to protect human health.

In addition to the 330,000 on-site systems for rural residents, more than 420,000 recreational houses are currently found in rural Norway (SSB, 20016). In the last decades, the average size of these recreational houses increased substantially as well as the standard of water and sanitary facilities (Kaltenborn et al., 2009, Rye and Berg, 2011). The latter has resulted into new challenges in terms of collection and treatment of wastewater produced by these high-standard houses. Soil infiltration is the dominant type of treatment system (29 %) in rural Norway (SSB, 20016). Geological conditions on high mountain areas, where a majority of the cottages are located, often limit the applicability of such natural based treatment systems. On particular places package treatment plants were installed as an alternative, but these systems were also shown to struggle with the highly varying loading conditions and limited maintenance, resulting into frequent malfunction periods with high discharge of pollutants (Schwemer and Wolfgang, 2016). Novel and more robust wastewater treatment systems should therefore be developed to handle the increasing environmental pollution from Norwegian recreation homes.

Source separating sanitation was pointed out as a potential solution to meet the challenges in rural wastewater management to fulfill the European water directive (Jenssen et al., 2016). In this approach, only the so called greywater originated from kitchen and washing facilities is treated locally while the notably higher polluted blackwater originated from toilets is collected and transported to a centralized treatment or recovery facility. Key advantage of these systems is a multi-stage treatment process consisting of several partially redundant treatment steps in series to obtain a relatively high treatment stability despite the variable loading rate. At present only little data are available on source separating sanitary systems and these are mainly gathered from larger-scale pilot installations in urban regions (Todt et al., 2015). This study performed a comprehensive experiment to assess treatment efficiencies and effluent quality for each particular treatment step in a rural configuration of a source separating sanitary system. Post treatment system using column filtration to mimic soil infiltration trench was carried out to study the application in vulnerable areas and where discharge requirements are very stringent.

Methods

Source separating sanitary system

This study was done with greywater (GW) and blackwater (BW) supplied by a student dormitory with 48 inhabitants. The BW collected with vacuum toilets having a flushing volume of 1.2 liter and the greywater is collected via a gravity sewer line to a pumping station from which both sewage fraction are transported in separate pipes into two separate stirred storage tanks in the laboratory. More details are given in Todt et al. (2015). For both wastewater fractions (GW, BW), grab samples were taken from the storage tanks. The concentration in a putative mixed raw sewage (C_{raw}) was calculated considering on an average fraction of 5.5% for BW on the total wastewater volume that have been determined by Todt et al. (2015). This calculation was done with help of random variable algebra considering the measured concentrations ranges for greywater (C_{GW}) and blackwater (C_{BW}) as normal (COD, BOD, TSS, P) or log-normal (Coliform bacteria) distributed random variables, while a constant value was taken for the volume fraction of blackwater (f_{BW}) to avoid ratio distribution (Eq. 1)

$$C_{raw}(\mu,\sigma) = C_{GW}(\mu,\sigma) * (1-f_{BW}) + C_{BW}(\mu,\sigma) * f_{BW} \qquad (1)$$

Greywater treatment system

The study used a greywater treatment GWT system (Ecomotive A02, Ecomotive AS, Runde, Norway) designed for cottages and small households (Heistad, 2008). The GWT system encompasses a sequence of a primary settler, an unsaturated fixed-film biofilter and a secondary clarifier. For the fixed film biofilter lightweight clay aggregates having a diameter of 10-20mm (LWA) (Filtralite, Saint-Gobain Byggevarer AS, Alnabru, Norway) is used. The filter bed has a thickness of 500mm. After primary settling, the greywater is distributed over the biofilter in intermittent pulses via full cone nozzles as described in Heistad (2008). The dosing pump was controlled by a level switch in the primary settler and a timer giving the pulse intervals. The filter is designed for a nominal load of 650L d^{-1}, which results into a surface load of 282 mm d^{-1}.

The GWT system was loaded based the European test protocol for package treatment plants (NS-EN 12566-3:2005+A2:2013) with a diurnal distribution of hydraulic load (Tab. 1). Feeding of the GWTP was performed with a peristaltic pumps (Bredel SPX, Whatson Marlos, Falmouth, UK) and hydraulic load was controlled with a flow meter (Optiflux2000, Krohne, Duisburg, Germany). Grab samples were taken from the effluent of the secondary clarifier. The power consumption was monitored with a power meter connected to the 230 V AC supply of the GWTP.

Table 1: diurnal distribution of greywater into the GWTP

Time frame	**Volume fraction**
0:00-07:00	no load
07:00-09:00	40%
09:00-12:00	15%
12:00-19:00	no load
19:00-21:00	30%
21:00-0:00	15%

The data from the GWTP were collected from April 2013 to Mai 2015. In total, the system was in operation for 458 days in four continuous periods lasting from 28 to 223 days related to different experiments and performance tests that were conducted with the system. The latter included different sequences with overload, underload and simulated power breaks as outlined more in detail in Tab. 2.

Table 2: loading sequences

Loading sequence	**Hydraulic load (L d^{-1})**	**number of periods**	**total length**	**number of samples**
nominal load (100%)	650	8	435 days	50
overload (150%)	975	2	10 days	7
underload (50%)	325	1	12 days	3
power break	650	4	8 days	8
loading breaks	no load	4	647 days	4[1]

[1] samples were taken within the first 3 days after restarting load

Infiltration trench as a polishing step for the GWTP effluent

To gather more data on the recommended post polishing in an infiltration drench, a column experiment was established. During this period, the GWTP was operated with nominal load. The experiment encompassed two parallel columns having a diameter of 600 mm each of them representing a discharge point in an infiltration trench. The infiltration material used in this experiment consists of 150 mm drainage layer of 11-22 mm crushed stone at the bottom and sequentially overlaid by 150 mm of 0.2-1.0 mm sand and 150 mm of 2-4 mm LWA (Filtralite, Saint-Gobain Byggevarer AS, Alnabru, Norway). Single geotextile cover separated the layers and the trench is covered with 200 mm of till soil (sandy loam) at the top for insulation (Fig. 1). Each of the infiltration columns was loaded with GWTP effluent with peristaltic pumps at an actual flow rate of 2.5 L h^{-1}. The infiltration took place via a pipe having 6 mm inner diameter to the centre of the column to the top of the LWA layer, giving a total filtration depth of 450 mm (Fig. 2). Loading of the columns coincided with the operation periods of the biofilter in the GWTP. The latter were determined to have a total length 15 h d^{-1} at the nominal load of 650 L d^{-1}. Considering these figures, each of the columns reached a hydraulic load of 37.5 L d^{-1} corresponding to 150 mm d^{-1} over the whole column cross section area.

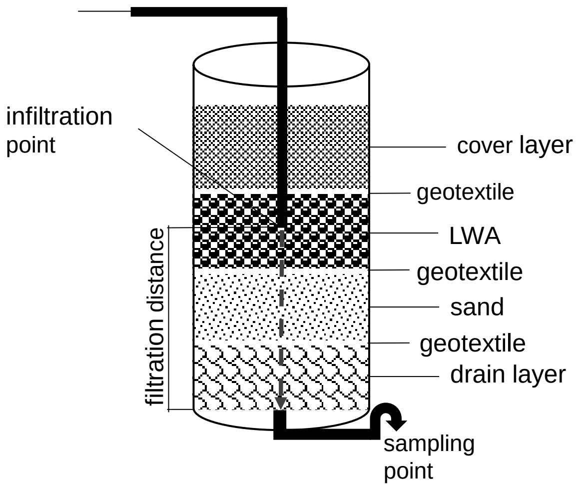

Figure 1. Cross section of an infiltration trench column consisting the following layers: 200mm of top soil (excavated at Aas, Norway); 150mm of lightweight aggregate LWA 2-4mm; 150mm of sand 0.2-1.0mm; 150mm of crushed stone 11-22 mm, giving a total filtration distance of 375mm.

Sampling from the infiltration columns was carried out in three 3-day sampling periods. The first period (P1) started 20 days, the second sampling period (P2) after 41 days and the third sampling period (P3) 118 days after the infiltration started. Analysis was done, based on grab samples taken from the centre of the bottom plate via a drainage pipe having 15mm diameter. For P1 and P2 the drainage pipe was open to the atmosphere, while for P3, a small syphon (50mm) was established to simulate a ground water level.

Lab analysis and mass load calculations

Grab samples were taken from inlet, GWTP outlet and final effluent under the normal loading and different stress events. BOD_5 was analysed with a manometric respirometric method (Oxitop, WTW, Weilheim, Germany). For COD, total phosphorous (P), total nitrogen (N) spectrophotometric test kits (Hach-Lange, Berlin, Germany) were used. Total suspended solids (TSS) were determined with 1.2µm glass fibre filters (Whatman GF-C, GE Healthcare, Little Chalfont, UK). Filtrated COD was taken from the filtrate. *E. coli* was determined following the standard analytical methods (American Public Health Association (APHA), 2005) using Colilert 18 test kits (IDEXX Laboratories Inc, Maine, US).

The obtained reduction efficiency (R_{eff}) for mass or cell numbers load within the different treatment steps are calculated based on the average values that have been determined for a putative combined raw sewage (C_{raw}) and the corresponding sampling place X C_X for each of the parameters (Eq. 2).

$$R_{eff} = C_X * (1-f_{BW})/C_{raw} \quad (2)$$

Results and Discussion

The performance of the source separating sanitary system was assessed by evaluating its removal efficiency for organic matter, TSS, total P and indicator microorganisms. The subsequent effect is the result of a combination of biological and mechanical processes. Figure 2 shows the average concentration of COD, BOD, TSS, P_{tot} and TC and *E. coli* for the combined sewage, raw greywater, GWTP effluent and infiltration trench effluent and the mass load reduction at each level. The mass load reduction line indicates the removal efficiency for each treatment step. For those parameters an overall treatment efficiency of >90% was reached at the effluent of the fixed-film biofilter and >95% at the bottom of the constructed infiltration columns (Fig. 2). For coliform organism, the overall system reached a reduction of 4-5 log of which the major reduction was observed in the infiltration columns (Fig. 2).

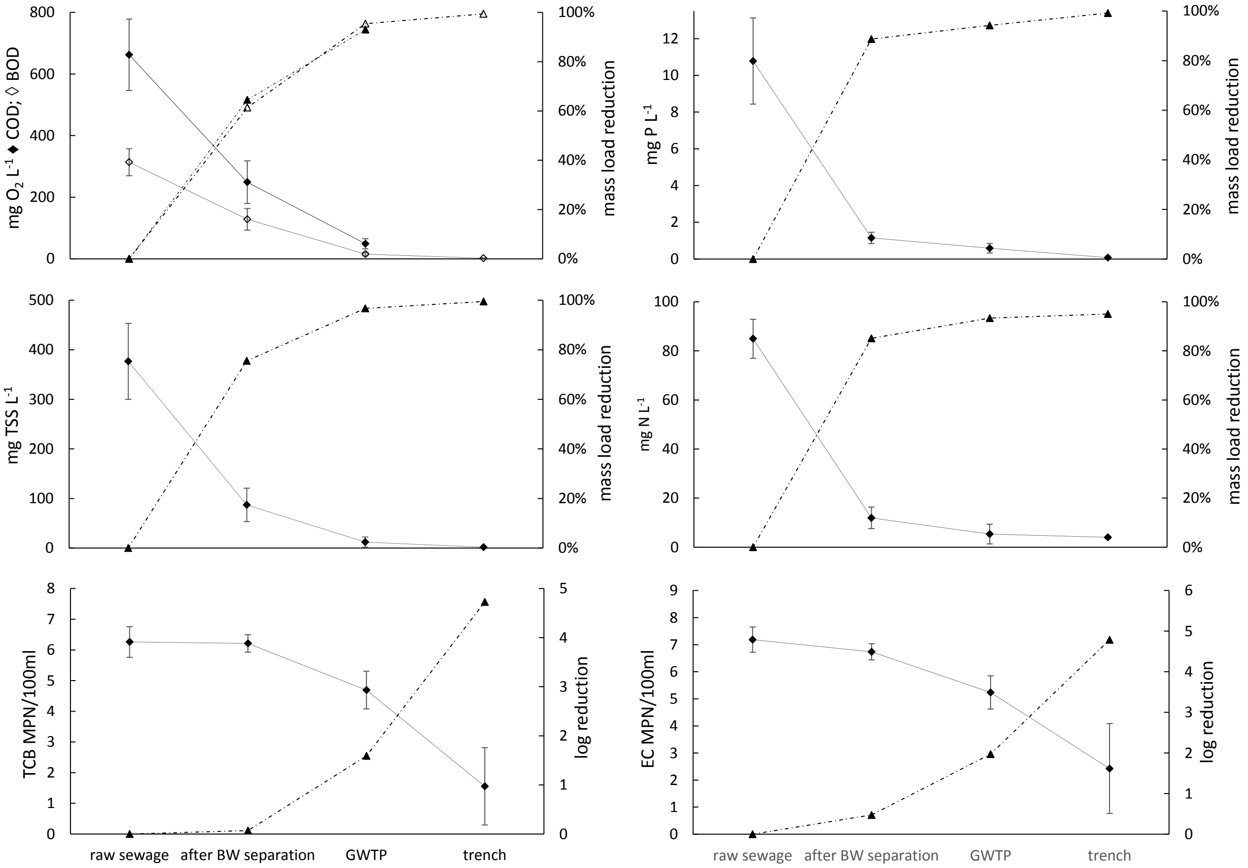

Figure 2: Calculated mean and average concentration for the combined sewage and measured mean and average concentration in the raw greywater, effluent of greywater treatment plant (GWTP) and bottom of infiltration trench (♦) and Calculated mass load and cell number reduction for separating blackwater, greywater treatment plant (GWTP) and infiltration trench (▲) for COD, BOD, TSS, N, P, total coliform bacteria (TCB) and *E.coli* (EC).

Separation and collection of blackwater

The separation and collection of BW resulted into notable reductions for COD, BOD, TSS, N and P accounting for 64%, 61%, 75%, 85 and 88%, respectively (Fig.2), which again is within a comparable range to the figures reported by other studies (Meinzinger and Oldenburg, 2009, Vinneras et al., 2006). The reduction of TCB and *E.coli* on the other hand was surprisingly low, only accounting for 0.5 log and 0.1 log for TCB and *E.coli*, respectively (Fig. 2). This is due to the high concentration of TCB and *E. coli* in the raw greywater of 6.2±0.4 and 6.7±0.3 log 100 ml^{-1}, respectively. Other GW studies reported comparable high concentrations on TCB ranging 7.2 to 8.8 log 100 ml^{-1}, but lower numbers for *E.coli* ranging from 3.2-6.0 log 100 ml^{-1} (Ottoson and Stenström, 2003). However, TCB and *E.coli* encompass both fecal and none-fecal organism (Ottosson, 2003, Ottoson and Stenström, 2003). A recent study showed that the mean concentration of coprostanol, a biomarker formed by the intestinal microflora, was 3.1 log lower in GW than in combined household wastewater. The fecal load estimated with the biomarker coprostanol in GW is 0.04 g $person^{-1}$ d^{-1} which is 2.1-3.2 log lower compared to 5.4 g and 65 g $person^{-1}$ d^{-1} when using the indicator bacteria *E.coli* and *Fecal enterococci* (Ottoson and Stenström, 2003). Hence, the indicator parameters TCB and E.coli used by this study likely overestimates the concentration of fecal pathogens in GW by 3 log (Ottosson, 2003). A majority of the detected TCB and *E.coli* in our GW are therefore likely not fecal origin but rather originated from the kitchen where high concentration up to 7.4 log were also reported elsewhere (Naturvårdsverket, 1995) or re-growth of particular *Coliform* species in sewer pipes (Manville et al., 2001). The latter likely occurred also in our GW sewer system which has a long hydraulic retention time of 36 h or more (Todt et al., 2015), with an average temperature of 15 °C.

These findings are supported by another study (Oliinyk et al., 2015) on our GW using quantitative PCR (qPCR) analysis for human specific *Bacteriods* and *Enterococci* in the BW and GW. The results showed that the number of gene copies was 3.7 and 1.5 log lower in GW than in BW for *Bacteriods* and *Enterococci*, respectively. Hence, in terms of fecal pathogens having human origin, a separation of BW likely results into 1 to 4 log reduction. More research is needed to assess the distribution of different pathogenic organism in the wastewater fractions and related health risks more in detail. Also a potential regrowth and decay of different, pathogenic and none-pathogenic microorganism across a sewer or treatment system has to be addressed more in detail.

Onsite treatment of greywater in a fixed-film biofilter

The concentration of raw greywater was 137±38 mg O_2/L for BOD, 267±71 for COD mg O_2 L^{-1}, 14 ± 3 mg L^{-1} for N_{tot} and 1.2 ± 0.3 mg L^{-1} for P_{tot}. No notable difference to our earlier sampling period (Todt et al., 2015) could be identified for these parameters, indicating that the GW composition remains constant over time. As evaluated in our previous study (Todt et al., 2015), load and composition of our GW is comparable to other studies in Europe, except for P, which is slightly lower, likely due to the absence of dishwashing machines at the dormitories. Detergents for dishwashing machines became the major source of P in GW after the introduction of phosphate free laundry agents.

Referring to raw GW, the GWTP reached a removal efficiency of 80%, 88%, 86%, 49% and 55% for BOD, COD, TSS total P and total N, respectively (data not shown). Together with a separation and collection of BW a removal efficiency of 93%; 95%; 96%; and 94% was obtained for BOD, total COD, TSS, and P, respectively. These figures are the average over the whole sample period, encompassing also periods with overloading, underloading and power breaks (Tab.2). In periods with nominal load, the removal efficiency reached > 9 % for BOD, COD and TSS and close to 60% for N and P. However, a reduced P-removal efficiency has to be expected on locations using phosphate in dishwashing agents, possibly in a range of 70-80% considering the range of P concentration reported by of other GW studies (Palmquist and Hanæus, 2005, Meinzinger and Oldenburg, 2009). An additional polishing step for P-removal may therefore be needed on particular places. The power consumption of the system was determined to 0.34 kWh m^{-3} hydraulic load (data not shown). By taking into account an average GW production of 108 L d^{-1} per person (Todt et al., 2015) this corresponds to 13 kWh y^{-1} $capita^{-1}$, which is almost one order of magnitude lower than 93-217 kWh y^{-1} $capita^{-1}$ that has been reported for onsite treatment of combined sewage (Straub, 2008).

The impact of overloading on the removal efficiency of the system was evaluated by comparing periods with 100% load to periods with 150% load (Fig. 3). Overloading with 150% of the nominal loading did not show significant difference on the removal of TSS and total P_{tot} ($p>0.05$) while, a significant lower ($p<0.001$) removal efficiency was observed for organic matter. The high surface loading rate of 423 mm d^{-1} might have resulted into a lower contact time with the biofilm which again could have reduced the degradation of organic substrates as reflected by the lower removal efficiency for BOD as well as filtered COD. Regardless the reduced organic matter degradation, the filter still achieved an average removal efficiency of 70 % for both BOD and COD during the 150 % loading periods, which proves the high stability of fixed-film biofilter systems.

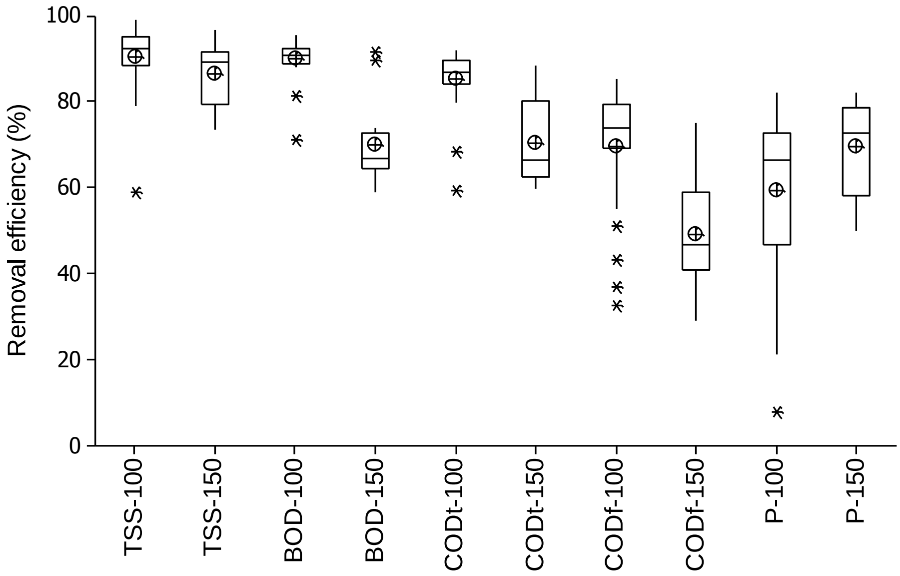

Figure 3: Removal efficiency for TSS, BOD, homogenized COD (COD_t), filtrated COD (COD_f) and total phosphorous (P) of a greywater treatment plant at 100% and 150% nominal load (25;50:75 percent quartiles in the box plots with 95% quartiles in the error bars; average is indicated in the point plot)

Post treatment

The results from the effluent polishing experiment are showing a significant reduction of 85-90% for BOD, TSS and total P across the filter columns. As a result, a TSS of < 2 mg/L, and total P < 0.1 mg P L^{-1}, BOD < 2 mg O_2 L^{-1} was achieved. Determination of total coliform bacteria and *E. coli* from the columns effluent in three periods showed significant reduction. Average TCB and *E. coli* log reduction during in the first period was 2.4 and 2.5 respectively. The reduction increased by more than 1 log after three weeks of operation. The average TCB and *E.coli* log reduction in the last two periods were 3.4 and 3.8, respectively (Fig. 4). The increase in log reduction of *E. coli* and TCB in the second and third period could be due to development of biofilm and an improved water distribution in the columns. This has been shown to increase the pathogen removal efficiency in filter systems (Heistad et al., 2009). Therefore, the polishing filtration step raised the total coliform and *E. coli* removal efficiency of the system up to 4.8 and 4.7 log reduction, respectively. This is in agreement with a previous study with biochar and Filtralite polishing filters (Eshetu et al., 2015).

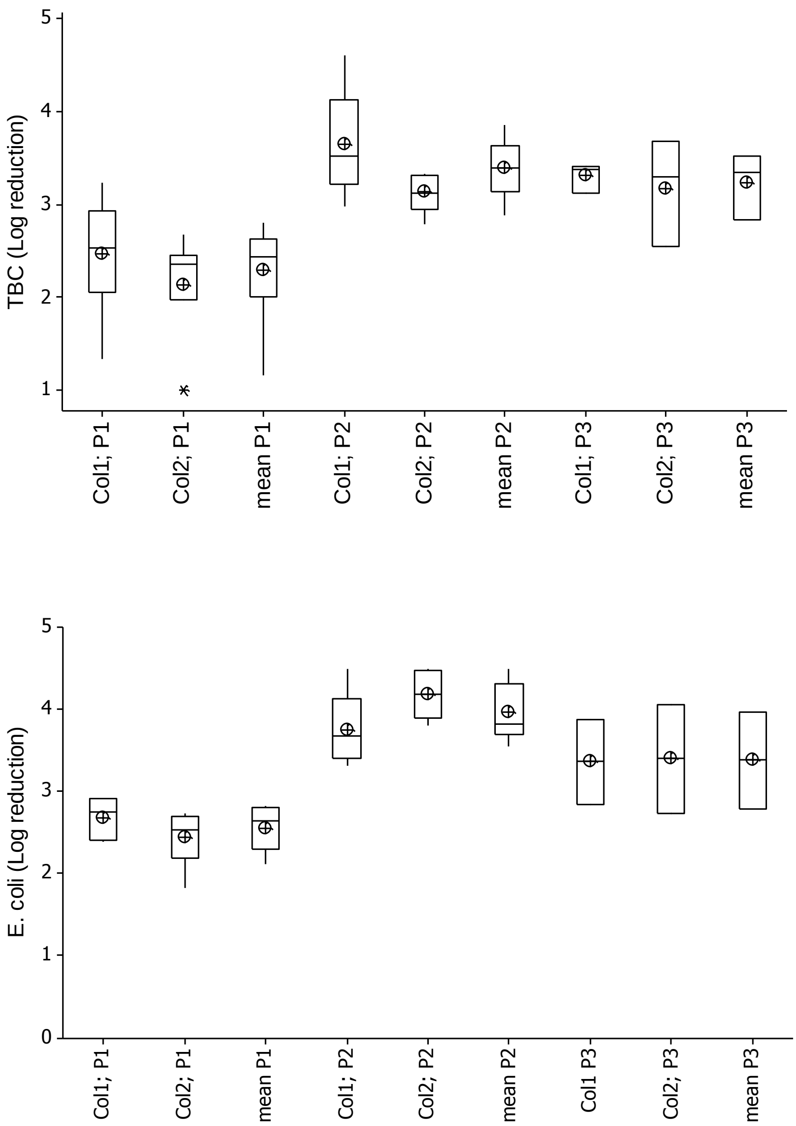

Figure 4. Reduction of total coliform bacteria (TCB, upper panel) and *E. coli* concentration in each of the two filter column replicates (Col1, Col2) and overall mean (mean) for three sampling periods P1, P2, P3.

The quality of effluent from the GWTP complies with the Norwegian discharge limit for discharge of treated household wastewater to sensitive recipients (Tab. 3). However, in terms of pathogen removal, only a 1-2 log reduction was observed. Although the present Norwegian regulations do not define discharge limits for indicator organisms (Tab. 3), the risks of faecal cross-contamination from blackwater should not be overlooked (Stenström, 2013). Without post polishing, the effluent of the GWTP do not fulfil the requirements for present reuse standards (Tab. 3) and may be rather critical for sensitive recipient that are close to drinking water sources. For sensitive recipients as well as reuse applications, a multiple barrier approach including a post polishing in an infiltration trench is needed in order to minimise the related health risks (Tab. 3).

Table 3: Average effluent quality in this study compared to present limits for discharge and reuse

Standards	Applicability	BOD_5 mg/L	Tot P mg/L	TSS mg/L	*E.coli* *MPN/100 ml*
Average effluent GWTP + infiltration trench	*discharge to sensitive recipients*	*<2**	*<0.1*	*<2*	*<5*
Average effluent GWTP	*discharge to none-sensitive recipients*	*12*	*0.6*	*14*	10^4-10^5
Norwegian discharge limit (Miljø Blad 100, 2010)	discharge household wastewater	<20	<1	-	-
US standard (NSF/ANSI 350-2012)	reuse of greywater	10	-	10	14
Australian Guideline (2011)	reuse of greywater	<20	-	<30	<30

*detection limit

Conclusion

- It was observed that separation of BW from the rest of household wastewater streams resulted into a significant reductions for COD, BOD, TSS, N and P accounting for 64%, 61%, 75%, 85 and 88%, respectively. Separate treatment of GW in a biofilter further reduced the concentration of organic matter and nutrients to discharge limit levels. Together with a separation and collection of BW a removal efficiency of 93%; 95%; 96%; and 94% was achieved for BOD, total COD, TSS, and P, respectively.
- In terms of removal of indicator organisms, further treatment is a necessity. Infiltration trench or filtration columns as effluent polishing can significantly reduce the microbial concentration in the effluent. Overall system reached up to 5-log reduction of coliform bacteria, of which the major reduction was observed in the infiltration columns.
- For reuse applications or in drinking water areas a separate collection of blackwater in combination with a multiple barrier approach for the treatment of greywater including soil infiltration as final polishing is recommended in order to minimise the related health risks.

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