The anaerobic baffled reactor (ABR): An appropriate technology for on-site sanitation

KM Foxon[1]*, S Pillay[2], T Lalbahadur[3], N Rodda[2], F Holder[3] and CA Buckley[1]

[1]*Pollution Research Group, School of Chemical Engineering, University of KwaZulu-Natal, Durban 4041, South Africa*

[2]*Biochemical Research Group, School of Life and Environmental Sciences, University of KwaZulu-Natal, South Africa*

[3]*Centre for Water and Wastewater Research, Durban Institute of Technology, South Africa*

Abstract

This project has studied the appropriateness of the ABR for on-site primary sanitation in low-income communities. The baffled design of the ABR ensures high solids retention resulting in high treatment rates, while the overall sludge production is characteristically low. Effluent COD values measured from a 3 000 ℓ pilot ABR using domestic wastewater at a wastewater treatment works were consistently below 200 mgCOD/ℓ at an HRT of 22 h, and a 1 log reduction of pathogen indicator organisms (E. coli and total coliforms) was observed. Analysis of results indicates that the operating flow rate was too high to allow complete fermentation of particulate COD; it is expected that better COD and pathogen removal will be obtained at smaller hydraulic/organic loads. This paper presents results obtained for a 5 month analytical period at a single operating point. Operational and institutional issues relating to the appropriateness of the technology for on-site sanitation are explored, as well as the acceptability of the technology to target communities. Health related aspects associated with reuse of the effluent for agricultural purposes are discussed.

Introduction

Water and sanitation provision in South Africa faces some stiff challenges in the next 20 years: South Africa has been classified as a category I water scarce country; we will experience severe water scarcity by 2025 (Seckler et al., 1999). At the same time, the South African government is in the process of implementing a programme of free basic water for all in which every household has the right to 200 ℓ/d free, safe, potable water (DWAF, 2003). In many rural and informal urban areas, there are insufficient formal sanitation services; In 2001, 18.1 million people out of a total population of 44.8 million (41%) did not have adequate sanitation services (DWAF, 2003). Rapid urbanization has led to the growth of densely populated informal and semi formal settlements, and local municipal structures in many cases do not have the capacity to formalise the housing arrangements, and provide appropriate sanitation services in the near future. On an environmental level, South Africa has many highly sensitive catchment areas including swamps and lagoons that are regarded as national heritage sites, the ecosystems of which are vulnerable to high nutrient loads and variations in salinity. In this background, the South African Water Research Commission is investigating innovative ways of managing potable water demand, appropriate sanitation and food security to provide for the needs of the population, while minimizing environmental impact.

In the current climate of reuse and recycling of resources, traditional concepts of treatment and disposal are constantly being challenged (Verstraete, 2002). Natural waterways must be protected from disposal of nutrient rich effluents and wastewaters since the presence of elevated nutrient concentrations, particularly nitrogen and phosphorus, results in uncontrolled growth of algae and water plants, causing choking of the water and oxygen depletion in the lower strata of the water way. Great effort and expense are therefore put into nutrient removal processes. However provided nutrients do not eventually contaminate nearby waterways, they may be regarded as a resource, rather than a contaminant in that the irrigation of crops with nutrient rich water will reduce the need for the application of costly fertilisers, thereby reducing wastewater treatment costs, and the cost of crop production (WHO, 1989). However, the financial advantages of irrigation with nutrient rich wastewater can only be achieved if the health of the local community is not jeopardised by the reuse of wastewater.

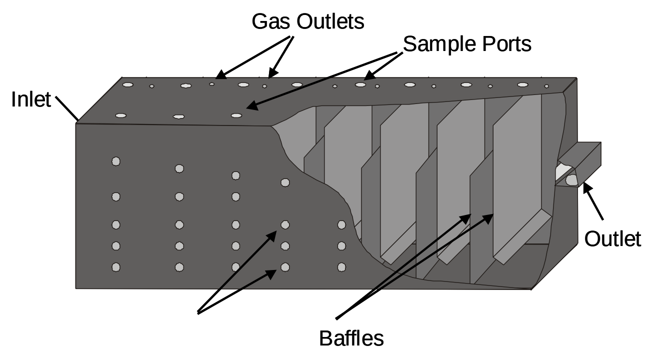


Figure 1
Schematic layout of the pilot ABR, showing hanging and standing baffles

This project has studied the appropriateness of the anaerobic baffled reactor (ABR) for on-site primary sanitation, particularly in low-income communities. The ABR consists of alternating hanging and standing baffles, which compartmentalise the reactor, and that force the liquid flow up and down from one compartment to the next (Fig. 1). Settling in the upflow region of each compartment results in the retention of high concentrations of biomass and high treatment rates can therefore be obtained, while overall sludge production is characteristically low.

This paper was originally presented at the 2004 Water Institute of South Africa (WISA) Biennial Conference, Cape Town, South Africa, 2-6 May 2004.

* To whom all correspondence should be addressed.
☎+2731 260-3375; fax: +2731 260-3241 ; e-mail: foxonk@ukzn.ac.za

The biological advantages of the ABR are well documented Barber and Stuckey, 1999). These include higher resilience to hydraulic and organic shock loads, longer biomass retention times and lower sludge yields than many other high rate anaerobic treatment systems. Concentration gradients of organic components should result in the development of populations that are microbiologically selected to best suit the conditions in each compartment. Differing populations of bacteria across the compartments has been shown to increase resistance to variations in feed load, temperature and pH.

The application of sanitation technology is constrained by considerations of topography and local regulations, which result in challenging design and performance requirements. It has been proposed that the ABR is an appropriate means of providing short or medium term sanitation solutions to low-income communities (Foxon et al., 2001) since:

- Flow within the reactor is directed by baffles under the force of the pressure head at the influent. No mechanical mixing is required (and may even be undesirable) since flow is brought into intimate contact with the biomass as it is forced through the sludge bed. Therefore, there are no power requirements during normal operation.
- The ABR has been shown to function effectively under a wide range of flow and load conditions (Barber and Stuckey, 1999). It is also more resistant to shock loads than most conventional anaerobic treatment processes.
- Little or no maintenance is required for an ABR. The end compartments promote endogenous respiration and are designed for low sludge carry-over rates. Desludging should be a function of the grit load only. Experience from Columbia has shown that desludging, if required at all, is infrequent (Orozco, 1997).
- The basic mechanical design of the ABR is very simple, and in situ installations need not have any parts outside the rectangular body.

This project has included an intense analytical study of the performance of a 3 000 ℓ pilot ABR at one hydraulic loading rate using domestic wastewater at a council-run wastewater treatment facility. Issues relating to the acceptability of the technology to target communities and the authorites have been investigated. Possible post treatment options have also been examined.

Materials and methods

Pilot reactor

The 3 000 ℓ pilot reactor was constructed of mild steel with the dimensions 3 m x 1 m x 1.2 m with a total headspace of 600 ℓ above the compartments. Sampling ports were supplied on the top and one side of the reactor (Fig. 1). Feed was obtained from a raw wastewater channel at the head of works, Kingsburgh wastewater treatment works, by a submersible pump. A programmable logic controller (PLC) was used to control flow rate; a proportional-integral (PI) control algorithm that feeds back from a flow measurement device on the outlet to a feed bypass valve on the inlet, was implemented by the PLC. The reactor was originally seeded with conventional digester sludge.

Sample collection and storage

Grab samples were obtained from the reactor feed box, and at the outlet pipe. Samples of the sludge column in the upflow region of each compartment were obtained using a specially designed sampling column, then mixed in a bucket and sampled for analysis. Samples for ammonia and phosphate were filtered and acidified to restrict biological activity between sampling and analysis. All samples were transported cold and analysed within 30 hours.

Analyses performed

COD, TSS, VSS, free and saline ammonia, orthophosphate analyses were performed according to *Standard Methods* (1995). Gas production rate measurements were performed using a manual constant pressure liquid displacement system. Pathogen indicator organisms, total coliforms and *Escherichia coli* were cultured on Chromocult Coliform Agar plates using the filtration method according to *Standard Methods* (1995). Reagent grade chemicals were used.

Health-related indicator organisms

Grab samples of mixed sludge and liquid fraction were serially diluted, vacuum-filtered through 0.45 µm membrane filters and the filters incubated on Chromocult® coliform agar (E. Merck) at 37°C for 24 h. Total coliform colonies and *Escherichia coli* colonies were identified by colour.

Fluorescent *in-situ* hybridisation

Mixed samples of the sludge column on the upflow side of each compartment were obtained from each of the 8 compartments of the ABR monthly. Cells were fixed, using 4% paraformaldehyde solution or ethanol for 1 h, washed and resuspended. Samples thus pretreated were fixed onto slides prior to dual staining with the DNA-intercalating dye 4',6-diamidino-2-phenylindole (DAPI) and the fluorescent 16S rRNA-targeted oligonucleotide probes listed in Table 1. The slides were viewed using a Zeis Axiolab microscope

TABLE 1
Specificities of the rRNA-targeted oligonucleotide probes used for whole-cell hybridisation in samples taken from compartments of the pilot ABR receiving domestic wastewater

Probe	Specificity	Sequence (5'-3')
EUB338	Bacteria (16S, 338-355)	GCTGCCTCCCGTAGGAGT
ARC915	Archea (16S, 915-934)	GTGCTCCCCCGCCAATTCCT
ALF1b	α-Proteobacteria (16S, 19-35)	CGTTCG(C/T)TCTGAGCCAG
BET42a	β-Proteobacteria(23S,1027-043)	GCCTTCCCACTTCGTTT
GAM42a	γ-Proteobacteria (23S,1027-1043)	GCCTTCCCACATCGTTT
SRB385	δ-Proteobacteria (16S,385-402)	CGGCGTCGCTGCGTCAGG
LGC354a	*Firmicutes* low G+C (16S, 354-371)	TGGAAGATTCCCTACTGC
HGC69a	High G+C (23S, 1901-1918)	TATAGTTACCACCGCCGT
DSB985	Desulfobaceriaceae (16S, 985-1004)	CACAGGATGTCAAACCCAG
DSV698	Desulfovibrionaceae (16S, 698-717)	GTTCCTCCAGATATCTACGG
MS821	Methanosacina (16S, 821-844)	CGCCATGCCTGACACCTAGCGAGC
MX825	Methanosaeta (16S, 825-847)	TCGCACCGTGGCCGACACCTAGC

TABLE 2
Average COD concentrations for whole inlet, outlet, filtered outlet and head of works samples

Average COD concentration[mgCOD/ℓ]			
Influent wastewater	Head of works measurement	Treated effluent	0.45 μm filtered effluent
716 ± 54.4(n=32)	697 ± 61.9(n=66)	192 ± 21.1(n=33)	82.1 ± 16.0(n=12)

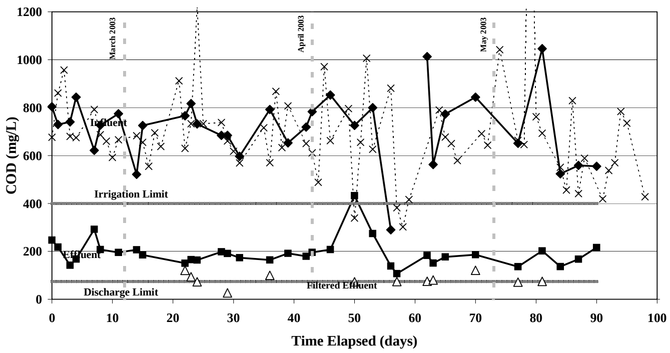


Figure 2a
COD profiles for whole inlet and outlet and filtered outlet of the pilot ABR treating a typical middle-income domestic wastewater, and compared to feed values measured by the municipality for a 3 month period

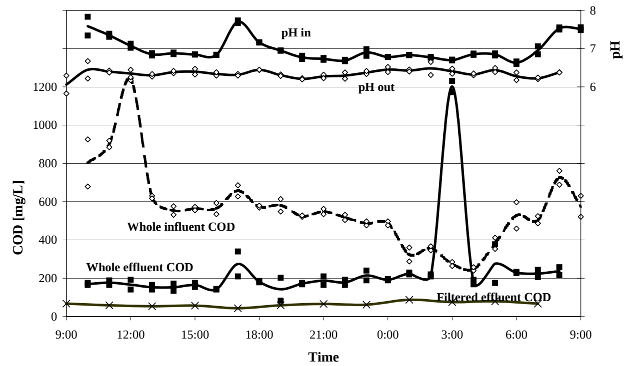


Figure 2b
COD profiles for whole inlet and outlet and filtered outlet of the pilot ABR treating a typical middle-income domestic wastewater for a 24 h sampling period

and image analysis software. Protocols were according to Hicks et al. (1992) and Amann (1995). Total cell counts were also obtained by subjecting pretreated samples to DAPI staining, using the membrane filtration method (Porter and Feig, 1980).

Scanning electron microscopy

Grab samples of sludge from each compartment were centrifuged and washed prior to fixation in 10% formaldehyde for 16 hours at room temperature. Thereafter, samples were processed for scanning electron microscopy according to standard protocols, including post-fixation in osmium tetroxide, dehydration and sputter-coating with gold (Bancroft and Stevens, 1990). Samples were viewed using a Cleo 1450 scanning electron microscope.

Results

The results presented below are for a hydraulic retention time of 22 h (approx. 2.3 ℓ/min)

Chemical and physical results

COD. Figure 2a presents the results obtained for COD concentration measured at the inlet and outlet of the ABR, and effluent filtered through 0.45 μm filters. Influent COD data for head-of-works samples (measured by the municipality at their accredited laboratories) are presented for comparison. Table 2 presents the averages measured. Based on the grab sample and composite sample measurements, an apparent COD removal of 72 ± 3 % was obtained, however a 24 h campaign of hourly COD measurements (Fig. 2b) indicated that these results could be weighted by the apparently higher influent COD at the normal sampling time (09:00 to 13:00), and the fact that solids loss occurs from time to time in the effluent (Fig. 2b), thereby increasing the average outlet COD measurement. From the 24 h data, the average influent COD measurement for the period sampled was 564 mgCOD/ℓ, and the effluent average was 238 mgCOD/ℓ, giving an average COD removal of 58%.

Nutrients. Measurements of free and saline ammonia and ortho-phosphate were made for a few grab samples. Table 3 presents the results obtained. Ammonia showed a slight increase with respect to compartment number. No statistical trend was observed in the orthophosphate profile against compartment number (i.e. it is statistically impossible to differentiate between inlet and outlet values). The average value for orthophosphate in all measurements was 5.5 ± 0.5 mg P/ℓ. Table 3 shows values measured by the municipality at their accredited laboratories for ammonia and orthophosphate for composite samples. The significant difference between these measurements and those measured on reactor influent and effluent samples is attributed to release of ammonia and phosphate in the (municipally sampled and measured) composite sample due to anaerobic degradation over the 8 h sampling period.

TSS and VSS. Total suspended solids (TSS) and volatile suspended solids (VSS) measurements of influent and effluent were obtained for the period February to May 2003. Effluent TSS values were between 50 and 400 mg TSS/ℓ (average = 225 mg TSS/ℓ). Effluent VSS values were between 50 and 200 mg VSS/ℓ (average = 127 mgVSS/ℓ).

Gas production. The rate of gas production for each compartment was measured on two occasions in the 5 months operating period using a manual constant pressure liquid displacement system. Recorded gas production rates were very low, the average total measured flow being 0.39 mol/h gas produced. From the average COD removal, 2.78 mol CH_4/h should be removed to close the mass balance. This is the minimum possible gas production rate that

TABLE 3
Average values of analyses for inlet and outlet samples of COD, pH, free and saline ammonia, orthophosphate, total suspended solids, volatile suspended solids, total coliforms for a typical middle-income domestic wastewater for the period February to June 2003 (Standards from DWAF, 1999)

	Unit	Inlet	Outlet	Discharge standard	Irrigation standard
COD	mgCOD/ℓ	716 ± 54.4 (n=32)	192 ± 21.1 (n=33)	75	400*
pH		6.9	6.5	5.5-9.5	6-9
Ammonia	mg N/ℓ	24.9 ± 4.2 (n=7)	33.2 ± 2.8 (n=6)	3	No limit
Phosphorus	mg P/ℓ	4.9 ± 4.1 (n=4)	5.5 ± 0.5 (n=5)	10	No limit
TSS	mg TSS/ℓ	480 ± 109 (n=14)	225 ± 55.2 (n=14)	25	No limit
VSS	mg VSS/ℓ	306 ± 60.8 (n=14)	127 ± 45.9 (n=14)	No limit	No limit
Total coliforms	cfu/100 mℓ	1.3 x10^8	5 x 10^7	1 000	100 000

* for a 500 kℓ/d discharge

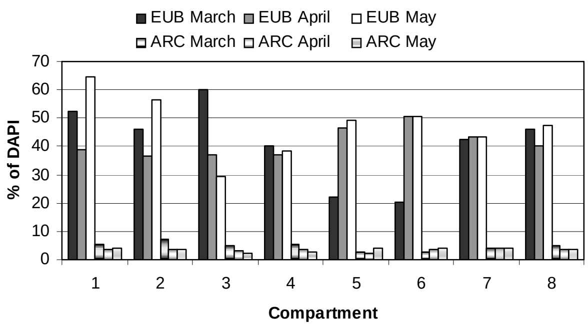


Figure 3
Relative proportions of eubacteria (EUB) and archeae (ARC) to total cells (DAPI stain), showing dominance of eubacteria over archeae. Data shown for March – May 2003.

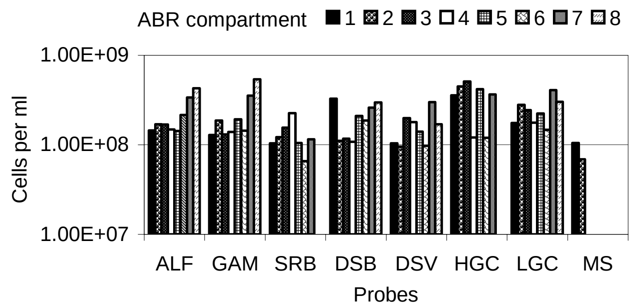


Figure 4
Absolute number of cells detected with each of ten oligonucleotide probes (Table 1) in samples from each ABR compartment (compartments as per legend). Data shown for May 2003, when the reactor was operating at steady state.

should be observed if the assumption of being near steady state is correct, since any CO_2 released would increase the gas production rate by the rate of CO_2 produced. Clearly, an error in the assumption of pseudo-steady state, or in the accuracy of the gas measurements has been made. Since large changes in sludge load in each compartment and performance measurements were not observed, it is presumed that the error is to be found in the gas measurement system. The error is probably as a result of the highly interactive nature of the liquid levels and gas pressures within the reactor.

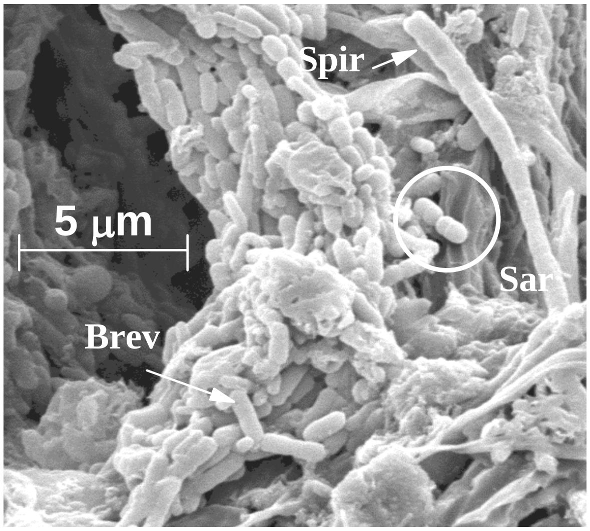
Microbiological results

Pathogen indicator organisms. Tests on the extent of deactivation of pathogen indicator organisms *Escherichia coli* and total coliforms were performed. Significant variation was observed in both influent and effluent samples. Mean removal efficiencies of 68% and 61% were obtained respectively for *E. coli* and total coliforms. This is less than a 1 log reduction in pathogen concentration, and the average effluent concentration of total coliforms was more than 60 million cfu/100 mℓ. (The target outlet concentration is 100 000 cfu/100 mℓ). At least a 3 log removal of pathogens is required for the effluent to be considered safe for human contact.

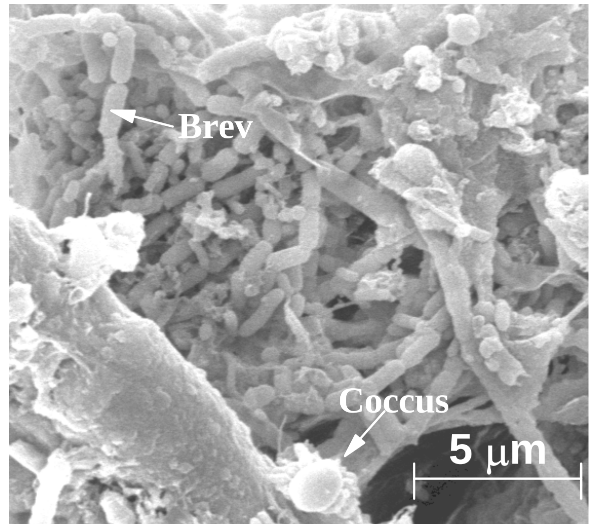
Fluorescent in-situ hybridisation. DAPI staining was performed on samples taken from each compartment for three months. No clear trend was obtained, with total cell counts within the same order of magnitude for all compartments. Fluorescent in situ hybridisation using probes EUB388 and ARC915 showed a dominance of the bacterial population over archeae (Fig. 3). This contrasted with the laboratory scale studies, using an industrial wastewater feed (Bell and Buckley, 2003). Of the eubacteria, an average of 60% of cells hybridised by the EUB 388 probe were detected by eight family- or genera-specific probes, selected to identify the common micro-organisms that participate in the different processes of anaerobic digestion. No clear trends in the distribution of species were observed (Fig. 4).

The archeae were further examined using only two specific probes, viz. for Methanosarcina (probe MS821) and Methanosaeta (probe MX825, filamentous). No Methanosaeta were found in any compartment of the reactor for any of the months tested, while Methanosarcina represented 100% to 0% of the archeae in each compartment. Methanosarcina were found only in the early compartments, and decreased in number with each subsequent compartment (Fig. 4). Conversely, unidentified archeae increased between the first and last compartments.

Microbiological results. FISH results were qualitatively confirmed by scanning electron microscopy (SEM) examination of sludge samples taken from the different compartments. As with FISH, No filaments resembling the morphology of Methanosaeta were observed in any of the samples viewed, while several micro-



a) Variety of methanogen-like bacteria from compartment 1, including Methanobrevibacter- (brev), Methanospirillum- (spir) and Methano-sarcina-like (sar) species



b) Aggregation of Methanobrevibacter-like species, with few Methanococcus-like (coccus) species from compartment 1

Figure 5

Scanning electron micrographs of representative methanogen-like bacteria found in compartment 1 ABR sludge samples

organisms with morphology typical of Methanospirillum, Methanobrevibacter and Methanosarcina (Wu et al., 1985) were observed in compartments 1 to 5. Methanosarcina-like organisms were present almost exclusively in compartment 1. Microorganisms resembling Methanococcus were unevenly distributed throughout the reactor. Typical SEM images are presented in Fig. 5.

Operational and institutional issues

The following sections discuss operational and institutional matters that may influence the location, application and appropriateness of an on-site pre-treatment system such as the ABR

Water use patterns

A subsidiary project investigated water use patterns among communities who received potable water at the second level of service viz. semi-pressure rooftanks. The rooftank is supplied directly from the water mains connection in the street and the level within the tank is controlled by a ball valve. Water within the house is only supplied from the tank at the pressure supplied by the elevation of the roof tank (hence "semi-pressure"). There is no daily limit on the amount of water that can be supplied to the roof tank: the consumer pays for their water consumption after the first 200 ℓ/day (or 6 Kℓ/month). Consequently, it is necessary for excess water fed to a household to be removed from the site since in general the sites under consideration cannot accept the load of greywater produced. Waterborne sanitation is therefore a pre-requisite for the installation of roof tanks, and consequently rooftanks have thus far only been installed in areas served with waterborne sanitation.

The use of an ABR in conjunction with some post-treatment will probably be targeted at households with semi-pressure rooftank water supply; lower levels of water supply are not sufficient to operate a wet-core (flushable) toilet, and the higher level, full mains pressure, may result in a wastewater that is too dilute, resulting in hydraulic overloading of the ABR. Full-pressure water users will in general be in a higher income bracket, where full water-borne sanitation can be afforded by the consumer, and therefore will be the only sanitation level acceptable to most people in this category. This exercise was a preliminary investigation into water use behaviour, the outcome of which was to generate recommendations on how to undertake a similar, more comprehensive exercise. For the preliminary study, 40 households were interviewed. The householders interviewed did not appear to have previously received specific education on water use or reuse. The water use of all householders interviewed exceeded the 6 kℓ/month free basic water. All households had one toilet and at least one kitchen tap. Of the 40 households, 27 (68%) had a shower, but 5 (18.5%) of the showers did not work. None of the interviewed householders reported washing hands, clothes, body or hair in a bucket; all washing was associated with the basin or in a few cases, the shower. Only two householders had a garden tap. These observations suggest that very little greywater is thrown out into the garden. All greywater is apparently directed into the sewer. Based on this limited sample of a small segment of the general population, it appears probable that many low-income households who have a semi-pressure roof-tank water supply do not reuse greywater, and that greywater return rates will probably be high as a result.

Further social studies will need to be performed to ascribe values to water consumption and greywater return in these communities. However, there appears to be potential for educating these householders on the reuse of greywater outside of the home for growing vegetables or gardens. This could have benefits from a quality of life perspective, and by reducing the hydraulic load to an on-site wastewater treatment system, increasing the concentration of organics in the wastewater, and thereby increasing the organic treatment capacity of the technology.

Reuse of treated wastewater

The quality of ABR effluent has been shown to consistently meet COD guidelines for irrigation, but not for discharge to surface water (Table 2). The use of an anaerobic effluent in irrigation carries the potential benefits of converting high nutrient levels in the effluent into a resource, and alleviating community poverty through food provision and creation of informal employment opportunities. A review of research performed on irrigation using effluent was undertaken to identify the areas of concern.

The presence of protozoan cysts (Giardia, Cryptospiridium), and the eggs of nematodes and helminths in a wastewater/effluent, has been shown to lead to contamination of crops (Amahmid, 1999; Bouhoum et al., 2002). Cysts particularly have been shown to persist after treatment, even when pathogen indicator organisms have been removed (Scott et al., 2002; DWAF, 1996).

There are three main risks associated with irrigation using pathogen-contaminated water:

- Pathogens may contaminate groundwater sources, or run-off from the site may result in contamination of nearby water resources.
- Workers may be exposed to infection by nematode worms (e.g. hookworm) from the soil.
- Consumers of edible crops, and handlers of any crops irrigated with wastewater or effluent may be exposed to infection by viable pathogens present on the crops themselves.

Clearly, an essential function of any system that provides effluent originating from raw wastewater must exhibit sufficient pathogen removal to minimise the possibility of reinfecting community members with waterborne pathogens.

Solids handling ability of the ABR

The ABR has been shown to degrade particulate biodegradable organic material to a certain degree. However, inert solids that enter the reactor will mostly accumulate in the first compartment. Solids with density less than that of water will float on the surface of the first compartment in a scum layer. If their density is greater than water, they will be retained at the bottom of the first compartment. Solids that have a similar density to water may be carried out of the first compartment, and through the reactor to be discharged with the effluent. This theory has been supported by the observation that the only solids retrieved at an outlet sieve of the pilot ABR have been anaerobic sludge, and occasionally the seeds of a tree growing near the reactor. Consequently, inert solids handling capability is associated with the feed line or the first compartment. The former may be managed by the addition of a screening unit on the feed line, and the latter by appropriate sizing and design of solids removal from the first compartment

Community acceptance of the technology

A concern about the appropriateness of the technology for low-income communities is related to the acceptance of the entire system, including pre- and post-treatment by the community. Low-income communities in Kwa-Zulu Natal have little cultural tolerance for the handling of faecal matter. For this reason, local metropolitan bodies are cautious of implementing any sanitation technology that requires active community participation. It is therefore imperative that the community is educated about keeping nonbiodegradable solids out of the system. However, it is nevertheless necessary to have some means of removing unwanted solids that do enter the system. In a situation where active community participation is possible, or the system is under municipal management, a manual screening unit should be installed on the feed-line to the ABR. If screening is not practical from an operational point of view, the first compartment should be designed to be large enough to allow a certain amount of nonbiodegradable solids accumulation. Solids must then be removed periodically in the same manner as a septic tank. For this reason, the unit should be accessible by road, and have an appropriately sized port in or removable lid on the first compartment.

Discussion

The results of operation of the 3000 ℓ pilot-scale ABR operated at a hydraulic retention time of 22 h are presented above. From these data, it can be seen that although the reactor is able to remove a considerable amount of organic matter (between 50 and 75%) at the specified retention time, it is clear by comparison with Table 3 that the effluent does not attain the required extent of pathogen removal (as inferred from pathogen indicator organism cultures) for discharge to a water resource or for use in the irrigation of crops. It is particularly important that the effluent does not pose any health risk to the community that the ABR will serve, given the high HIV infection rate in the province, and consequently, the susceptibility of the local populace to infection. It is therefore necessary that an appropriate post-treatment be applied to the ABR effluent. Possible solutions include the use of reedbeds, wetlands, or membrane filtration.

It is also noted that the other parameters that have never complied with the General Standards for discharge to a water resource are the nutrients, ammonia and phosphorus. However, as stated in the introduction, these nutrients may be regarded as a resource from an agricultural point of view, and once the concept of water reuse as opposed to treatment and discharge is firmly established, will enhance the value of the effluent to the community, if it can safely be used for agricultural purposes.

The microbiological study has indicated that the amount of methanogenesis compared to the amount of fermentation that occurred in the reactor at the reported flow rates was considerably lower than would be expected in healthy anaerobic digestion. This is also observed in a low pH value throughout the reactor (in general below pH 6.5). It is concluded that insufficient breakdown of particulate biodegradable matter is being obtained, and that short chain fatty acid (SCFA) precursors to methanogenesis are being scavenged at low concentrations, preventing the establishment of a healthy methanogenic population. This implies that the solids retention time is insufficient for the complete degradation of biodegradable particulates, which are leaving the reactor in the effluent. Furthermore, the low concentration of archeae (methanogens) means that these populations will be susceptible to deactivation and souring through shock loading or washout, in contradiction to the published advantages of the ABR Barber and Stuckey, 1999).

The implications of these results are two-fold:

- Firstly, a better understanding of the hydraulic and solid retention design limitations must be obtained so that appropriate flow rates/reactor sizes are used for the type of feed studied (raw domestic wastewater). It seems probable that, at the current wastewater organic concentration, the hydraulic retention time used has been too short; The first recommendation is therefore to reassess reactor performance at a longer hydraulic retention time, and adjust the design recommendations according to the results of this phase of the study.
- Although more deactivation of pathogen indicator organisms may be expected at longer hydraulic- (and therefore solids-) retention times, it is nevertheless probable that some post treatment will be required before the effluent may be safely reused in horticulture. The second recommendation is that appropriate post-treatment options should be assessed and that post-treatment be regarded as an integral part of the technology.

Conclusions

The ABR has potential as a primary sanitation pre-treatment option in low-income communities: it has been shown to remove between 58 % and 72 % of COD entering in the feed and to reduce total suspended solids and pathogen indicator organisms in the wastewater. The design limits of the technology have not been fully investigated for this application. Results at a 22 hhydraulic retention time (HRT) using a typical middle-income domestic wastewater suggest that the reactor has been hydraulically overloaded; at the prevailing flow rates, the sludge retention time has been too low to establish a sufficiently concentrated active biomass, or to achieve complete hydrolysis of the particulate solids in the feed. Further investigations into reactor performance at different mean flow rates are currently underway.

Examination of the ABR effluent at the reported HRT shows that the effluent is not of a sufficiently good quality to be discharged to river. The presence of pathogen indicator organisms in the effluent indicates that some post-treatment is necessary before the effluent may be used for irrigation of crops. Although no legislation specifically controls irrigation with this kind of effluent for purposes other than crop-growing, given the high incidence of HIV infection in Kwa-Zulu Natal, and consequently the vulnerability of the populace to any kind of exposure to pathogens, it is clear that an appropriate post-treatment must be implemented in conjunction with the ABR. It is also necessary that specific pathogens in the effluent are quantified, particularly those pathogens that may survive in cysts or oocysts.

It is clear that community education and acceptance of the technology will have a strong influence on the success or failure of the ABR and associated post-treatment. The biological functioning of the reactor will be enhanced by separating greywater before treatment and thereby increasing the organic concentration of the feed, and the exclusion of nonbiodegradable solids from the raw wastewater will simplify operation and maintenance, and reduce the risk of blockage. It is necessary to perform a quantitative, community-based study on the amount and quality of wastewater that a typical low-income community in the target areas in Kwa-Zulu Natal generates per household, and the attitude that householders would have to their sanitation system.

Acknowledgements

This research was funded by the Water Research Commission of South Africa, project K5/1248, and the National Research Foundation. Thanks are extended to members of the project team and the steering committee, especially Prof. Ekama of the University of Cape Town for input and advice.

References

AMAHMID O, ASMAMA S and BOUHOUM K (1999) The effect of wastewater reuse in irrigation on the contamination level of food crops by Giardia cysts and Ascaris eggs. *Int. J. Food Microbiol*. **29** 19.

AMANN R (1995) *In situ* identification of microorganisms by whole cell hybridisation with rRNA-targeted nucleic acid probes. *Molecular Microb. Ecol. Manual*, 3.3.6, p.1.

BANCROFT JD and STEVENS A (1990) *Theory and Practice of Histological Techniques* (3rd edn.) Churchill Livingston, Edinburgh.

BARBER WP and Stuckey DC (1999) The used of an anaerobic baffled reactor (ABR) for wastewater treatment: A Review. *Water Res*. **33** (Orozco, 1997) 1559.

BELL J and BUCKLEY C (2003) Characterisation of the methanogenic populations in an operating anaerobic baffled reactor. The International Water Association Conference on Environmental Biotechnology, Advancement on Water and Wastewater: Applications in the Tropics, Universiti Teknologi Malaysia, Johor Bahru, Malaysia.

BOUHOUM K, AMAHMID O and ASMAMA S (2002) Impact of wastewater treatment on pathogens in arid climate (Marrakech, Morocco). IWA Regional Symposium on Water Recycling in Mediterranean Region, Iraklio, Greece.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY (DWAF) (1996) *South African Water Quality Guidelines* (2nd edn.). Volume **4**: Agricultural Use: Irrigation.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY (DWAF) (1999)General authorisations in terms of section 39 of the National Water Act, 1998 (Act no. 36 of 1998) *Government Gazette* no. 20526 1999.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY (DWAF) (2003) Strategic framework for water services (http://www.dwaf.gov.za/Documents/Policies/Strategic%20Framework%20approved.pdf).

FOXON K, DAMA P, BROUCKAERT C and BUCKLEY C (2001) Design considerations for the implementation of an anaerobic baffled reactor in low-income settlements in Kwa-Zulu Natal. *Proc. of the IWA Conf. on Water and Wastewater Management for Developing Countries*, Kuala Lumpur, Malaysia.

HICKS R et al. (1992) Dual staining of natural bacterioplankton with 4',6-diamidino-2-phenylindole and fluorescent oligonucleotide probes targeting kingdom level 16S rRNA sequences. *Appl. and Environ. Microbiol.* **58** 2153-2163.

OROZCO A (1997) Pilot and full-scale anaerobic treatment of low-strength wastewater at sub-optimal temperature (15ºC) with a hybrid plug-flow reactor. *Proc. of the 8th Int. Conf. on Anaerobic Digestion*, Sendai, Japan. **2** 183-191.

PORTER K and FEIG Y (1980) The use of DAPI for identifying and counting aquatic microflora. *Limnol. and Oceanogr.* **25** Barber and Stuckey, 1999) 943-948.

SCOTT TM, McLAUGHLIN M, HARWOOD V, CHIVUKULA V, LEVINE A, GENNACCARO A, LUKASIK J, FRRAH S and ROSE JB (2002) Reduction of pathogens, indicator bacteria, and alternative indicators by wastewater treatment and reclamation processes. IWA Regional Symposium on Water Recycling in Mediterranean Region, Iraklio, Greece.

SECKLER D, BARKER R and AMARASINGHE U (1999) Water scarcity in the twenty-first century. *Int. J. of Water Resour. Develop.* **15** 29.

STANDARD METHODS (1995) *Standard Methods for the Examination of Water and Wastewater* (19th edn.) American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC, USA.

VERSTRAETE W (2002) Environmental biotechnology for sustainability. *J. Biotechnol*. **94** 93-100.

WORLD HEALTH ORGANISATION EXECUTIVE SUMMARY (WHO) (1989) *Guidelines for the Safe Use of Wastewater and Excreta in Agriculture and Aquaculture*. WHO, Geneva.

WU W et al. (1985) Properties of granular sludge in upflow anaerobic sludge blanket (USAB) and its formation. In: *Anaerobic Digestion*, China State Biogas Association, Guangzhou, China. 339.