Operation of a full-scale pumped flow biofilm reactor (PFBR) under two aeration regimes

E. O'Reilly, M. Rodgers and E. Clifford

ABSTRACT

A novel technology suitable for centralised and decentralised wastewater treatment has been developed, extensively tested at laboratory-scale, and trialled at a number of sites for populations ranging from 15 to 400 population equivalents (PE). The two-reactor-tank pumped flow biofilm reactor (PFBR) is characterised by: (i) its simple construction; (ii) its ease of operation and maintenance; (iii) low operating costs; (iv) low sludge production; and (v) comprising no moving parts or compressors, other than hydraulic pumps. By operating the system in a sequencing batch biofilm reactor (SBBR) mode, the following treatment can be achieved: 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD) and total suspended solids (TSS) reduction; nitrification and denitrification. During a 100-day full-scale plant study treating municipal wastewater and operating at 165 PE and 200 PE (Experiments 1 and 2, respectively), maximum average removals of 94% BOD_5, 86% TSS and 80% ammonium-nitrogen (NH_4-N) were achieved. During the latter part of Experiment 2, effluent concentrations averaged: 14 mg BOD_5/l; 32 mg $COD_{filtered}$/l; 14 mg TSS/l; 4.4 mg NH_4-N/l; and 4.0 mg NO_3-N/l (nitrate-nitrogen). The average energy consumption was 0.46–0.63 kWh/$m^3_{treated}$ or 1.25–1.76 kWh/kg $BOD_{5\ removed}$. No maintenance was required during these experiments. The PFBR technology offers a low energy, minimal maintenance technology for the treatment of municipal wastewater.

Key words | attached growth, decentralised wastewater treatment, low energy requirement, nitrification, pumped flow biofilm reactor

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INTRODUCTION

There is a growing world-wide market for environmental technologies that remove organic carbon, solids, nitrogen and phosphorus from municipal, industrial and agricultural wastewaters. This market arises from increasingly stringent environmental and health protection regulations, e.g., the EU Water Framework Directive (Directive 2000/60/EC). Such technologies are also required to be efficient in terms of energy usage and have low maintenance requirements.

Eutrophication of surface waters is a major issue in Europe (Hering *et al.* 2010). Urban wastewater discharges, despite recent improvements, still account for 50% phosphorus and 30% nitrogen emissions to freshwater (European Environment Agency 2010). In Ireland over the past 15 years, as a result of rapid economic growth and an expanding population, increased wastewater loadings have been applied to an old and inadequately developed wastewater treatment infrastructure, increasing pollution threats to receiving waters. The number of Irish plants that cater for populations between 500 and 2,000 population equivalents (PE) has increased from 244 in the Irish Environmental Protection Agency (EPA) reports of 2000/2001 to 297 in the reports of 2004/2005 (EPA 2003, 2007). The Irish EPA also reported that only 19% of plants with a PE less than 2,000 were compliant in the years 2004/2005. When not operated and maintained properly, these smaller plants pose a high pollution risk to receiving waters. As the Irish EPA has been recently given regulatory control over all local authority wastewater systems, there is an increased incentive to improve the treatment of all municipal wastewaters and this provides opportunities for the use of new sustainable technologies.

One new municipal wastewater treatment technology, suitable for centralised and decentralised wastewater treatment and known as a *pumped flow biofilm reactor* (PFBR),

doi: 10.2166/wst.2011.653

was developed and patented in National University of Ireland, Galway (NUI Galway) (Rodgers et al. 2004; Zhan et al. 2006; O'Reilly et al. 2008) and installed at the NUI Galway Water Research Facility (WRF). The WRF is used to carry out on-site research on the treatment of municipal wastewater using new technologies. The aim of this study, lasting 100 days, was to examine the performance of the new PFBR technology in treating municipal wastewater with a capacity of 165–200 PE with and without a dedicated anaerobic phase. The PFBR's performance was examined by analysing influent and effluent data, phase studies detailing individual treatment cycles, on-line multi-sensors, and energy-requirement data.

METHODS

The novel process comprised two reactor tanks (Reactors 1 & 2) located side-by-side, each having a working volume of 20.86 m^3. Each reactor contained stationary plastic biofilm media modules comprising vertical trapezoidal tubes averaging 30 mm × 22 mm (in plan) and providing a specific surface area of 180 m^2/m^3, giving a total surface area of about 4,250 m^2 (including internal tank wall surfaces). At any one time, no more than one reactor volume of water was in the two-tank reactor system and was cycled between the reactors using gravity and hydraulic pumps. To achieve aeration, the biofilm in each reactor was alternately exposed to wastewater and atmospheric air as the reactors were filled and emptied, respectively, during the cycling process.

The complete PFBR system installed at the NUI Galway WRF comprised: primary settlement tanks; a balance tank; and Reactors 1 and 2. The PFBR was located at a local authority wastewater treatment plant (WWTP) (25,000 PE) where a side-stream of the influent wastewater (comprising a mixture of municipal wastewater and some landfill leachate) was pumped to the PFBR system.

The PFBR was operated as a sequencing batch biofilm reactor type process with typical phases detailed in Table 1. Combining these phases and introducing rest periods allowed organic carbon, suspended solids, nitrogen and phosphorus removal. During the 100-day study, the PFBR was operated and examined during two aeration regimes: Experiment 1 (48 days) and Experiment 2 (52 days). Both experiments used the following treatment phases: fill/draw; aerate; and settle. An anaerobic period was included in Experiment 1 to encourage the establishment of phosphorus accumulating organisms within the system. During Experiment 2, the operation was changed to optimise the PFBR for nitrification and nitrogen removal.

The PFBR was controlled by a programmable logic controller (PLC) that allowed the users to vary control parameters such as: water levels; pause times; and aeration cycle counts. The PLC also received signals from a number of dissolved oxygen (DO), oxygen reduction potential (ORP) and pH probes installed in the reactors with the resultant data used to generate the respective concentration profiles during individual treatment cycles at three different depths in each reactor. All process information was displayed on a human machine interface (HMI) and logged by the PLC every 5 min. An internet connection on-site provided remote interrogation capabilities.

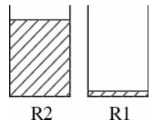
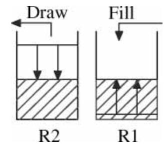
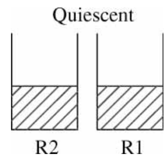
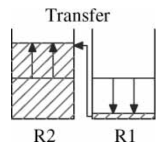
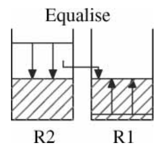
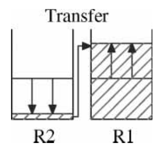
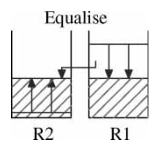
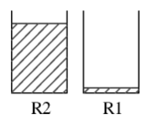
Municipal wastewater (containing landfill leachate) was pumped to the primary settlement tanks at regular intervals from the local authority WWTP and flowed by gravity through the primary settlement tanks and the balance tank. Settled influent wastewater was pumped from the balance tank to Reactor 1 at the beginning of each treatment cycle.

The main operational differences between the two experiments were the absence of the anaerobic period and the increased aeration time in Experiment 2 – 398 min in Experiment 2 versus 275 min in Experiment 1. The cycle time in Experiments 1 and 2 was 431 and 428 min, respectively. Taking account of reactor tank volumes, media surface area provided, influent wastewater characteristics and volumes (8.7 m^3/cycle and 7.8 m^3/cycle for Experiments 1 & 2, respectively), organic loading rates and hydraulic retention times, the number of aeration circulation cycles was calculated on the length of time taken to completely transfer the bulk fluid between the reactors.

Throughout the 100-day study, daily wastewater samples were taken – using refrigerated automatic samplers – from the balance tank at the beginning of a treatment cycle and from Reactor 2 at the end of the corresponding settlement phase. Grab samples were also taken from the primary settlement tanks with all samples analysed in accordance with the Standard Method (APHA et al. 2005) for the following parameters: 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonium-nitrogen (NH_4-N), nitrite-nitrogen (NO_2-N), nitrate-nitrogen (NO_3-N) and total suspended solids (TSS).

Three phase studies were conducted during the 100-day study: one during Experiment 1 and two during Experiment 2. During each phase study, samples were taken at frequent intervals during an individual treatment cycle and tested for the aforementioned parameters. DO, ORP and pH profiles for the three phase studies were also recorded using the PLC.

Table 1 | Description of the treatment process in a typical cycle for the PFBR system

Phases	Description		Schematics of water levels
Initial set-up[3]	R2: full with treated wastewater R1: empty at the start of a treatment cycle		
Fill/draw	Simultaneously, treated effluent was discharged from R2 and settled influent wastewater was pumped into R1		
Anaerobic[1]	Untreated wastewater remained quiescent in R1 to encourage anaerobic conditions to develop		
Aeration[2]	Transfer to R2	The water in R1 was pumped to R2 and remained quiescent in R2 for 9 min	
	Equalisation	A motorised valve was opened allowing water from R2 to flow by gravity into R1	
	Transfer to R1	The remaining water in R2 was pumped to R1 and remained quiescent in R1 for 9 min	
	Equalisation	A motorised valve was opened allowing water from R1 to flow by gravity into R2	
Settle	Water was pumped to R2 and remained quiescent for a brief settlement period		

Notes: [1]anaerobic phase was included for Experiment 1 only; [2]aeration steps were repeated a number of times during each treatment cycle; [3]biofilm media modules not shown.

RESULTS AND DISCUSSION

Overall results

Organic carbon. The wastewater oxygen demand was analysed as BOD_5 (influent samples), carbonaceous BOD_5 ($cBOD_5$, effluent samples) and total and filtered COD (COD_t and COD_f, respectively). The absence of the anaerobic phase and increased aeration time during Experiment 2 showed an improved performance in an average BOD_5 removal efficiency in the reactors of 88%, compared with 74% during Experiment 1. In Experiment 2, between Days 70 and 100, the average effluent $cBOD_5$ and COD_t concentrations were 14 and 50 mg/l, respectively, representing removal efficiencies of 94 and 80% (Table 2); when the removals in the primary settlement tanks were included, the respective overall removal

Table 2 | Average influent and effluent organic carbon, nitrogen, and phosphorus concentrations during the 100-day study[1]

(mg/l)	Experiment 1 Influent[2]	Effluent[3]	% removal	Experiment 2 Influent[2]	Effluent[3]	% removal
BOD_5	199 (79)	43 (5)	74	201 (63)	24 (15)	88
COD_t	262 (42)	86 (17)	67	208 (60)	69 (21)	67
COD_f	187 (48)	66 (10)	65	112 (51)	41 (15)	63
NH_4-N	34.7 (9.9)	20.9 (4.9)	40	24.7 (5.8)	7.0 (3)	72
NO_3-N	0 (0.02)	0.93 (0.57)	–	0.03 (0.06)	3.12 (0.97)	–
PO_4-P	3.05 (0.40)	2.51 (0.22)	18	2.51 (0.54)	2.15 (0.52)	14

Note: [1]standard deviations given in parenthesis; [2]samples taken from the balance tank; [3]samples taken from Reactor 2 during settle phase.

efficiencies increased to 96 and 87%. This represented organic loading rates of 1.37 and 1.25 g BOD_5/m^2 d for Experiments 1 and 2, respectively, and 2.8 and 2.3 g BOD_5/m^2 d for the system as a whole (including primary settlement). The full-scale PFBR consistently complied with the EU Urban Waste Water Treatment Directive (UWWTD) discharge limit of 125 mg COD_t/l and with the 25 mg BOD_5/l limit for the final 30 days of Experiment 2.

Nitrogen. The additional aeration time provided during Experiment 2 resulted in an increase in the nitrification efficiency. Little NO_3-N was evident in the effluent during Experiment 1 where average DO concentrations were lower during the aeration phase than in Experiment 2. Good NH_4-N removal was recorded in Experiment 2 with an average removal efficiency of 72% recorded (Table 2). This efficiency improved between Days 70 and 100 with an average removal efficiency of 80% achieved.

Ortho-phosphate. One of the initial aims of the 100-day study was to examine the performance of the full-scale PFBR at removing phosphorus biologically. However, little or no phosphorus removal occurred during the 48-day period when the anaerobic phase was in effect (18% during Experiment 1). The presence of landfill leachate in the influent may have inhibited biological P removal. Other contributing factors for the lack of phosphate accumulating organisms (PAO) activity could be attributed to (i) the DO concentration during the 'anaerobic' phase not reaching zero until after 100 min (Figure 2), and (ii) the availability of readily biodegradable organic carbon being limited (low COD removal during the Phase Study 1 aerobic phase). A longer study with a higher readily biodegradable organic carbon fraction may allow PAOs to develop within the reactors. The higher readily biodegradable organic carbon fraction may also aid in the reduction of DO during the anaerobic phase. In previous laboratory PFBR studies, over 92% P removal was achieved when treating a synthetic wastewater containing 19.5 mg PO_4-P/l (Rodgers *et al*. 2008).

Total suspended solids (TSS). Excellent TSS removals were recorded in Experiment 2, and in particular between Days 70 and 100, when an average effluent concentration of 14 mg TSS/l and an average removal efficiency of 79% were achieved in comparison with 53 mg TSS/l and 40% during Experiment 1 and 22 mg/l and 70% during Experiment 2 as a whole. The average effluent TSS concentrations during the last 40 days of Experiment 2 remained well within the EU WWTD discharge limit of 35 mg TSS/l. The TSS removal efficiencies increased to 85 and 86% for Experiments 1 and 2, respectively, when the data from the primary settlement tanks were considered. In all cases, effluent TSS concentrations were measured in Reactor 2 after a brief settlement period; no dedicated clarifier was used.

Phase studies

Three phase studies (PS 1, 2 and 3) were undertaken during the 100-day study of the full-scale PFBR, one during Experiment 1 (PS 1, Day 37) and two during Experiment 2 (PS 2, Day 83 and PS 3, Day 99). During these phase studies, wastewater samples were taken at regular intervals from both Reactors 1 and 2 and analysed for COD, NH_4-N and NO_3-N. DO, ORP and pH profiles were also recorded during each phase study with readings logged every 5 min.

COD. Limited COD was removed in PS 1 during the anaerobic phase while the water in the reactors remained quiescent. As the bulk fluid from both reactors was mixed and bulk fluid DO concentrations increased, a 50% reduction in COD_t was recorded over the aerobic phase. Less COD_f removal occurred throughout PS 1 with a 40% removal efficiency observed. Organic carbon removal in the full-scale PFBR occurred quickly when the anaerobic phase was removed in Experiment 2. In PS 2, 71% COD_f and 62% COD_t were removed during the first 22 min of the treatment cycle as sufficient oxygen was available for the heterotrophic bacteria to effectively oxidise the organic carbon in the bulk fluid. Overall, 77% COD_t and 76% COD_f was removed during PS 2.

Nitrogen. A clear improvement in NH_4-N removal was evident between the three phase studies (Figure 1). In PS 2 and 3, NH_4-N could be seen to be removed in two distinct periods; initial aeration stage (first 60 min), and remaining aeration stage (remaining cycle time). NH_4-N was rapidly reduced as the organic carbon was depleted in the initial aeration stage. The immediate supply of oxygen to the biofilm after the Fill Phase and the simultaneous rapid reduction in organic carbon then allowed the nitrifying autotrophs to begin oxidising the remaining NH_4-N. This was most effective during PS 3, where the final NH_4-N concentration at the end of the treatment cycle was 0.5 mg/l, representing a 97% NH_4-N removal efficiency, compared with 41% for PS 1, and 76% for PS 2. Similar nitrification trends from Figure 1 show that nitrification was well established on Day 83 (PS 2, where 0.006 mg NO_3-N/l min was formed) and was confirmed during the phase study on Day 99 (0.009 mg NO_3-N/l min formed). The presence of landfill leachate in the local authority WWTP may have inhibited the growth of nitrifying bacteria in the PFBR, preventing full nitrification from occurring.

Definitive denitrification was undetermined during the phase studies as no total nitrogen data was available. However, an uptake of 10–13 mg N/l (NH_4-N + NO_3-N) was observed during the initial aeration stage for both PS 2 and 3, possibly in heterotrophic growth. For the remaining aeration stage, there was a reduction in the sum of NH_4-N + NO_3-N from 14 to 10 mg N/l in PS 2 and from 9 to 6 mg N/l in PS 3. This latter reduction could be due to denitrification. Denitrification could occur in biofilms while aerobic conditions prevailed in the bulk fluid as NO_3-N may penetrate deeper into the biofilm than O_2 in areas within the reactors where O_2 concentrations are lower than NO_3-N (Henze *et al.* 2000). This may have occurred in the lower section of the reactors where the biofilm was exposed less frequently to the atmosphere. Alternatively, Biesterfield *et al.* (2003) reported anoxic layers within biofilms in trickling filters even when aqueous O_2 concentrations were as high as 5 mg O_2/l.

Sensor probes. A set of DO, ORP and pH probes was installed near the top, in the middle, and near the bottom of each reactor to measure the concentrations in the bulk fluid. Both the top and middle probes were exposed to atmospheric air each time a reactor was emptied. The bottom probe remained constantly submerged in water throughout the treatment cycle. Concentrating on the lowest readings of each probe during each phase study (Figure 2), an upward trend in DO and ORP was generally noticed for all phase studies as the treatment cycle progressed through the aeration phase and the DO and ORP in the bulk fluid increased, corresponding to a decreased organic load. The pH was generally at the lower end of the optimum range for nitrification to take place (Henze *et al.* 2000) with maximum activity reported at a pH of 8.2 for a submerged biofilter (Villaverde *et al.* 1997). A slight general decrease in pH was observed, consistent with the decrease in pH when nitrification was occurring. The average lowest reading of each set of top, middle and bottom probes is presented for the three phase studies in Figure 2.

During PS 1, and as expected, the average DO concentrations remained lower throughout the treatment cycle than in PS 2 and PS 3, with an average of 3 mg DO/l achieved by the end of the treatment cycle. A similar trend is observed for ORP. The general increase in the bulk fluid DO concentrations from one phase study to the next coincided with increased NH_4-N reductions and NO_3-N formation. The phase studies show clear relationships between DO and ORP for both carbon removal and nitrification. It is

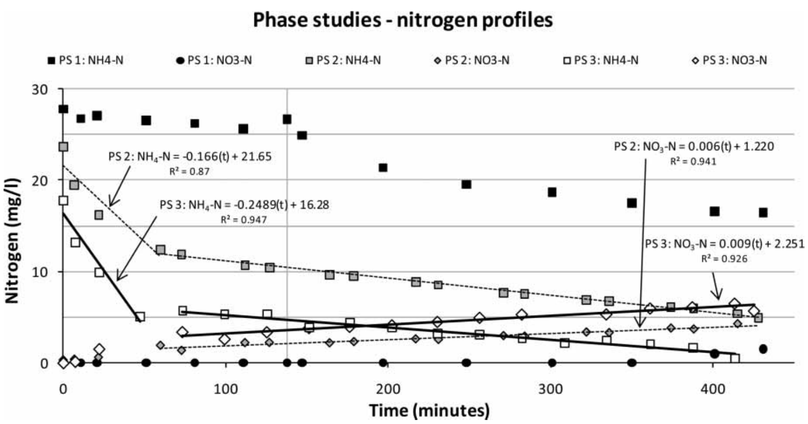


Figure 1 | Phase study nitrogen profiles (vertical dashed line represents the end of the anaerobic phase for PS 1).

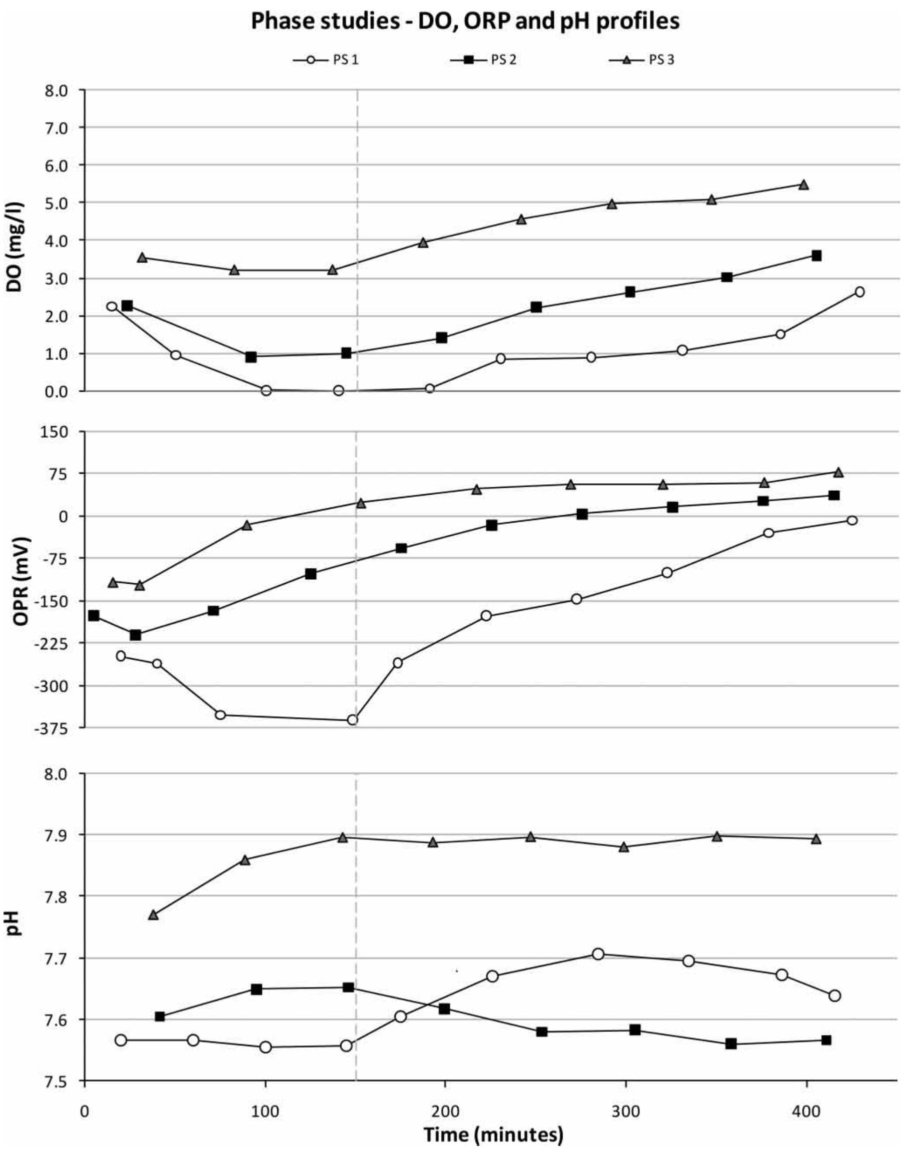


Figure 2 | Average DO, ORP and pH profiles for PS 1, 2 and 3 (vertical dashed line represents the end of the anaerobic phase for PS 1 only).

possible that these cost effective, robust sensors could be used to optimise plant control and thus achieve further energy savings. Further studies could concentrate on reducing the high DO concentrations during PS 3 while maintaining the treatment efficiency. This could be done by defining DO set points using the DO probes and the PFBR controls. Alternatively, introducing rest periods during the aeration phase could achieve the same effect.

Energy consumption

The total energy consumed (kWh) by the PFBR system incorporating primary and secondary treatment included the energy utilised by the following system pumps: (i) a 1.5 kW foul pump; (ii) a 1.4 kW feed pump; (iii) two 2.4 kW circulation pumps; (iv) a 2.4 kW discharge pump; and (v) three 1.0 kW sludge pumps. The control equipment and probe energy were also included in the monitored energy. With an energy usage of 0.46–0.63 kWh/m^3, or 1.25–1.76 kWh/kg $BOD_{5\ removed}$, the PFBR comes in at the lower end of the range for oxidation ditches and activated sludge plants (0.44–2.07 and 0.30–1.89 kWh/m^3, respectively) as reported by Mizuta & Shimada (2010). It is reasonable to assume that the energy efficiency of the PFBR would further improve when operated at a larger scale and optimised in terms of tank and pump design.

Desludging and maintenance

Sludge was removed from Reactors 1 and 2 only after the 100-day study was concluded and pumped to a sludge holding tank. No desludging took place, or was required, during the study period. Estimates were made on the overall sludge production for the study period by considering the effluent volumes and effluent TSS concentrations, and the waste sludge volumes and TSS concentrations in the waste sludge when desludging took place. From these figures, it was estimated that 57.4 kg effluent TSS exited in the effluent stream during the study when treating 2,645 m^3 municipal wastewater and 11.4 kg of TSS was removed from Reactors 1 and 2 due to desludging. This corresponded to an estimated sludge yield of about 0.13 g TSS/g $COD_{t\ removed}$. This figure compares well with a reported average of 0.315 g TSS/g$COD_{t\ removed}$ for 30 activated sludge plants from a study conducted by Ginestet & Camacho (2007) and could be attributed to the low sludge yields in attached growth processes – a well established advantage of the attached growth process. The development of the biofilm within the reactors was not monitored during this study due to the limited access to the biofilm media in the reactor tanks at the time. However, analysis of the biofilm from different locations within both reactors is now being carried out in a separate study.

Due to the employment of no moving parts except for those in the hydraulic pumps and motorised valve, maintenance was kept to a minimum. During this 100-day study, probe cleaning was the only maintenance required to ensure that the readings from the DO, ORP and pH sensors were not influenced by biofilm growth. Pumps are usually maintained on a bi-annual basis or when required. However, in discussions with various contractors and local authorities, the requirement of only maintaining pumps has been highlighted as a major advantage when compared to other technologies.

CONCLUSIONS

Throughout this 100-day full-scale study at the NUI Galway Water Research Facility, the PFBR has been shown to offer a viable solution to the issues surrounding de-centralised wastewater treatment. The PFBR was easily operated and maintained with relatively low running costs. Despite being a difficult wastewater, average maximum BOD_5, TSS and NH_4-N removals of 94, 86 and 80% were achieved, respectively, at a maximum media surface area organic loading rate of 2.3 g BOD_5/m^2 d, with an estimated sludge yield of 0.13 g TSS/g $COD_{t\ removed}$.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support received from the Irish Environmental Protection Agency under the STRIVE initiative, Galway County Council and Enterprise Ireland.

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First received 25 January 2011; accepted in revised form 12 April 2011