Advanced biological unit processes for domestic water recycling

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Abstract The potential of advanced biological unit operations for the recycling of grey and black waters has been evaluated. The membrane bioreactor (MBR) demonstrated the greatest efficacy towards water recycling in terms of all the quality determinants. Both the biologically aerated filter (BAF) and the MBR were able to effectively treat the organic and physical pollutants in all the types of wastewater tested. The main difference was observed in terms of the microbiological quality, measured as total coliforms. The open bed structure of the BAF enabled passage of coliforms whereas the complete barrier of the MBR produced a non detectable level in the effluent. The MBR process complied with commonly adopted water recycling quality standards for the all determinants during the grey water trials and failed only in terms of total coliform counts once black water had been introduced into the feed. The MBR was seen as a particularly suitable advanced biological process as it was very effective at stabilising out the considerable load variations encountered during the trial.
Keywords Greywater; black water; biological aerated filters; membrane bioreactors; water recycling

Water Science and Technology **Vol 43 No10 pp 211–218** © IWA Publishing 2001

Introduction

Increased demand for water, particularly for domestic users has led to an increasing stress being placed on water supplies. In the UK this has traditionally been negated by the construction of new reservoirs. However, key drivers such as environmental issues and capital expenditure strategies have focused the debate on demand management rather than augmentation of supplies. In turn this has brought forward the issues of leakage control and water recycling. Water recycling can be split into two categories, internal as domestic or industrial, and external where the discharge from a sewage works is used for aquifer recharge or irrigation. Domestic recycling is an attractive option in the UK where urban water use is proportionally higher than in all other EU member states at approximately 40% of the total water use. This is coupled with high populace intensification; 50% of the population reside in towns of 100,000 residents or greater (Boschet *et al.*, 1998).

The focus to date has been towards grey water recycling of bath, shower and hand basin water for toilet flushing or turf irrigation. The paucity of water quality standards, technological data and public perception information has led to a diverse range of technologies being tested. Initial preferences have been for purely physical systems in single houses that have relied upon short residence times within the systems to negate the need to process the water beyond coarse filtration. They offer a disinfection operation through slow release chemical disinfection blocks either as chlorine or bromine (Diaper *et al.*, 2000). More advanced systems have been developed for interconnected houses or large multi occupancy buildings such as hotels and colleges. These have included advanced physical processes such as membranes or multi unit operations in series incorporating biological, physical and chemical stages (Holden *et al.*, 1998; Surendran, 1998). Current preferences are for a combination of physical and biological processes in order to produce water low in turbidity, pathogens and organics. An example of grey water recycling at a very large scale is the Millennium Dome in the UK where a biological stage is followed by membrane processes to allow 100,000 m^3/d of hand basin water to be recycled for toilet flushing (Hills and

English, 1999). The water produced is of a near potable standard and demonstrates the ability to treat any water to any quality with current technologies. The challenge is to develop the simplest technological strategies that satisfy all the requirements.

The acceptability of recycled water for any particular end use is dependent on its physical, chemical and microbiological quality. Development of a clear strategy towards domestic water recycling has to a certain degree been hampered by a lack of water quality standards that address these needs. No standards exist in the UK and apart from a proposed criteria by the Building Services Information and Research Association (BSIRA) no standards have been developed. Table 1 shows the appropriate standards for water recycling in other parts of the world where grey water reuse is practiced or standards that have been suggested as appropriate for grey water applications.

Other standards exist around the world but all show some commonalties by including a parameter for biological, physical and microbiological pollution. Public health protection is the key consideration and as such all water recycling standards include parameters relating to the potential for disease transmission. Indicator organisms are generally preferred due to their ease of measurement and the familiarity in the water industry. However, there is no consensus about which and how they should be interpreted with respect to recycling (Asano, 1998). One issue is that no correlation between the concentration of indicator organisms and actual pathogens exists; a positive coliform concentration only demonstrates a potential pathway for disease transmission rather than any actual risk of illness. At one stage the EPA suggested that a level of 200 counts per 100 ml of fecal coliforms could be adopted from bathing water regulations. However, the added gastrointestinal illness rate at this level has been calculated at 19 illnesses per 1000 swimmers which is now being considered too high a rate by some of the regulatory bodies in the US (Asano, 1998). This is exasperated as some virus strains are more resistant to disinfection than the indicator species. This has led to a conservative approach in some areas with a non detectable level being introduced. Combining technology and quality requirements improves the applicability of surrogate measures such as total coliforms and is now forming the basis of reuse standards proposed by the EPA (Asano, 1998). In the case of the standards relevant to domestic reuse the technologies stated are secondary treatment followed by filtration and disinfection.

Technologies that encompass several of these requirements offer an attractive alternative to some of the more traditional approaches. Two technologies that fall into this category are membrane bioreactors (MBR) and biological aerated filters (BAF). Both are intensifications of traditional secondary treatment providing both biological and physical treatment offering small footprint, high product quality processes. In particular, the amal-

Table 1 Summary of water quality standards and criteria suitable for domestic water recycling (Smith and Dudley, 1998)

	Total coliforms Count/100 ml	Fecal coliforms	BOD_5 (mg/l)	Turbidity (NTU)	Cl_2 Residual (mg/l)	pH
Bathing water standards*	<10,000	<2,000				6–9
USA, NSF Federal minimum		<240	45	90		
USA EPA	Non detectable		10	2	1	6–9
Australia	<1	<2	20	2		
UK (BSIRA)	Non detectable					
Japan	<10	<10	10	5		6–9
WHO*	<200					

* suggested as appropriate for domestic water recycling

gamation of a suspended growth reactor with a membrane filtration device has led to the development of MBR for in building reuse in Japan. To illustrate this; by 1983 100 grey water treatment systems had been installed, 25% of which comprised of MBR technology taking advantage of there ability to retain all solid material including bacteria and macromolecules (Rowden, 1996).

This paper presents the results from a pilot plant investigation into the application of advanced biological treatment systems for in building domestic water recycling. The paper focuses on the performance of the two systems, a membrane bioreactor and a biological aerated filter in terms of the water quality determinants discussed above.

Materials and methods

A process flow diagram of the pilot facility is shown in Figure 1. The feed system comprised of four 1 m^3 plastic tanks enabling the generation of different strength feed waters by mixing individual components of concentrated grey water, black water or tap water. The feed was then pumped to parallel process trains allowing direct comparison of two small scale treatment processes for a continuous 283 day trial period. The feed system was set up to mimic the characteristics of a multiple occupancy dwelling such as a hotel or college. Grey water was prepared as an analogue from a grey water recipe described previously (Jefferson *et al.*, 1998) and black water was taken as a partially thickened primary sewage, pumped from the university's sewage treatment works. The characteristics of the different sources is presented in the results section and will be discussed there.

The MBR consisted of a perspex bioreactor chamber with a working volume of 0.066m^3. Two 0.24 m^2 plate and frame polysulphone membranes with a mean pore size of 0.4 μm were immersed into the bioreactor. Flow through the unit was hydraulically driven via a constant head device that maintained the immersion depth to 0.6 m. Compressed air was supplied at a rate of 20 l min^{-1} via aeration stones, providing both aeration to the biomass and scour to the membrane surface.

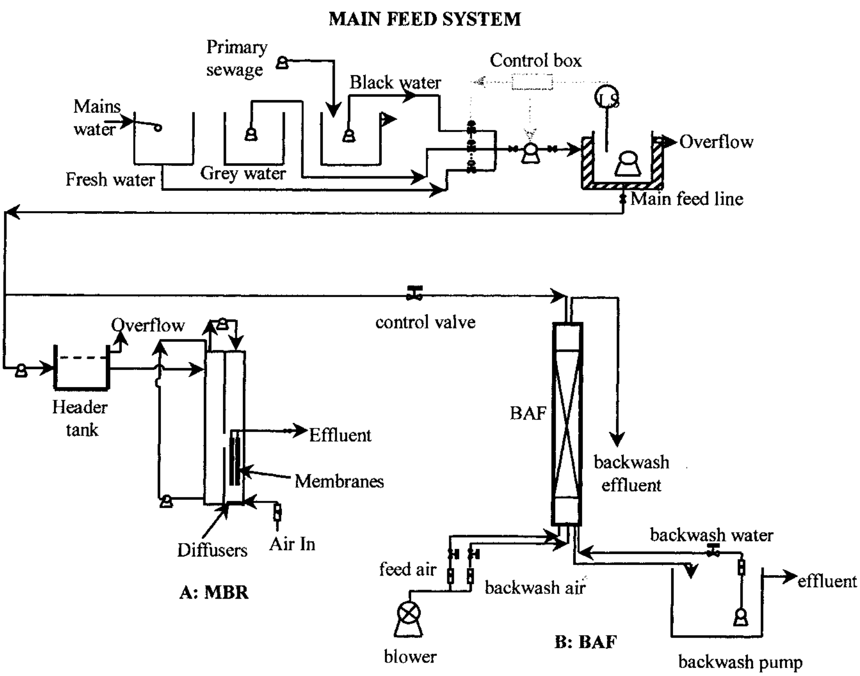

Figure 1 Process flow diagram for MBR and BAF water recycling trials

The biological aerated filter comprised of an 0.165 m diameter vertical column with plastic media filled up to a 1.75 m depth unto which a biofilm developed. Feed was pumped counter currently to compressed air, the latter being supplied at 15 l min^{-1}. Back washing of the bed was instigated by head development and was trigged by a level sensor in the column. The backwash involved a combined air and water cycle, water for 3 minutes at 20 l min^{-1} followed by air and water at 15 and 20 l min^{-1} respectively.

Chemical oxygen demand (COD) and suspended solids were carried out in accordance with Standard Methods (1992, Methods 5210 A and 2540 D, respectively). Turbidity was analysed using a Turbidimeter Model 2100N (Hach Laboratory) and Total coliforms, *E.coli* and Fecal coliforms were analyzed using the IDEXX Quanti-Tray 2000 system.

Results and discussion

Organic parameters

The influent concentration varied considerably during the course of the experiments shown in terms of the standard deviation of the COD ranging from ±74.4 to ±102.3 for grey and black water respectively. These variations are consistent with other studies that have found the characterisation of grey water to be a particularly difficult exercise (Holden and Ward, 1998). The variations were found to be most pronounced in terms of the suspended fraction of the COD whose concentration varied between 78±61 mg/l and 243±104 mg/l for the grey and black waters respectively.

Mean effluent concentrations of 9.6±7.4, 10.6±5.5 and 15.5±7.5 mg/L for the MBR and 15.2±13.1, 20.7±15.8 and 52.3±23.9 for the BAF were measured for the three different feed types. In general both processes were able to treat the organic components of the waste resulting in removal efficiencies that ranged from 77 to 89% for the BAF and 89 to 97% for the MBR. The variations in the influent were effectively buffered by both treatment processes although greater variations in effluent concentration were observed for the BAF. The lower variation and overall concentration from the MBR is a reflection of the processes ability to treat a higher proportion of the recalcitrant fractions of the COD. This is an advantage that all MBR processes experience and is explained in terms of the membranes ability

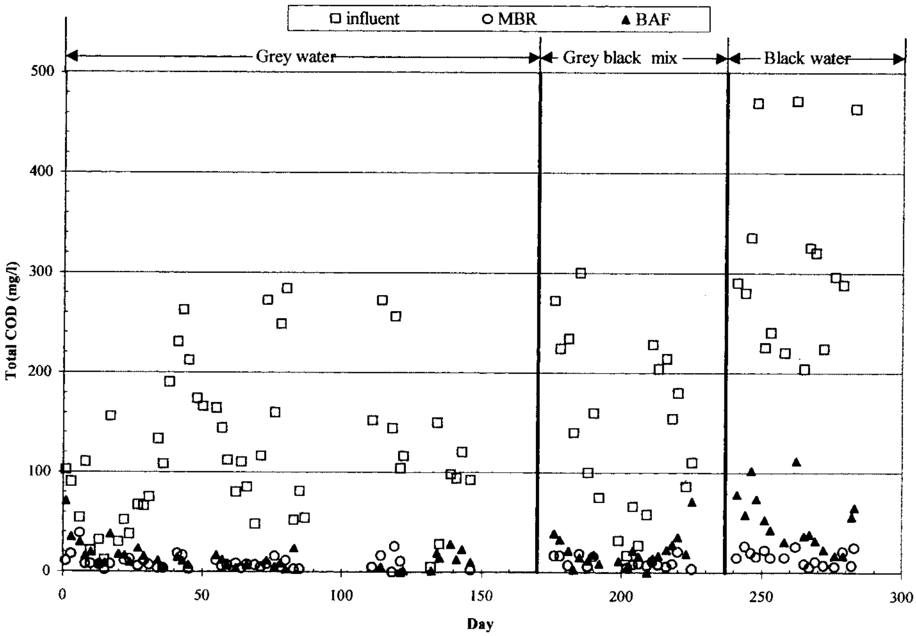

Figure 2 Total COD of influent and effluents from MBR and BAF during grey and black water trials

Table 2 Summary of performance in terms of COD

		Mean (mg/L)	HRT (h)	Loading rate (kgCOD.m^{-3}.d^{-1})	Removal efficiency (%)
Influent	Grey	120.4±74.4			
	Grey-black	144.1±85.7			
	Black	323.1±102.3			
BAF	Grey	15.2±13.1	2.7±0.46	1.09±0.73	77±23
	Grey-black	20.7±15.8	2±0.4	1.2±1.1	76±16
	Black	52.3±28.4	2.8±0.4	2.45±1.	28 89±6
MBR	Grey	9.6±7.4	31.5±3.4	0.14±0.07	89±13
	Grey black	10.63±5.5	29.2±5.5	0.16±0.08	92±6
	Black	15.5±7.5	34.2±3.1	0.18±0.11	97±25

to retain solids and macromolecules together with very low sludge loading rates which encourage the development of specialised micro-organisms (Rosenburger, 1999). However, the greater HRT may be in part responsible for the improved removal. Although similar removal efficiencies have been demonstrated with much lower hydraulic retention times (Brindle and Stephenson, 1996).

The volumetric loading rates of the two processes were an order of magnitude different ranging from 1.09±0.73 to 2.45±1.28 kgCOD.m^{-3}d^{-1} for the BAF and 0.14±0.07 to 0.18±1.28 kgCOD.m^{-3}d^{-1} for the MBR. The difference in the loading rates is an artifact of the different hydraulic throughputs of the two units reflecting the relative resistance to flow between a membrane and a porous bed of media. The flow from the MBR described in terms of flux decreased from an initial value of 28 l m^{-2} h^{-1} to a stable flux of 8 l m^{-2} h^{-1} over a period of 76 days indicating a build up of fouling layer on the membrane surface. The stable flux that develops is a characteristic of submerged membrane bioreactor systems. The low trans-membrane pressures experienced, 0.06 bar, is insufficient to incur internal fouling of the membrane pores. The reduction in flow is then due to the build up of a cake layer on the membrane surface that is kept in a dynamic equilibrium due to air scour across the membrane. Reduction in the air flow rate reduced this flux to 4 l m^{-2} h^{-1} but this recovered to its original value once the initial air flow rate had been reinstated.

Physical parameters

A major benefit of the two processes is their ability to function at two levels of treatment offering both biological and physical removal in one unit process. Table 3 shows the performance of the two processes in terms of suspended solids concentrations and turbidity. Similar variations in influent concentration were observed as with the organic pollutants highlighting the relative importance of the suspended fraction in grey and black water. The suspended solids effluent concentrations remained consistently below 16 mg/L for all but the black water run with the BAF. This is attributed to the much greater solids concentration challenging the BAF; overloading the beds capacity for solids removal.

Overall the MBR demonstrated a greater efficacy in terms of the removal of physical pollutants in grey water. This is most clearly shown in terms of turbidity where the MBR produced an effluent always below 1NTU. This is important in terms of compliance with water reuse standards that are shown in Table 1. The standard commonly adopted are between 2 and 5 NTU for which the BAF would fail to meet 50%, 28% and 95% of the time for the grey, grey-black and black water feeds respectively. The overall performance appears largely independent of the load variations that occurred. However, the lack of a specific barrier in the BAF results in the failure rate observed, especially when a highly solids laden influent is tested.

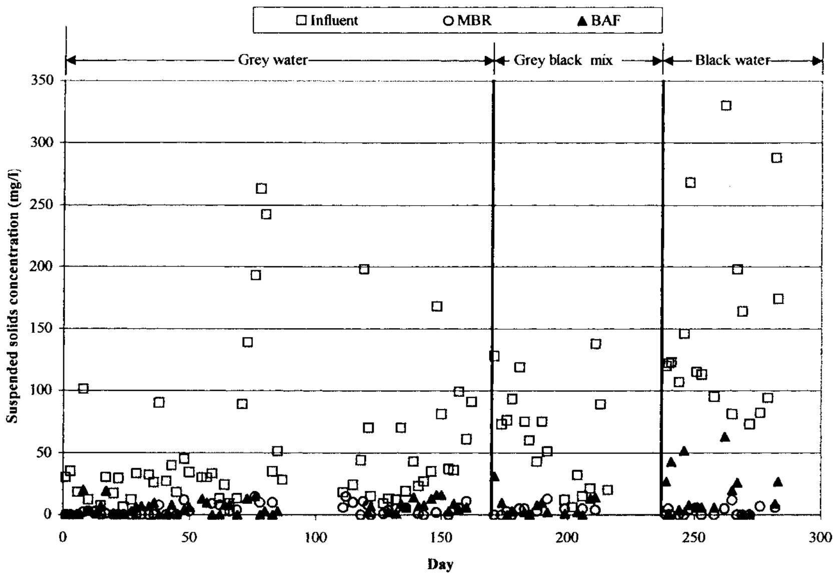

Figure 3 Suspended solids concentrations of influent and effluent from the M and BAF during the experimental trial

Table 3 Summary of physical performance of the MBR and BAF during the domestic waste water reuse trial

		SS (mg/L)	Removal efficiency (%)	Turbidity (NTU)
Influent	Grey	52.2±57.8		
	Grey-black	62.6±40		
	Black	148±77		
BAF	Grey	5.9±5.5	81±22	3.2±8.9
	Grey-black	6.8±8.6	88±16	2.8±3.9
	Black	18±20.2	88±12	12.6±27.3
MBR	Grey	3.9±4.5	85±26	0.32±0.28
	Grey black	3.6±3.7	90±15	0.4±0.28
	Black	2.8±3.7	98±4	0.34±0.2

Microbiological parameters

Public health protection and the perception of public health protection are likely to be the key drivers to selecting acceptable water recycling technologies. This is most commonly determined in terms of indicator organisms such as shown in Figure 4. The indicator organism chosen was total coliforms which is the most conservative available, but similar results were observed for *E.coli* and faecal streptococci. Large variations in count were observed in the influent for the grey water trial. This effect was decreased once black water had been added although the overall count increased by 2 to 3 logs. Removal of total coliforms was very different for the two processes but remained consistent between feed types. The MBR gave much higher levels of rejection producing an effluent with a non detectable level during most of the trial period. This represents up to an 8 log reduction in count and compared favourably with the 2–3 log reduction observed with the BAF. Neither process provided complete compliance with all the water recycling standards suggested in Table 1 but the MBR would meet 100% compliance for grey water recycling for the two standards suggested as generally appropriate for the domestic situation. In practice an independent disinfection stage is inevitable such as chlorine to guarantees total kill and provides the safety of a residual concentration. The low turbidity and organics levels in the MBR effluent then have an added value. Particle shielding and chlorination of organics can dramatically reduce the

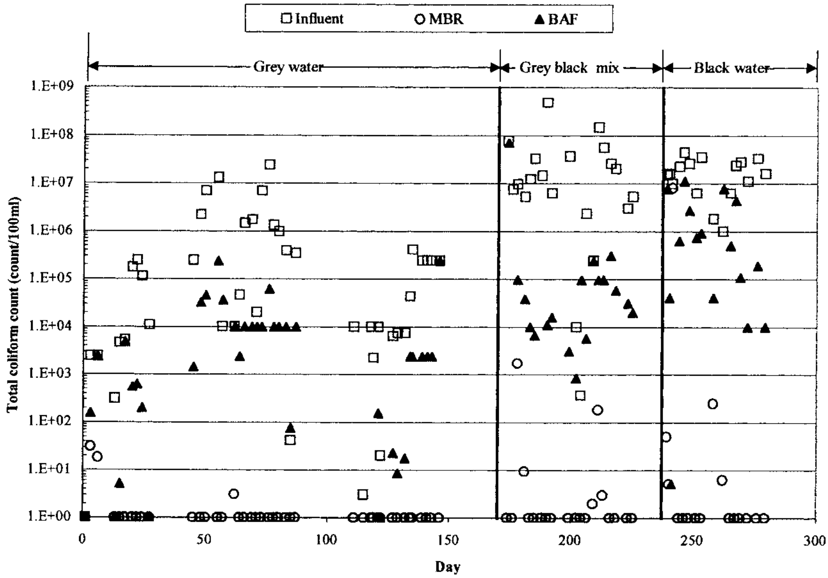

Figure 4 Total coliform concentration for influent and effluent from the MBR and BAF during the grey to black water trials

effectiveness of chlorine. In particular the chlorination of organic produces THMs which are hazardous to human health and impart an odour load on the system. Thus the low levels of organics in the MBR maximise the effectiveness of any possible disinfection stage while simultaneously minimising any negative byproduct problems.

Conclusions

Advanced biological processes have been shown to be an effective technological solution for the treatment of domestic wastewaters for reuse applications. Both the MBR and BAF process provided high levels of treatment in terms of biological and physical parameters. Throughout the trial period the average performance of the MBR was better than that of the BAF. This is explained as a result of the membrane in the MBR providing a permanent barrier to transport of pollutants. This difference is most pronounced in terms of microbiological removal where the open bed structure of the BAF allows transport of coliforms into the effluent. The MBR on the other hand provides almost complete disinfection of the effluent at all times meeting several of the less stringent water quality standards for recycling.

The membrane bioreactor complied with all the water quality criteria in terms of grey water and only fails in terms of coliform counts once black water has been introduced into the water. In practice a dedicated disinfection operation would be included in any treatment scheme and so the water reuse quality standards would be meet at all times. The recycled water quality produced from the MBR had other associated benefits. The product water is visibly clear and low or free of pathogens and organics reducing odour levels and potential regrowth problems. All of these are likely to be key drivers in terms of public acceptability which will probably control the development of any technology for recycling in many developed countries. In practical terms the process has many benefits; it is a small footprint high product quality process that operates independently of load variations and produces no sludge. All these highlight the potential that advanced biological process and specifically MBR have for water recycling.

Acknowledgements

The authors wish to thank the UK Engineering and Physical Sciences Research Council, Thames Water and Yorkshire Water for supporting this work.

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