

# **PERFORMANCE OF AN ANAEROBIC BAFFLED REACTOR-MEMBRANE BIOREACTOR (ABR-MBR) TREATING BLACKWATER**

Pillay S., Foxon K.M. and Buckley C.A.

Pollution Research Group, School of Chemical Engineering, University of KwaZulu-Natal,  
Howard College, 4041, phone: +27 31 260-1490; fax: +27 (0)31 260-3241;  
email: [Foxonk@ukzn.ac.za](mailto:Foxonk@ukzn.ac.za)

## **ABSTRACT**

This paper presents the performance of a combined anaerobic baffled reactor-membrane bioreactor (ABR-MBR) treating blackwater. The blackwater was comprised of a faecal and urine slurry obtained from ventilated improved pit latrine (VIP) toilets and was diluted to form a medium-strength (687 mg/L) blackwater that was fed to a four-compartment ABR. The ABR was able to achieve COD and TS removal efficiencies of 63% and 55%, respectively. This removal, however, was not sufficient to allow for discharge to surface water according to the Department of Water Affairs and Forestry (DWA) guidelines. Membrane technology was evaluated as a post-treatment step. Two membrane modules were used in this study, a microfiltration (MF) and an ultrafiltration (UF) membrane. The limiting flux of each module was assessed using the transmembrane (TMP)-step method. Although the limiting flux of the MF membrane was higher (8 L/m<sup>2</sup>.h) than the UF membrane (5 L/m<sup>2</sup>.h), the pressure (approximately 4 kPa) at which this plateau occurred was similar. Consequently, both membrane modules were operated at a constant hydraulic head of 4 kPa for short-term filtration experiments with ABR effluent. The MF membrane was able to operate at a higher flux (average flux = 4 L/m<sup>2</sup>.h) than the UF membrane (average flux = 3 L/m<sup>2</sup>.h) at 4 kPa, but COD removal efficiency was lower than the UF membrane (86% compared to 92%). Membrane polishing of the ABR effluent was successful as both membrane modules were able to achieve the COD discharge limit to surface water whilst fouling was reversible, with only mechanical cleaning (washing with water) required to restore membrane permeability and resistance to its original state.

## **INTRODUCTION**

The provision of water and basic sanitation is a South African development priority. The country aims to alleviate potable water and sanitation backlogs by 2010. Whilst significant progress has been made towards the delivery of potable water to previously unserved communities, the eradication of the sanitation backlog is proving to be more difficult. In 2007, an estimated 15 million people were without access to basic sanitation (1). One of the major challenges municipalities face is the delivery of sanitation services to unserved communities that lie outside the sewered network system and densely-populated peri-urban areas which lack formalised housing arrangements. Large infrastructural, operational and maintenance costs are required to serve these communities using conventional treatment systems. This has resulted in municipalities adopting novel approaches to alleviating sanitation backlogs. The eThekweni Municipality (Durban), for example, has implemented a programme of providing on-site dry sanitation systems, such as urine diversion (UD) toilets, to those communities without access to sanitation and which fall outside the sewered network, as means of alleviating sanitation backlogs. The

main advantages of on-site dry sanitation systems are that they are less expensive and simpler to construct than conventional waterborne sewage systems, and they do not require water. The disadvantages are that construction can be difficult, especially in rocky terrain, and that their implementation and maintenance relies on community acceptance and active participation, respectively. This can be difficult as many communities aspire to waterborne sanitation and are not keen on handling faecal material. Consequently, there is a technological gap for waterborne sanitation options that are both practical and sustainable for these areas. One of the technological solutions being considered is an anaerobic baffled reactor (ABR) combined membrane bioreactor (MBR).

The ABR can be described as a compartmentalised septic tank that requires no moving parts for mechanical mixing, making it inexpensive to construct and operate relative to a conventional centralised system. Vertical baffles divide the reactor into compartments, forcing incoming wastewater through compartmental sludge beds at the bottom of the reactor. The wastewater can therefore come into contact with a large amount of active biomass, providing high treatment rates. The advantages of this design have been well documented by numerous authors (2, 3, 4). First, the washout of biomass is reduced as solids move from one compartment to the next (2). Secondly, it creates a concentration gradient of organic constituents along the length of the reactor which allows for the spatial separation of anaerobic microbial consortia (3, 4), although this seems limited in low-strength applications (5). This separation has been shown to confer greater protection against toxic substances, changes to feed load and environmental parameters, and higher treatment rates (3, 4).

A previous project evaluated the performance of a 3 000 L pilot ABR treating domestic wastewater at a council-run wastewater treatment facility (5). The purpose of that study was to evaluate the appropriateness of an ABR as a decentralised waterborne sanitation option. The results revealed that the ABR was able to achieve higher treatment rates, resilience and better recovery times from shock loads relative to septic tanks, the ABRs closest relative (5). Despite these advantages, nutrients were not removed by the process, and more importantly, the pathogen load in the effluent could not be reduced to an acceptable level without some polishing step (5). Of the many post-treatment steps available, membrane filtration is seen as the most promising as it can be integrated with ABR technology, with little change to the reactor design. It is envisaged that membranes be installed in the last compartment of the ABR where the concentration of biodegradable constituents are the lowest and operated under a suitable hydraulic head (no power requirements) to produce the twin benefits of a pathogen-free effluent that is rich in biological nutrients. This safe effluent can then be reused as a fertiliser replacement in agricultural irrigation to alleviate food shortages among low-income groups whilst encouraging efficient water usage. Furthermore, the methane generated from the digestion process can be harvested as a fuel.

In this paper, the performance of a laboratory ABR-MBR treating ventilated improved pit latrine (VIP) toilet waste is presented. The waste, a combination of faeces and urine, can be regarded as blackwater that accumulates in the pits to a level where desludging becomes necessary. This presents several problems for municipalities. First, the removal of pit contents can be difficult, especially in areas which are inaccessible to desludging equipment. Second, the disposal of pit contents has become a dilemma for many municipalities. Anaerobic digestion is seen as feasible option for the treatment of VIP contents as the pit contents are concentrated due to the lack of availability of water while ambient temperatures are generally high throughout the year. In this context, the present

study has two main aims. The first has the dual objective of evaluating the performance of the ABR as a decentralised sanitation option for the pre-treatment of blackwater and as a pre-treatment step for the disposal of VIP waste. The second aim was to establish the conditions under which membranes can operate in an ABR treating blackwater. This is particularly challenging as the membrane must be operated without aeration for scouring, whilst the overall condition in the tanks where membranes will be installed will be different to aerobic systems and other anaerobic technologies, and hence fouling behaviour will be different.

## MATERIALS AND METHODS

### 2.1 Laboratory ABR-MBR

The experiments were conducted on a laboratory-scale ABR coupled to an external MBR (Figure 1). The ABR was designed according to recommendations from a previous pilot study (5) and consisted of a large feed tank (200 L feed capacity) and four identical reactor box compartments (20 L each) connected in series. Each reactor box represents a compartment of the ABR and consists of three identical internal downflow and upflow pipes representing hanging and standing baffles, respectively. This modification allows for compartments to be added or removed from original ABR design. Water-seal lids keep the reactor compartments anaerobic and allow for the collection of biogas via a valve connected to plastic Tedlar® bags (Anatech). All compartments were constructed out of stainless steel (Laser CNC). Each compartment was seeded to one-third of its working volume with sludge from a pilot ABR and the remaining volume filled with a combination of diluted VIP waste and greywater. The reactor was manually fed through a lid on the feed tank and the effluent generated was collected in plastic tanks and pumped via a peristaltic pump (Watson Marlow 313 Du) to an external MBR unit consisting of a hollow-fibre (outside-in) membrane module. Two membrane types were used for this study, a microfiltration (MF) membrane and an ultrafiltration membrane (UF) (Polymem). Details of the membrane modules used are provided in Table 1.

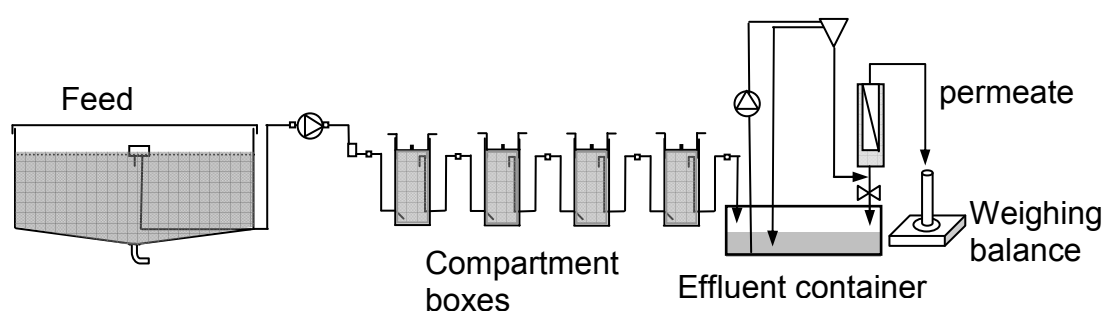


Figure 1: Schematic diagram of laboratory ABR-MBR system.

Table 1: Characteristics of membranes used during study.

Membrane	Type	Area	Molecular weight cut-off	Model	Supplier
Ultrafiltration	Hollow-fibre	1 m <sup>2</sup>	0.08µm	UF2522 S3	Polymem, Fr.
Microfiltration	Hollow-fibre	1 m <sup>2</sup>	0.20µm	MF2522 S	Polymem, Fr.

### 2.2 Description and preparation of raw wastewater

The raw wastewater (blackwater) was comprised of VIP waste that had been collected from VIP toilets in the Magwaveni area near Tongaat (approximately 37 km north of

Durban). The waste was removed from a single VIP toilet that contained no pit additives and was previously desludged (100 L from top of waste heap) 5 months earlier. The waste was sealed in airtight containers on-site and transported to the laboratory where it was screened to remove undesirable materials, such as glass, stones and plastics, and stored in the cold room at 4 °C. A portion of the screened waste was removed when feeding was required (approximately every 2 d), diluted with water and homogenised in a blender for 5 min. This homogenised waste was further diluted to form medium-strength blackwater (approximately 500 mg COD/L), which was fed through a lid on the feed tank.

### 2.3 Physico-chemical analyses

COD, TS and VS measurements were performed according to Standard Methods (6). For filtered COD, samples were first filtered with 0.45 µm glass fibre filters (Munktell). The value of pH was obtained using a digital pH meter (Hanna Instruments) and the temperature recorded using a thermometer.

### 2.4 Filtration experiments

The transmembrane pressure (TMP) was calculated by measuring the difference in height between the water column on the feed side of the membrane and the permeate pipe. Permeate flow was measured using a weighing balance (Ohaus Adventurer) on the permeate side of the membrane. The temperature was also recorded during each experiment to account for changes in viscosity, and a temperature correction included into the calculation of the permeate flux (7).

Filtration experiments were performed at constant TMP as opposed to constant permeate flux. Although the latter operation has been shown to cause less fouling and hence less overall damage to membranes (8), constant TMP filtration was necessary to establish the limiting flux of each module. The limiting flux, which is defined as the pressure independent plateau reached by flux in constant TMP experiments (8), is used to select a TMP for short-to long-term experiments (hours to months).

The TMP-step method was used to evaluate the limiting flux for each module (7). In this method, the flux is recorded during progressive increases in TMP over time. First, the flux of distilled water ('clean water' flux) over a range of constant TMP is recorded to calculate the initial membrane resistance and permeability. Thereafter, the flux of ABR effluent is recorded at constant TMP for 30 min before increasing to the next pressure level (Figure 2). A second set of distilled water filtrations over constant TMP is performed immediately after effluent filtration to calculate the increase and decrease in membrane resistance and permeability due to fouling, respectively. Finally, distilled water filtration over constant TMP is performed after cleaning (mechanical and chemical) to evaluate the efficiency of cleaning protocols.

Once the limiting flux has been determined, the membrane module is operated at a constant hydraulic head until the flux declines to a point at which membrane cleaning becomes necessary. As with the TMP-step method, the filtration of distilled water with progressive increases in TMP is recorded before and after fouling.

## **3. RESULTS AND DISCUSSION**

### Performance of the ABR

The laboratory ABR was operated over a period of 267 d at an average of HRT of 3 d. A total of 18 900 L of raw wastewater (diluted VIP waste) was treated. Reactor downtime

was reported for 52 d, with a total of 19 d of non-operation due to maintenance issues and electrical faults. Sludge and scum removal was necessary in the feed tank to prevent solid build-up and clogging of reactor box pipes. A total of five desludging and descumming events were recorded with a total of 217 L and 40 L of sludge and scum removed from the feed

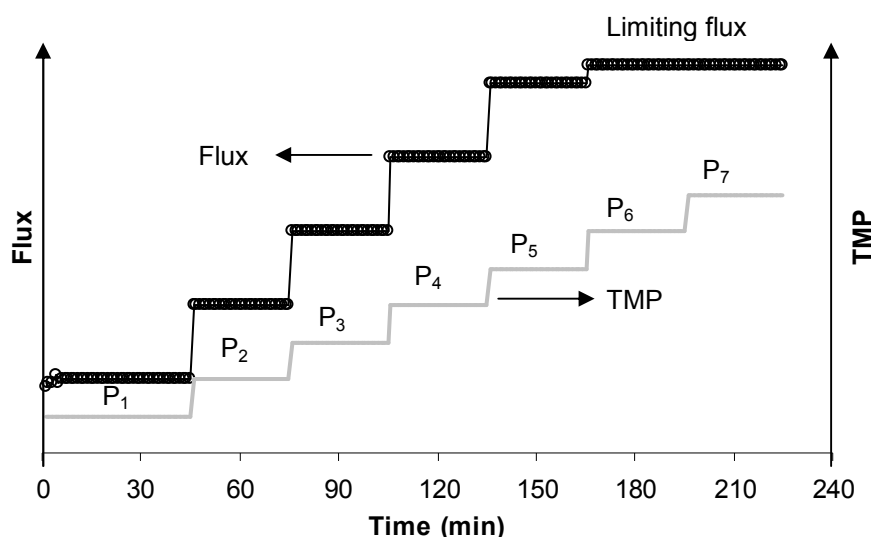


Figure 2: Description of the TMP-step method used in this study. The permeate flux is recorded with step-wise increases in the TMP ( $P_1$ - $P_7$ ). Each pressure step lasts 30 min except for the first pressure step, where an additional 15 min was allocated to allow for flux stabilisation. The plateau reached by the flux is referred to as the limiting flux.

tank, respectively. No desludging and minor scum removal (less than 1 L) was required in ABR compartment boxes.

The characteristics of the raw wastewater (diluted blackwater from VIP toilet) and the effluent are presented in Table 2. The feed ratio of VIP waste to water varied between 4 and 12 g VIP waste/L, with an average feed ratio of 7 g VIP waste/L. This equated to an average COD, TS and VS concentration of 687, 309 and 142 mg/L (Table 2).

Table 2: Characteristics of raw wastewater (blackwater) and ABR effluent.

Parameter	Unit	Raw wastewater ( $n$ )			ABR Effluent ( $n$ )		
		Min	Max	Average	Min	Max	Average
COD <sub>(total)</sub>	mg/L	149 ± 4	1034 ± 101	687 ± 53 (18)	101 ± 18	733 ± 32	252 ± 23 (29)
COD <sub>(0.45 μm)</sub>	mg/L	88 ± 31	434 ± 88	266 ± 147 (6)	67 ± 15	105 ± 10	86 ± 14 (6)
pH		7.12	7.32	7.23 (5)	6.98	7.42	7.25 (5)
TS	mg/L	309 ± 41	1069 ± 41	715 ± 244 (9)	209 ± 27	379 ± 2	315 ± 48 (9)
VS	mg/L	56 ± 13	218 ± 22	142 ± 55 (8)	29 ± 7	260 ± 28	144 ± 86 (7)

At a HRT of 3 d, the ABR treating blackwater could produce an effluent with an average COD, TS and VS of 252, 315 and 144 mg/L. This equated to COD, TS and VS removal efficiencies of 63, 55, and 0%, respectively. Similar removal efficiencies have been reported in ABRs treating blackwater under Vietnamese conditions (9, 10). The average COD of the effluent was higher than the Department of Water Affairs and Forestry (DWAFF) discharge limit to surface water (75 mg/L), but below than the allowable limit for

agricultural irrigation (400 mg/L for a 500 kL/d discharge) (11). Effluent polishing is still required, however, before any reuse or release strategy can be realised as the average solids concentration was higher than DWAF limits for discharge into water bodies and reuse in agriculture. Moreover and more importantly, pathogen removal in the ABR system is known to be limited (5).

#### Filtration using the TMP-step method

Figures 3 and 4 present the simultaneous variations of permeate flux and TMP with time for Polymem UF and MF membranes treating ABR effluent. For both membranes, the first two TMP steps are characterised by relatively constant flux, while during further step increments in TMP, the flux peaks before declining towards a plateau. Similar observations have been made in an aerated MBR treating municipal wastewater (8) and the microfiltration of blood (12). In the latter study, the authors attributed the decline of flux to the adjustment of the concentration polarisation and permeate flux to the new TMP. This trend was more distinguishable in the MF membrane, which had higher fluxes at identical TMP. Accordingly, the MF membrane produced a greater total volume of permeate (36 L) than the UF membrane (24 L).

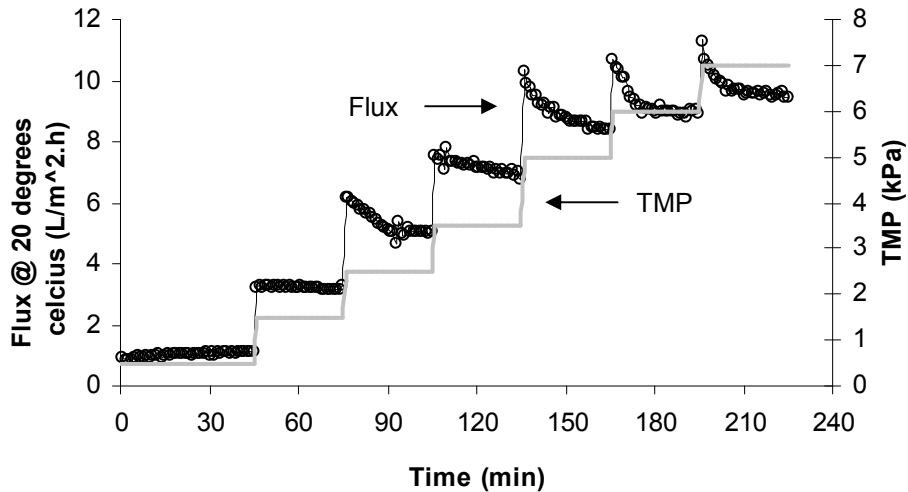


Figure 3: Variation of permeate flux with time using the TMP-step method for Polymem MF membrane.

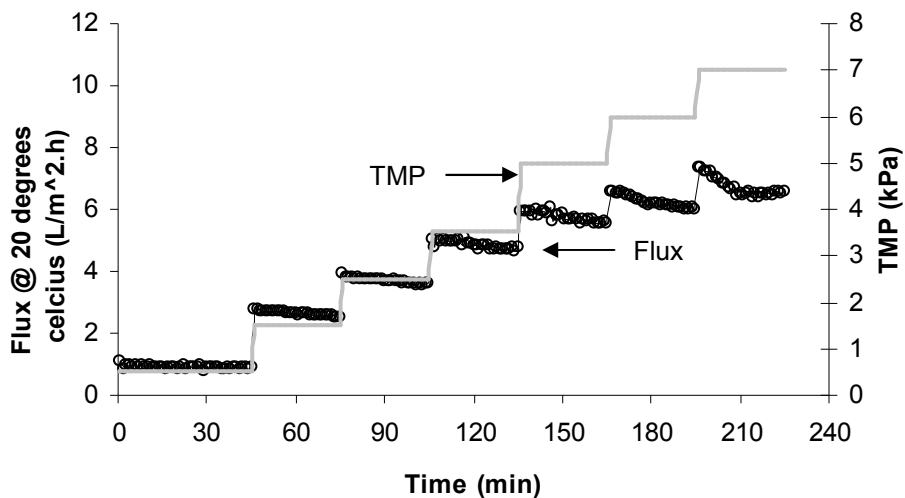


Figure 4: Variation of permeate flux with time using the TMP-step method for Polymem UF membrane.

Figures 5 and 6 presents the average permeate flux for each TMP step. For both membranes, there is an initial linear increase in flux after which the flux becomes less dependent on pressure. This could be extrapolated to give a limiting flux, which is higher for the MF membrane (approximately 8 L/m<sup>2</sup>.h) than UF membrane (approximately 5 L/m<sup>2</sup>.h). Interesting, there was only a slight difference in the TMP at which this occurred, with the limiting flux being reached at approximately 4.8 kPa and 4.2 kPa for the MF and UF membranes, respectively. Based on these results, it was decided that a hydraulic head of 400 mm (4 kPa) would be an appropriate starting point for the constant pressure filtration experiments.

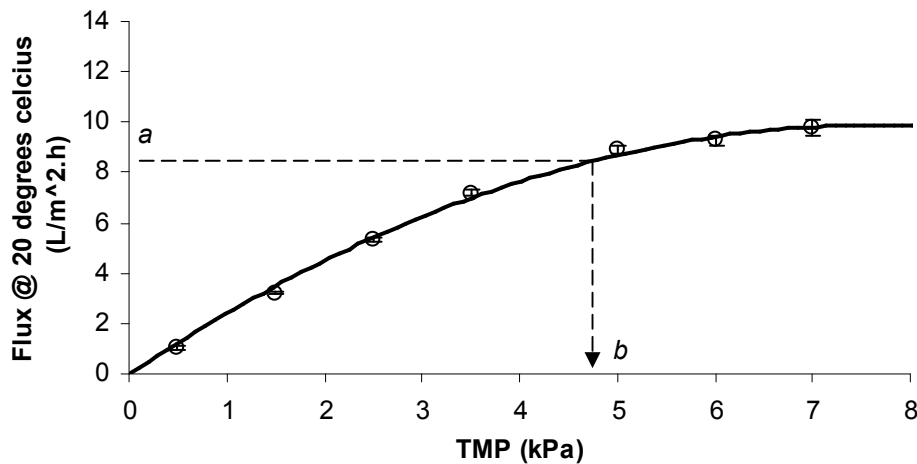


Figure 5: Plot of average flux for each pressure step for Polymem MF membrane. The limiting flux is denoted by *a* whilst the corresponding TMP at which it occurs is denoted as *b*.

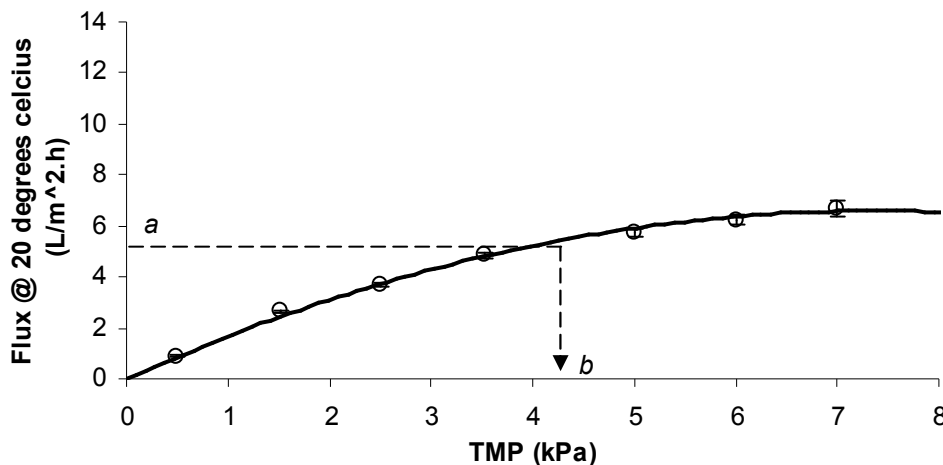


Figure 6: Plot of average flux for each pressure step for Polymem UF membrane. The limiting flux is denoted by *a* whilst the corresponding TMP at which it occurs is denoted as *b*.

Short-term filtration at a constant TMP

Short-term filtration experiments were performed for a hydraulic head of 400 mm (4 kPa). The treatment performance of the membranes is presented in Table 3. The ABR was able to reduce the COD in the raw wastewater to 234 mg/L, with a removal efficiency of 82%. The COD was further reduced to 34 and 18 mg/L using MF and UF membranes, respectively. Although the UF membrane was more efficient than the MF membrane in removing COD from the ABR effluent (92% compared to 86%), both membranes were able to reach COD discharge limits to surface water (9). Furthermore, it is anticipated that the discharge limit for pathogens and suspended solids parameters could be easily achieved based on molecular weight cut-off for both membranes (refer to Table 1).

Table 3: COD treatment efficiencies of the processes for the respective stages.

Parameter	Raw Feed	Effluent		MF		UF	
	COD (mg/L)	COD (mg/L)	Removal (%)	COD (mg/L)	Removal (%)	COD (mg/L)	Removal (%)
COD <sub>(total)</sub>	1 304 ± 101	234 ± 4	82	34 ± 8	86	18 ± 4	92
COD <sub>(0.45 µm)</sub>	391 ± 35	95 ± 14	76				

Figure 7 presents the variation of flux for the Polymem MF and UF membranes over a constant TMP of 4 kPa. For the MF membrane, the permeate flux peaked (approximately 7 L/m<sup>2</sup>.h) during the first 20 min of filtration followed by a gradual flux decline to approximately 4 L/m<sup>2</sup>.h. In contrast, the permeate flux of the UF membrane peaked during the first 10 min of filtration, followed by a sharp decline to a plateau of approximately 3 L/m<sup>2</sup>.h for the remainder of the experiment. Interestingly, the MF membrane had not reached this plateau state. Based on these results, it is possible that the permeate flux of both membranes could intersect over time.

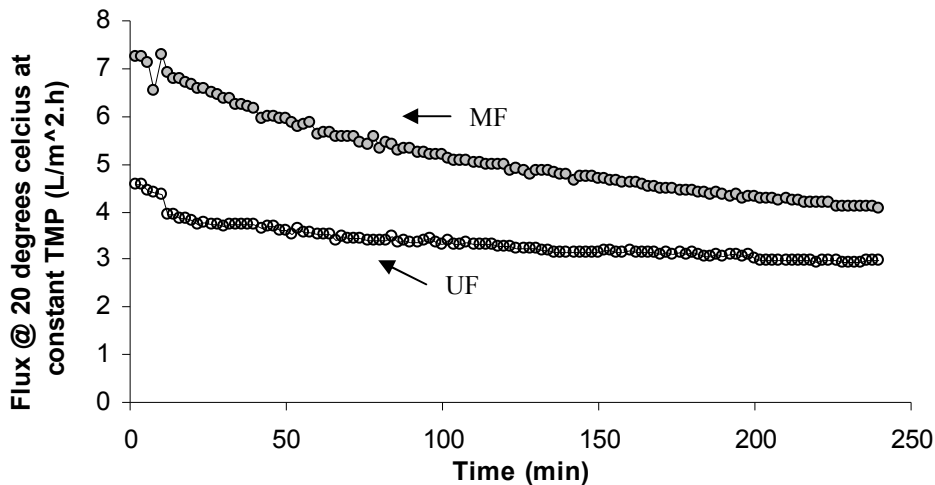


Figure 7: Variation in flux at a constant TMP of 4 kPa over 4h for Polymem MF and UF membranes.

### Membrane cleaning

The frequency and duration of membrane cleaning is a major limiting factor to the economic implementation of MBR. More frequent cleaning can significantly raise the cost of operation and reduces the attractiveness of the technology. For this reason, the integrity of the membrane and the effectiveness of membrane cleaning procedures were assessed by calculating the membrane ( $R_m$ ) before and after fouling experiments, and after cleaning regimes. The results revealed that fouling in both modules was minimal and mostly reversible, with only a slight increase in  $R_m$  observed after fouling while only mechanical cleaning (rinsing with a combination of tap and distilled water) was required to restore the  $R_m$  and permeability to near its original (virginal) state. The results suggest that conditions were favourable for the long-term filtration of effluent from an ABR treating blackwater composed of diluted VIP waste.

There are a number of possible explanations for the observed fouling behaviour. The first is that the low flux strategy employed during experiments had resulted in less adsorption of dissolved substances on membrane pores. The reversible fouling observed for both membranes is therefore due to the build-up of large solid particles on the membrane pores, which are easily removed by washing. Another explanation for the observed fouling behaviour is related to the concentration of fouling constituents, such as extracellular polymers (EPS, a mixture of proteins, carbohydrates and nucleic acids), in the effluent. Whilst it is possible that the ABR had sufficiently reduced these fouling constituents through the reactor, it is more plausible to believe that the lack of fouling constituents is due to the nature of raw wastewater (in terms of biodegradability). The raw wastewater was composed of VIP waste that had been standing in a pit for an uncertain length of time. During this time, it is possible that most of readily biodegradable substances were removed by microorganisms in the pit. Hence, the feed to the ABR would be mostly unbiodegradable, resulting in less by-product (EPS) generation in the reactor and probably less irreversible fouling. Future studies will require a more comprehensive chemical campaign to assess the biodegradability of the feed material and the quantities of EPS through the ABR.

## **4. CONCLUSIONS**

The ABR proved to be an adequate pre-treatment system for both the disposal of VIP waste and for the pre-treatment of blackwater in areas with inadequate sanitation. The reactor was able to achieve COD and SS removals of 63 and 55%, respectively. As with septic tanks, excess sludge and scum must be removed and disposed over time. This problem, however, is predicted to be much lower in the ABR system than a septic tank (5). Membrane post-treatment was an appropriate post-treatment option with permeate quality meeting discharge guidelines to surface waters. Membrane fouling was reversible as indicated by the restoration of membrane permeability to near its original state with no chemical cleaning required. The lack of irreversible fouling may be due to a number of factors, including the utilisation of a low flux strategy and the nature of the raw wastewater.

## **5. FUTURE WORK**

The project will continue to examine the performance of the ABR system for the pre-treatment of domestic wastewater. Future investigations will to be performed include:

- an assessment of the biodegradability of VIP waste contents in relation to other blackwater sources.
- identifying the possible constituents that may cause fouling in an ABR system.
- evaluation of the performance of membrane modules for longer time periods under anaerobic conditions.

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