An energy-efficient membrane bioreactor for on-site treatment and recovery of wastewater

Rahel Künzle, Wouter Pronk, Eberhard Morgenroth and Tove A. Larsen

ABSTRACT

The present study describes the development of a new type of aerated membrane bioreactor referred to as a biologically activated membrane bioreactor (BAMBi) for on-site treatment of high-strength wastewater. The treated wastewater is reused for flushing and personal hygiene. BAMBi is an adaptation of a gravity-driven membrane reactor, originally developed for the purpose of treating river water to drinking water quality. Initially, a series of reactor configurations were tested and it was found that the simplest possible configuration could treat the wastewater to an acceptable standard, provided that a polishing step for color removal and disinfection was introduced. A commercial electrolysis unit was utilized for polishing. The energy consumption of BAMBi is 0.8 kWh/m^3 of water treated, which can be considered low for an on-site membrane bio reactor application.

Key words | Blue Diversion, maintenance, resilience, sustainable development, urban slums

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ABBREVIATIONS

BAMBi	biologically activated membrane bioreactor
COD	chemical oxygen demand
GDM	gravity-driven membrane filtration
MBBR	moving bed biofilm reactor
MBR	membrane bio reactor
SCR	screen
SED	sedimentation
TF	trickling filter
TMP	trans-membrane pressure
TSS	total suspended solids
UDDT	urine-diverting dry toilet
UF	ultrafiltration

INTRODUCTION

Worldwide, 2.5 billion people have no access to a safe toilet (UNICEF & WHO 2012). Especially in urban slums where piped water and sewers are lacking, it is difficult to make available suitable technology for personal and urban hygiene as well as adequate water pollution control. According to UN-Habitat (2013), currently more than 2.6 billion people live in slums, and sanitation belongs to the least developed parts of urban infrastructure in all developing regions. Therefore, we developed the *Blue Diversion Toilet* intended for urban slums (BDT; Larsen *et al.* 2015, Figure 1). The BDT is a urine-diverting dry toilet with an integrated water cycle. The water is used for handwashing, anal cleansing, menstrual hygiene, and flushing of the urine bowl. The main part of the excretions are collected separately below the toilet and treated in a semi-centralized resource recovery plant (McConville *et al.* 2014). The wastewater from the toilet, polluted by traces of feces and urine as well as with soap and blood, is treated in a reactor integrated in the back-wall of the toilet and re-used on-site. There is only one water cycle and after the first filling, only water lost through normal use of the toilet (e.g., through evaporation) must be replaced.

In this paper, the development of a new type of reactor is discussed, which can treat this type of wastewater. On-site wastewater treatment in an urban slum requires high resilience, low demand for maintenance, and low

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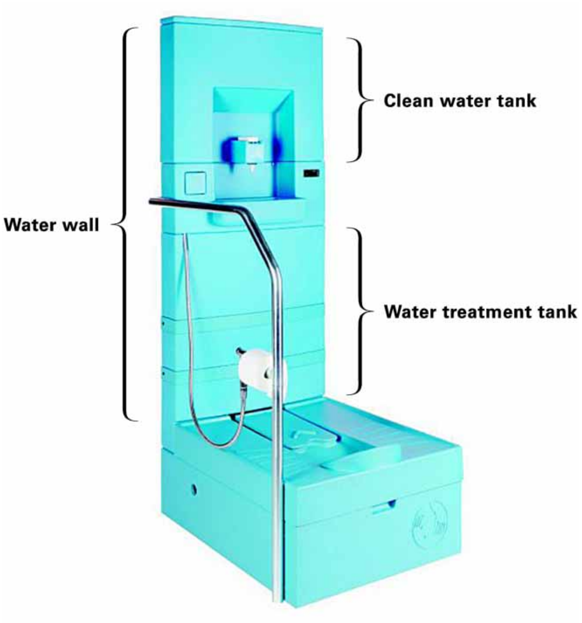

Figure 1 | The BDT (Larsen *et al.* 2015).

costs. It was hypothesized that a technology based on gravity-driven membrane (GDM) filtration would be a suitable option. GDM filtration has been developed for on-site treatment of surface water to drinking water quality in developing countries (Peter-Varbanets *et al.* 2010). Surface water (in some cases contaminated with wastewater) with a concentration of chemical oxygen demand (COD) up to around 50 $g_{COD} \times m^{-3}$ is filtered through an ultrafiltration (UF) membrane with gravity as the only driving force to support a continuous flux of water. Owing to biological activity in the biofilm on the membrane surface (grazing by higher organisms (Derlon *et al.* 2013)), the flux rapidly stabilizes without any cleaning measures, albeit with a flux of only 4–10 $L\,m^{-2}\,h^{-1}$. Owing to decreasing costs of UF membranes, the technology has become affordable for producing small amounts of drinking water for family use (Peter-Varbanets *et al.* 2010).

We expected the COD concentration of BDT wastewater to be at least a factor of 10 higher than previously tested (Table S1). At high organic loads without aeration, oxygen restricted conditions may occur, leading to denser fouling layers and lower flux values (Peter-Varbanets *et al.* 2012). A pure GDM reactor may thus be oxygen-limited and even with aeration, it was anticipated that clogging would eventually occur.

METHODS

We tested six different treatment configurations (Figure 2), with and without pretreatment to reduce the organic loading. Based on these six experiments (in two sequential trials), the best reactor configuration was established. In a long-term experiment we evaluated whether the chosen reactor configuration would lead to a stable flux without any maintenance of the membrane. Disinfection with chlorine and electrolysis was tested, but only the resulting technical solution for field-work is presented here.

Feed water

Simulated wastewater consisted of a mixture of feces and urine. In some experiments, a local soap from Kampala and/or calf blood was added. The composition can be found in Table S1.

System set-up

The experimental set-up (Figure 2) offers the possibility to reduce the organic load in one or more pretreatment steps, followed by a GDM-based unit (with or without aeration) for removal of COD (biological) and pathogens (UF), and a final disinfection step to prevent regrowth (and reduce color intensity).

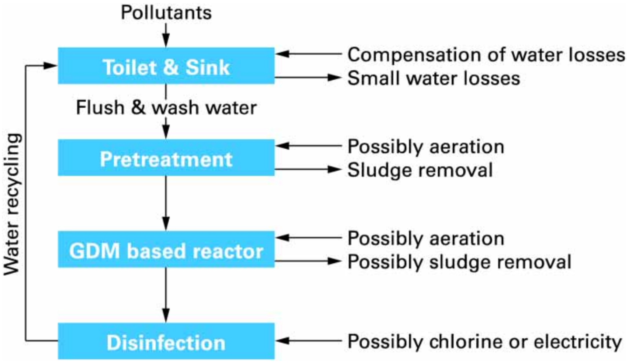

Figure 2 | BDT wastewater treatment. Pretreatment is followed by a GDM-based reactor combined with a disinfection step. The treated water is reused for washing and flushing.

Table 1 | Three parallel reactors (Units 1–3) were tested in three experimental phases (A–C) in different combinations of a GDM unit with pretreatment

	Pretreatment					**Main reactor based on GDM**			
							Aeration		
Phase	**SED**	**SCR**	**TF**	**MBBR**	**None**		**No**	**Yes**	**Feces/Urine (% of excretion*)**
A1	x					GDM 1		x	5/2
A2	x	x				GDM 2	x		5/2
A3	x		x			GDM 3	x		5/2
B1				x		GDM 1		x	2.5/1
B2					x	GDM 2	x		2.5/1
B3					x	GDM 3		x	2.5/1
C1					x	GDM 1		x	2.5/1
C2					x	GDM 2		x	2.5/1
C3					x	GDM 3		x	2.5/1

*Assuming 90 $g_{COD} \times p^{-1} \times d^{-1}$ of feces and 1 $L \times p^{-1} \times d^{-1}$ of urine. Membrane installation: 0.3 m^2 per person.
SED, sedimentation; SCR, screen; TF, trickling filter; MBBR, moving bed biofilm reactor; None = no pretreatment.

Experimental set-up of phases A, B, and C

The experiments were set up according to Figure 2 and Table 1. Soap and blood were added in Phase C (C1); recycling was introduced in C2 and C3. Four pretreatment options were tested alone or in combination: sedimentation (SED), filtration through a screen (SCR; pore size 500 and 100 μm), trickling filter (TF) using plastic cross-corrugated structured packing as biofilm support media, and an aerated moving bed biofilm reactor (MBBR; filled with well-used Kaldnes media (Type K1) and started up 6 days before the beginning of the experiment). The main treatment unit was an aerated (4–6 L_{air} per $L_{reactor\ volume}$ an hour) or non-aerated reactor based on the GDM principle (Figure 3). The water volume of the GDM unit was between 13 and 48 L. There was no purposeful sludge removal, but 500 mL mixed reactor content/week was removed for analysis.

UF membranes

Flatsheet polyethersulfone membranes (Microdyn Nadir, Germany) with a nominal cutoff of 100 kDa were used. The clean water permeability of the membrane was 346 ± 20 $L \cdot h^{-1} \cdot m^{-2} \cdot bar^{-1}$ (viscosity corrected to 20 °C, see Supplementary information, System set-up, available online at http://www.iwaponline.com/washdev/005/116.pdf). The set-up of the membrane module is shown in Figure 3. The new membranes were fixed in plastic containers and operated with deionized water for 24 hours to remove conservation agents.

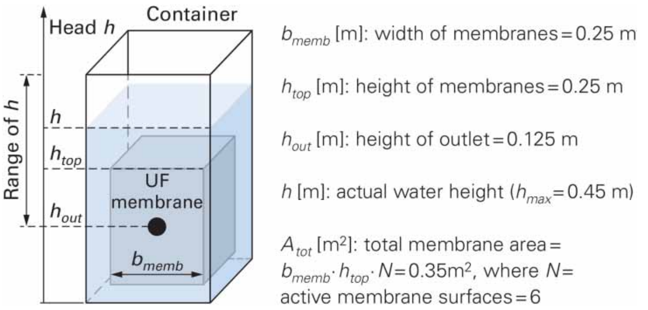

Figure 3 | The experimental set-up of the UF unit, the core of the BDT wastewater treatment. One unit contains three sheets and both sides of the membranes are active.

The water flux was gravity driven only and the membranes were neither flushed nor cleaned during the experiments. The permeate flux (J, $[L \cdot h^{-1} \cdot m^{-2}]$), trans-membrane pressure (TMP, [bar]), and the permeability (P, $[L \cdot h^{-1} \cdot m^{-2} \cdot bar^{-1}]$) were calculated according to Equations (1)–(3).

$$J = \Delta V / (\Delta t \times A_i) \tag{1}$$

$$\mathrm{TMP} = (h - h_{\mathrm{out}}) \times 0.09806 \tag{2}$$

$$P = J/\mathrm{TMP} \tag{3}$$

where ΔV is volume of water collected, Δt is collection time, and A_i is the immersed membrane surface area. For the definitions of h, see Figure 3.

Polishing step (electrolysis)

A commercial electrolysis cell (WaterDiam Sarl, Delémont, Switzerland) was installed in the clean water tank of the BDT water wall (Figure 1).

Analytical methods

Grab samples (~100 mL) were analyzed for COD and TSS. COD was analyzed photometrically (Hach Lange test tubes COD LCK 014, 114, 314, 414, and 614). The sample was homogenized with an ultraturrax T25 (Faust Laborbedarf AG, Schaffhausen, Switzerland). The concentration of total suspended solids (TSS) was determined by filtering through pre-dried 0.45 μm filter followed by drying (1 hour, 105 °C) and cooling in an exsiccator (1 hour). Dissolved oxygen (O_2) was measured directly in the reactors with the dissolved oxygen meter Oxi 340 from WTW (Wissenschaftlich-Technische Werkstätten GmbH, Weilheim, Germany).

RESULTS

Identifying the optimal system configuration

During Phases A and B different pretreatment technologies and operation modes (Table 1) were evaluated with respect to resulting flux (at a TMP of 31 mbar ~ 31 cm water column) and removal of COD.

The Phase A results (Figure 4, A1–A3) showed that SED combined with an aerated GDM unit (A1) resulted in the highest flux, whereas COD removal was equal in A1 and A3 (SED + TF + non-aerated GDM). The TF thus provided no advantage over the simpler option of an aerated GDM. A2 (SED + SCR + non-aerated GDM) was not competitive. Although SED effectively removed more than half the COD, the resulting sludge concentration was low (data not shown). At the same time, parallel developments in toilet design showed that the loading of excreta was overestimated whereupon the inlet concentration in Phase B was halved and SED abandoned. Owing to problems with the TF (flies), which may have resulted in less than optimal treatment efficiency, a different biological pretreatment was tested in Phase B.

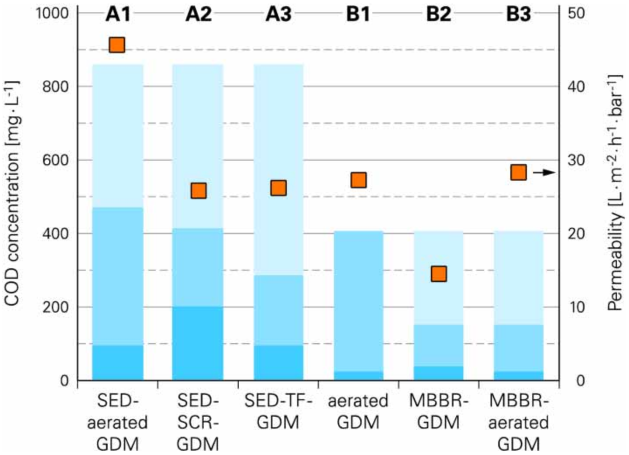

Figure 4 | Results from Phase A and B (cf. Table 1): (A) high inlet concentration of COD (5% of feces) and SED; (B) low inlet concentration of COD (2.5% of feces) and no SED. Section bars indicate removal of COD in pretreatment (upper part), removal in GDM-based reactor (middle part) and concentration of COD in permeate (lower part). Permeability is shown as squares. SED, sedimentation tank; SCR, screen; TF, trickling filter; MBBR, moving bed biofilm reactor; GDM, GDM filtration unit.

The results from Phase B (Figure 4, B1–B3) showed the best flux and the highest COD removal in the two set-ups with an aerated GDM (B1 and B3), but no advantage of the additional biological pretreatment in B3. A comparison between A1 and B1 showed that SED would be effective for increasing the flux, but at the price of increased complexity. It was thus concluded to test a simple aerated MBR based on the GDM principle. We referred to this potential new type of reactor as BAMBi (biologically activated membrane bioreactor) hypothesizing that a biological ‘activation’ of the membrane (i.e., grazing by higher organisms as found in the GDM unit discussed in the Introduction) could stabilize the flux without any membrane maintenance.

Long-term stability of BAMBi

In Phase C, the hypothesis of a stable BAMBi was tested under realistic conditions, including recycling of permeate as would be the case for the BDT. All three GDM units were run as single-stage BAMBi (fed directly without pretreatment and aerated). Please note that BAMBi is a semi-batch reactor (without defined hydraulic retention time). The water volume varied between 13 and 48 L, and most of the time, flow rates varied between 0 and 1.7 L/h, with only a few outliers. The detailed feeding protocols and the cleaning procedure for GDM unit 2, which was run under anaerobic conditions during Phases A and B, are reported in the Supplementary information (available online at http://www.iwaponline.com/washdev/005/116.pdf).

Permeability

Stable permeability of the membrane without maintenance is the most important requirement of BAMBi. The permeability in Phase C was, in general, higher than in Phases A and B, but the variation was much larger (Figure 5). The initial high permeability observed in GDM unit 2 is an artefact from the cleaning procedure referred to above.

The higher permeability during Phase C is observed in all three reactors despite the higher organic loading of unit 1 (due to the addition of blood and/or soap) and the recycling of permeate in units 2 and 3. During the entire operation time of more than 250 days, the flux of the aerated GDM units remains at or above a level of $50\,\mathrm{L\cdot h^{-1}\cdot m^{-2}\cdot bar^{-1}}$, indicating that stable flux without maintenance is possible in this new type of MBR (Figure 5).

Influence of feed composition on permeability and COD reduction

Only a few percentages of excreta ends up in wastewater, but all soap and potentially all blood from menstruating women. Consequently, the COD load increases massively when soap and/or blood is added (Table 2).

In both cases, however, COD removal remained high (96%) and average permeability increased with time (with soap from 42 to $90\,\mathrm{L\cdot h^{-1}\cdot m^{-2}\cdot bar^{-1}}$ and with soap and blood to $120\,\mathrm{L\cdot h^{-1}\cdot m^{-2}\cdot bar^{-1}}$). As an effect of 80% recycling (C2 and C3), the inlet COD concentration increased by a factor of 5 because the flow rate was reduced to 20% at the same COD load (Table 2). The permeate COD concentration increased by a factor of 2 within 80 days and the effluent color intensified. Average permeability increased from 42 to $75\,\mathrm{L\cdot h^{-1}\cdot m^{-2}\cdot bar^{-1}}$ (Table 2),

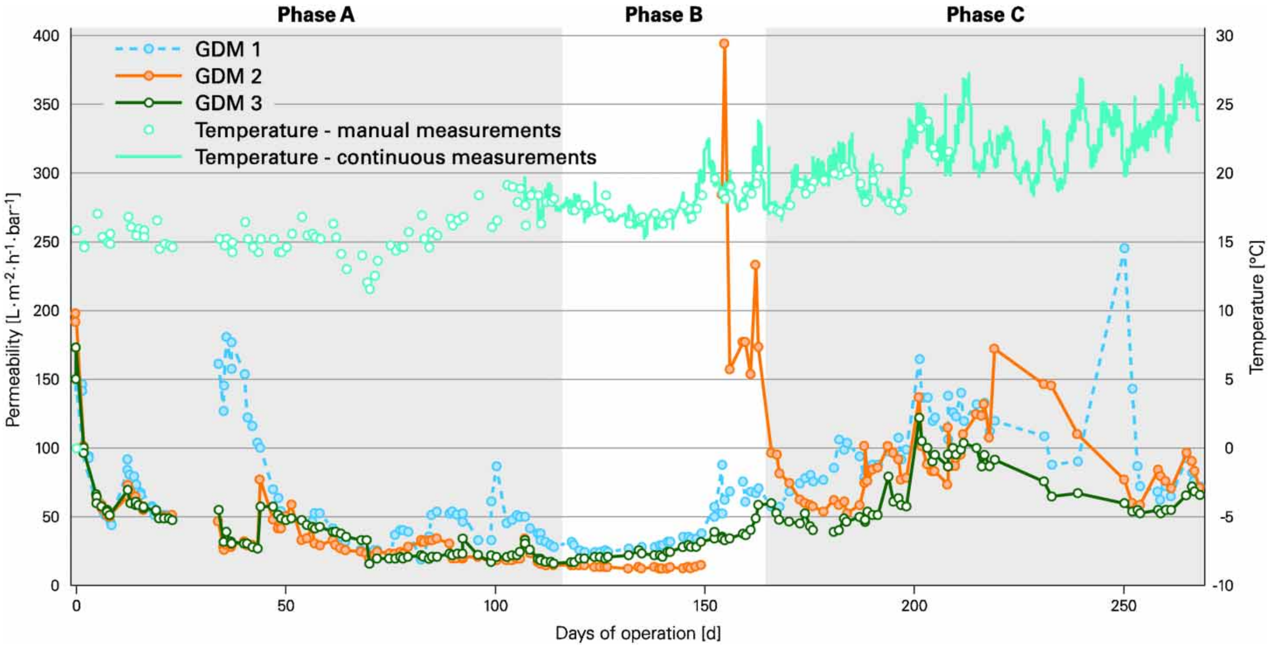

Figure 5 | Permeability of the three GDM-based units and the water temperature over time. The three phases (A, B, C) are indicated at the top. In Phase C, C1 is additionally fed with blood and/or soap, whereas C2 and C3 are run with 80% recycling of permeate (without soap/blood).

Table 2 | COD concentrations [$mg_{COD} \cdot L^{-1}$], resulting COD reduction and permeability [$L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$] during Phase C. Average results from Phase B are included for comparison

	Phase B		**C1**		**C1**		**C2 and C3**	
	No additives no recycling		**+Soap**		**+Soap and blood**		**No additives 80% recycling***	
Inlet [$mg_{COD} \cdot L^{-1}$]	374	± 76	898	± 218	1,567	± 367	1,546	± 338
Effluent [$mg_{COD} \cdot L^{-1}$]	35	± 8	35	± 8	50	± 17	66	± 21
COD reduction	89%	± 5%	96%	± 0%	96%	± 0%	95%	± 1%
Permeability [$L \cdot h^{-1} \cdot m^{-2} \cdot bar^{-1}$]	42	± 19	90	± 31	120	± 10	74	± 25

*With 80% recycling of the effluent, the concentration in the inlet rises by a factor of 5 in order to keep the load constant. Small deviations in load are inevitable.

considerably lower than in the C1 unit. Independent of loading and recycling conditions, COD removal was ≥95% during Phase C. With an assumed load of 3–12 $g_{COD}\ p^{-1}d^{-1}$, this results in a net COD emission from BAMBi of less than 0.15–0.6 $g_{COD}\ p^{-1}d^{-1}$. This organic load should preferably be degraded in the polishing step in order to prevent accumulation of organic matter and regrowth of microorganisms. If the polishing step is based on chlorination, as suggested in this paper, stable nitrification will be important in order to economize on chlorine. In this study, we could not demonstrate stable nitrification, but in subsequent experiments in the same system, stable nitrification and denitrification could be obtained by controlling the aeration intensity (Ravndal *et al.* submitted).

TSS

A large degree of sludge stabilization was found in the reactors (see Figure S1). In another study we have found that COD removal was independent of sludge retention time (in the range from 7 to 1,000 d), but the higher sludge retention time (i.e., without sludge removal) resulted in a lower color intensity (Ravndal *et al.* submitted).

Polishing step

Electrolysis

Based on preliminary tests (data not shown), a commercial electrolysis unit was chosen for polishing of the effluent. The unit was optimized with respect to energy consumption, primarily by reducing the recycling of water through the unit (Figure 6). Owing to the presence of chloride (Cl^-) in the feed water, it can be expected that this is oxidized at the anode to hypochlorite (ClO^-), which is known as a disinfectant. During several weeks of field testing and based on plating for *E. coli*, it indeed could be shown that the hygienic quality of the water was sufficient to meet bathing water requirements (own data, unpublished). However, more research is required to show that the system is suitable for long-term field use.

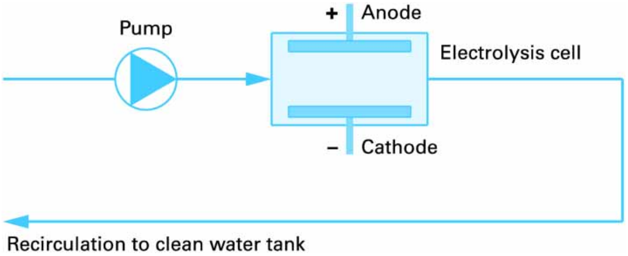

Figure 6 | Schematic view of the electrolysis cell installed in the BDT toilet.

Energy efficiency

Owing to the principle of BAMBi, i.e., minimal aeration for providing oxygen for biological activity, but no requirement for energy to provide biofilm control or external pressure, BAMBi is essentially an energy-efficient MBR. However, the entire set-up is small, which normally results in less energy-efficient operation. We optimized the entire reactor configuration consisting of a BAMBi reactor followed by an electrolysis unit to an energy demand of 28 Wh/p/day (with the assumed loading and water consumption). The electrolysis unit causes two-thirds of the energy demand, while one-third is equally distributed between electronics for operation

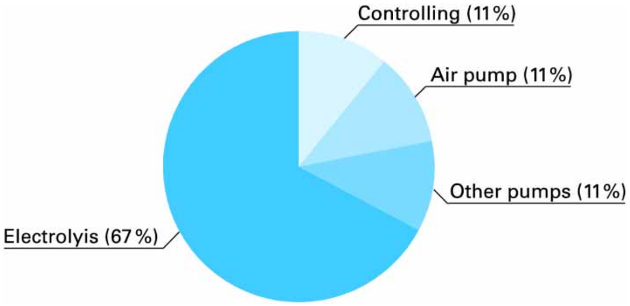

Figure 7 | Distribution of energy demand in the BDT (total: 28 Wh/p/day).

control for the BDT (mainly for securing separation of flows (Larsen *et al.* 2015)), air pump, and 'other pumps' (Figure 7). If we generously attribute the aeration as well as the pumping to the BAMBi reactor, this results in an energy demand of 60 Wh/day for providing 75 L/day of clean water, corresponding to about 0.8 kWh m^{-3} (Table 3). This is astonishingly low for an on-site reactor, which has to function with very small and thus energy-inefficient pumps. For electrolysis, further energy optimization may be possible.

DISCUSSION

In Table 3, BAMBi is compared to its two 'parent' reactors, the MBR and the GDM. The main advantage of BAMBi is that wastewater can be treated in a membrane reactor without any regular membrane cleaning. Operation over months without flux decline was demonstrated in the BAMBi compared to traditional MBRs where stable periods are in the order of weeks to 1 month (Brookes *et al.* 2006). The main disadvantage is the relatively low flux through the membrane. BAMBi will thus primarily be competitive in decentralized settings with low water consumption.

It is not clear why permeability of the aerated GDM units is higher in Phase C than in Phases A and B (Figure 5 and Table 2). The only systematic differences applying to all reactors is the higher temperature in Phase C. However, no systematic testing of such a possible causality was performed since the natural performance variation is too high for any correlation analysis to be convincing.

CONCLUSIONS

- Simple aeration of a GDM-based reactor without any pretreatment was effective and for an on-site application generally superior to a GDM-based reactor in combination with pretreatment. We refer to the resulting reactor as BAMBi.
- Removal of organic matter in BAMBi was above 95%.
- Membrane permeability in BAMBi was stable over months, albeit variable. At temperatures between 20 and 25 °C, permeability varied between 50 and 150 L m^{-2} h^{-1} bar^{-1}.
- Water treated in BAMBi is slightly colored and not stable from a microbiological point of view. Chlorine production by electrolysis was effective for color removal and for maintaining hygiene during a few weeks of field study. Stable nitrification was not obtained in this study, but in subsequent ones. This is important for a polishing step based on chlorine.
- The development of BAMBi shows that resilience of complex biological systems can be obtained in low-loaded systems, even for very small on-site applications.

Table 3 | Comparison of BAMBi with the parent reactor types MBR and GDM. The data from Bambi is based on lab experience and tested ranges

Reactor type	Typical medium	Filter loading [g_{COD}·m^{-2}·h^{-1}]	Active aeration	Membrane cleaning	Pressure [mbar]	Flux [L·$m^{-2}h^{-1}$]	Energy demand [kWh·m^{-3}]
MBR	Wastewater	0.02–5.0	Yes[d]	Yes	300–500	20–100	0.4–2.5[b]
GDM	Surface water	0.01–0.02[a]	No	No	40–150[a]	4–10[a]	0
BAMBi	Wastewater	0.1–1.8	Yes[e]	No	20–100	0.5–1.5[c]	0.5–1[c]

[a] Peter-Varbanets *et al.* (2010).
[b] Krzeminski *et al.* (2012).
[c] Own results.
[d] To transfer oxygen, for reactor mixing and for increasing shear at the membrane surface.
[e] Mainly to transfer oxygen plus some limited mixing of the bulk phase, but not to provide shear at the membrane surface.

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