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Operation of an integrated algae pond system for the treatment of municipal sewage: a South African case study

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ABSTRACT

Integrated algae pond systems (IAPS) combine the use of anaerobic and aerobic bioprocesses to effect sewage treatment. In the present work, the performance of IAPS was evaluated to determine the efficiency of this technology for treatment of municipal sewage under South African conditions. Composite samples were analysed over an 8 month period before and after tertiary treatment. Spectrophotometric assays indicated that the treated water from this IAPS was compliant with the discharge limits for phosphate-P, ammonium-N and nitrate/nitrite-N, and mean values were: 5.3, 2.9 and 12.4 mg L^{-1}, respectively. Chemical oxygen demand (COD), however, fluctuated significantly and was dependent on full function of the IAPS. Mean COD of the final treated water was 72.2 mg L^{-1}. Although these results suggest that the treated water discharged from this IAPS operating under South African conditions meets the standard for discharge, mean total suspended solids (TSS) was routinely above the limit at 34.5 ± 13 mg L^{-1} and faecal coliforms were higher than expected. Tertiary treatment using a maturation pond series (MPS), slow sand filtration (SSF), or a controlled rock filter (CRF) ensured that the final treated water from the IAPS was of a quality suitable for discharge to the environment with CRF > SSF > MPS.

Key words | Integrated algae pond system (IAPS), sewage, tertiary treatment

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INTRODUCTION

Sewage and industrial pollution of water in South Africa pose risks to human and environmental health through the dispersal of waterborne pathogens, and toxic organic and inorganic molecules. At present greater than 80% of South Africa's sewage treatment works are in disrepair, underperform or are overloaded. A rapid implementation of robust, easy to deploy and operate sewage treatment technologies is urgently required. Furthermore, climate change together with reduced water availability has major food security implications for South Africa, its neighbours and other arid, water-poor countries. These two factors alone have profound management implications for both government and business. Correct implementation and management of integrated algae pond systems (IAPS) developed for South African conditions can produce clean water for recycling and reuse (Rose *et al.* 2002), provide energy and generate a biomass suitable for valorization (Green *et al.* 1995a; Oswald 1995; Grönlund *et al.* 2004; Park *et al.* 2011; Craggs *et al.* 2012). Even so, and as with any treatment technology, there is an element of risk and/or failure to render a suitably treated final effluent.

The primary goal of the South African National Waste Management Strategy (NWMS) is the achievement of the objectives of the Waste Act, which are, in summary: (1) minimizing pollution, environmental degradation and the consumption of natural resources; (2) implementing the waste hierarchy; (3) balancing the need for ecologically sustainable development with economic and social development; and (4) promoting universal and affordable waste services (Republic of South Africa Waste Act 2008). Framed within the context of the overall goals, approach and regulatory model of the NWMS, implementation of a novel technology for the treatment of sewage demands that the final effluent meet General Authorizations in

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terms of Section 39 of the Water Act (Republic of South Africa Water Act 1998) for discharge into a water resource that is not a listed water resource, and comply with the General Limit Values which are: faecal coliforms (per 100 mL) ≤1,000; pH 5.5–9.5; ammonia nitrogen ≤3 mg L^{-1}; nitrate/nitrite nitrogen ≤15 mg L^{-1}; *ortho*-phosphate ≤10 mg L^{-1}; electrical conductivity (EC) 70–150 mS m^{-1}; and chemical oxygen demand (COD) ≤75 mg L^{-1} (after removal of algae). Performance monitoring data for IAPS as a sewage treatment technology in South Africa are therefore needed not only to inform and educate through dissemination but also to develop a roll-out strategy for implementation of full-scale commercial plants.

Prior research focused on the four component ponds of the IAPS as standalone processes and the optimization of each but did not address performance of the system as a whole (Rose *et al.* 2002, 2007). As a consequence, there exists the perception that the treated effluent from IAPS does not meet the final COD and total suspended solids (TSS) concentrations due, in part, to suspended algae moving over the weir of the algae settling ponds (ASP). In fact, a recent report on the operation of hectare-scale high rate algae oxidation ponds (HRAOP) for enhanced waste water treatment strongly advocated additional treatment of the outflow from ASP by polishing to meet specific discharge standards (Craggs *et al.* 2012). These authors recommend the inclusion of one or a combination of maturation ponds (MP) and UV treatment by storage prior to discharge, or rock filtration of the MP effluent, or direct UV treatment if insufficient land is available and, if funds are available, membrane filtration to achieve a high quality final effluent for re-use. Clearly, there is therefore a need to establish an appropriate tertiary treatment unit (TTU) for implementation with IAPS and which compliments the low cost, environmental aspect of this sewage treatment technology. Despite concerns and in an effort to redress prevailing oversight, studies were initiated to examine the water quality of the final effluent from an IAPS treating municipal sewage. In this paper, we report on the operation of an experimental IAPS treating municipal sewage, the quality of the treated water, and on the contribution of various tertiary treatment processes used to polish and enhance water quality prior to discharge.

MATERIALS AND METHODS

IAPS configuration and operation

The IAPS used in this study is located at the Institute for Environmental Biotechnology Rhodes University (EBRU), adjacent to the Belmont Valley Waste Water Treatment Works (WWTW) (33° 19′ 07″ South, 26° 33′ 25″ East) and operates continuously to treat 75 m^3 d^{-1} of municipal sewage; a schematic showing the operating configuration and process flow is presented in Figure 1. The complete system comprises an advanced facultative pond (AFP) with surface area of 840 m^2 containing a single in-pond digester (IPD) or fermentation pit (225 m^3), two 500 m^2 HRAOP and two algal settling ponds (ASP). Upflow velocity in the fermentation pit is maintained at 1–1.5 m d^{-1} while hydraulic retention times (HRTs) in the fermentation pit and AFP are 3 and 20 d, respectively. Screened raw sewage is sourced directly from an off take immediately after the inlet works and enters the system via the IPD, where suspended and dissolved solids are

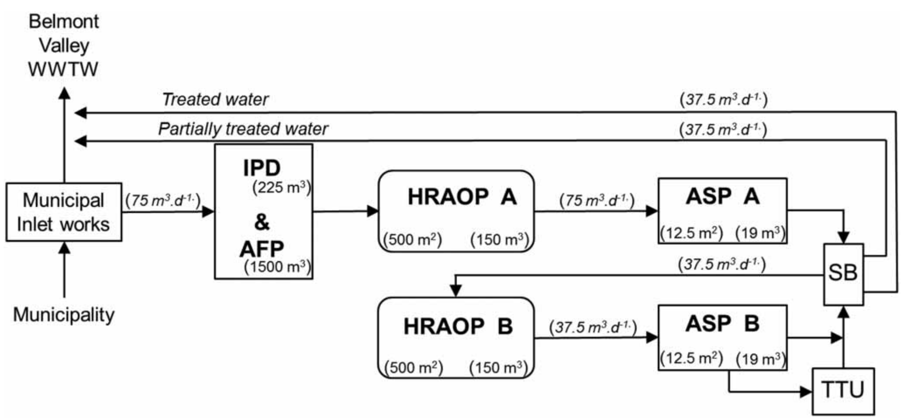

Figure 1 | Process flow and configuration of the experimental IAPS located at the Belmont Valley WWTW. The system receives raw sewage, screened for the removal of plastics via a grit or detritus channel. Pond and reactor surface area, volume, and flow rates are shown in parentheses. Effluent enters at the bottom of the IPD some 6 m below water level. SB = splitter box; TTU = tertiary treatment unit.

anaerobically degraded. Effluent then flows into the buffering AFP and is detained for 20 d before gravitating to the first HRAOP which has HRT of 2 d and then to an ASP for half a day. Mixing, or turbulent flow, is essential to maintain optimum conditions for maximum algae productivity in the HRAOPs, and in the current system is 0.15 m s^{-1}. Typically, linear velocity is required to prevent stratification and is achieved using paddle wheels powered by a small electrical motor (0.25 kW). Due to the configuration of the pilot demonstration and in accordance with original design parameters (Rose *et al.* 2002), partially treated water from the first ASP is pumped to the second HRAOP where it is detained for 4 d before release to the second ASP, where the bulk of suspended algae biomass is removed by sedimentation prior to tertiary treatment and eventual discharge of the treated water.

Tertiary treatment systems

For the purposes of the present study, three tertiary treatment processes were configured in parallel and investigated to determine water polishing efficacy. A maturation pond series (MPS), slow sand filtration (SSF), and a controlled rock filter (CRF) were plumbed to receive effluent from the IAPS immediately after separation of the algae biomass by passive settling in the ASP. These TTUs were allowed to equilibrate for a period of 4 weeks prior to commencement of sampling of the respective final effluents and water analysis.

Three MPs were used and were configured in series. MP 1 was constructed with a water depth of 1 m, from an inlet set at 1.2 m, to prevent water overflow and increase UV light penetration. As stated by Pearson *et al.* (1995), positioning and depth of inlet and outlet pipes tends to be more important for effluent quality and treatment competence than pond geometry itself. A retention time of between 10 and 20 d is sufficient for faecal coliform removal to levels less 1,000 MPN per 100 mL (Craggs 2005). Thus, a total retention time across the MPS was, based on flow rate, configured to 12 days, i.e. 4 days in each pond. MP 1 was constructed using PVC lining (5 × 1.2 m) which was supported by steel fencing on the outside. The baffle, also of PVC lining was supported at the bottom by a weight to allow water flow under the baffle. MP 2 and MP 3 were 1 m^3 plastic containers equipped with an identical baffle system, and the systems were plumbed using 15 mm piping. HRT and flow through the MPS was constrained by the size of the receiving unit(s). Thus, the first MP with area 19.63 m^2 and depth 1.02 m, allowed for a holding volume of ~20 m^3. Using the expression:

$$A = Q \cdot \theta m1/D$$

where A = area (m^2); Q = influent flow (m^3/day); $\theta m1$ = retention time (days); and D = depth, the flow rate to MP 1 was 4.9 m^3 d^{-1}, with both MP 2 and MP 3 receiving effluent at a flow rate of 0.2 m^3 d^{-1} to give an HRT of 12 d.

SSF was achieved using a 1,500 L JoJo® tank (1.5 × 1 m internal diameter) containing a 0.2 m layer of gravel covered by Geofabric (BIDIM®), followed by a 0.5 m layer of river sand covered in Geofabric and a head of water increasing to 0.8 m. A high water head pressure was required to overcome the effect of the Schmutzdecke (biofilm) which can cause clogging and decrease water flow into and through the system (Massmann *et al.* 2004). Thus, and according to recommendations (McNair *et al.* 1987), two SSFs were constructed in parallel – one in operation while the second was cleaned (scraping the biological layer from the surface of the sand). HRT and flow through the SSF were constrained by size and with area 0.785 m^2 and volume 1.18 m^3, a hydraulic loading rate (HLR) of ~1.3 m·d^{-1} was possible.

A CRF was constructed using three plastic containers connected in series, each measuring 1.0 × 1.0 × 1.0 m and containing a 0.8 m layer of gravel (average particle size of 15–22 mm) as defined by Hussainuzzaman & Yokota (2005). The inlet pipe (15 mm i.d.) was positioned at the base of the CRF to ensure water upflow into the filters and system performance (Middlebrooks *et al.* 2005). Flow rate into the CRF was 0.5 m^3 d^{-1} with HLR of ~1.5 m d^{-1}.

Water sampling and analysis

Composite sample collection was carried out weekly over an 8 month period in the summer from September 2012 to May 2013, during which the mean daily maximum and minimum temperatures were 24 ± 6 and 11 ± 4°C, respectively. Secondary and tertiary treated water was collected at intervals spanning 24 h from points of discharge from both the IAPS and each of the three TTUs (i.e. MPS, SSF and CRF), thoroughly mixed and a 500 mL subsample abstracted. EC and temperature were measured immediately using an EC Testr 11 Dual range 68× 546,501 m (Eutech Instruments, Singapore), while dissolved oxygen content was determined using a Eutech DO 6+ meter (Eutech Instruments, Singapore). The pH was measured using a Hanna HI8 424 microcomputer pH meter (Hanna Instruments, Woonsocket, RI). Total suspended solids were measured according to APHA (1998) and nutrient analyses carried out according to the manufacturer's instructions using nitrate, phosphate, ammonium, sulphate and COD test kits purchased from Merck Chem. Co., Darmstadt, Germany. A Thermo Spectronic Aquamate spectrophotometer (ThermoFisher Scientific, Waltham, MA) was used to interpolate values for the final concentrations from the respective limit curves. Whatman No. 2 filter paper with a 8 μm pore size was used to derive $COD_{filtered}$ values. Microbial analyses were carried out using MacConkey and m-Fc agar (BIOLAB CHEMICALS CC, South Africa) prepared according to the manufacturer's instructions. Petri dishes were spread-plate inoculated using 100 μL aliquots of treated water and incubated at 30 and 45°C, respectively, for 24 h prior to estimation of colony forming units (CFUs).

RESULTS

Composite sampling was used to ensure that the values for the measured parameters were indeed thorough and comprehensively derived indicators of system performance. Sampling was at weekly intervals over an 8 month period and analysis of the physical, chemical and microbial characteristics of the treated water revealed the trends illustrated in Figures 2–5.

Figure 2 summarizes the physicochemical characteristics of the treated water after passage of municipal sewage through the IAPS process. Both DO and EC were in accordance with the General Authorization for discharge to a water course (Figures 2(a) and 2(b)) whereas pH was routinely near or slightly above the upper limit (Figure 2(a)).

Figure 3 presents the time course of change in TSS and COD (after removal of algae, i.e. $COD_{filtered}$) in the treated water from the IAPS. In addition, data for rainfall events were captured in an effort to account for any dilution effect on soluble COD and TSS concentration. Rainfall did not appear to have any significant impact on COD while values for TSS were reduced (Figure 3(b)). Thus, there appears to be an interrelationship between precipitation events and TSS of treated water at point of discharge from IAPS, presumably as a result of dilution. For discharge of treated water to a water course according to South African regulations, the TSS should not exceed 25 mg L^{-1}. As shown in Figure 3(b), extreme fluctuations in TSS were evident for treated water from the IAPS with minimum and maximum values of 5 ± 1 and 90 ± 9 mg L^{-1}, respectively, and a mean for the 8 month period of 34.5 ± 13 mg L^{-1}.

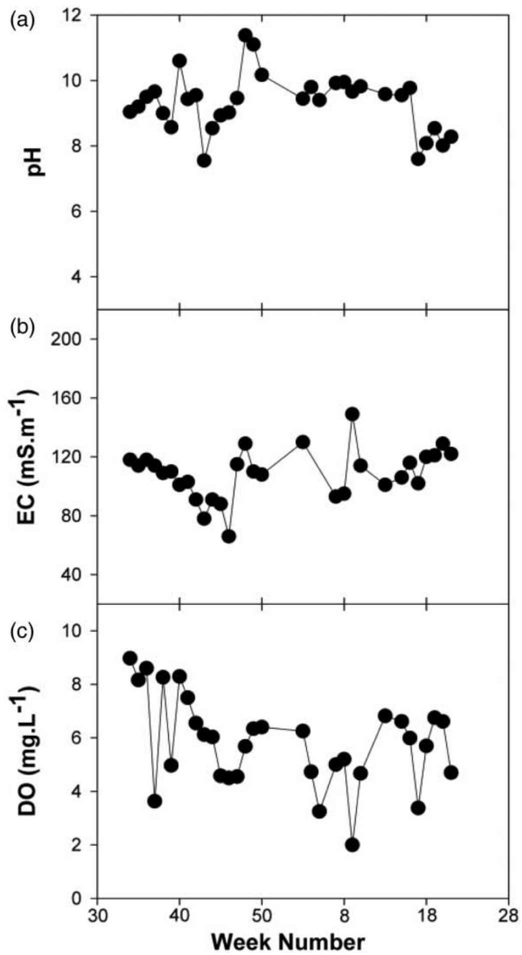

Figure 2 | Physicochemical characteristics of water following sewage treatment using an IAPS. (a) pH, (b) EC, and (c) dissolved oxygen (DO) were determined for composite samples collected weekly for 24 h over a period of 8 months. Data presented are the average of duplicate measurements.

Following removal of algae by filtration the $COD_{filtered}$ of the IAPS-treated water fluctuated from a minimum of 46.7 ± 6 mg $L^{-1}$to a maximum of 98 ± 3 mg L^{-1} (Figure 3(c)) and yielded a mean $COD_{filtered} = 72.2 \pm 13$ over the 8 month period of analysis indicating that the effluent generated by this method of municipal sewage treatment does not consistently comply with the General Authorization and that a tertiary treatment process is required to further polish the treated water prior to discharge.

Nutrient removal efficiency of the IAPS was determined by analysing the ammonium-N, nitrate-N and phosphate-P concentration in composite samples abstracted weekly from the final effluent stream, and the results are shown in Figure 4. Aside from some initial noise in the data (scatter), water treated by the IAPS during the 8 month period of monitoring appeared to comply with the General Authorization standard for environmental discharge for phosphate-P, nitrate-N and

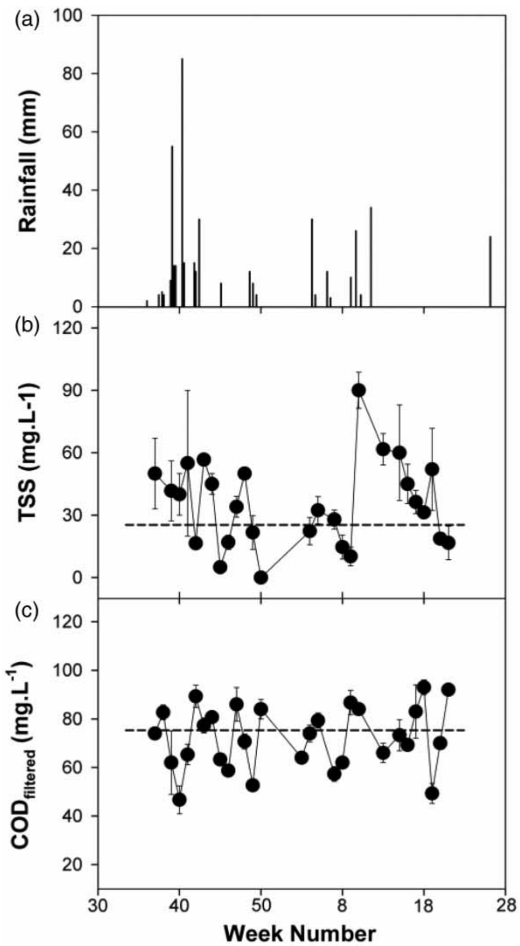

Figure 3 | Relationship between rainfall events and TSS and COD of treated water from the IAPS at point of discharge. (a) Precipitation was recorded weekly and, (b) TSS and (c) COD ($COD_{filtered}$) were determined for composite samples harvested weekly over a 24 h period for 8 months. Stippled line indicates the General Limit Values for TSS and $COD_{filtered}$. Data presented are the average of duplicate measurements.

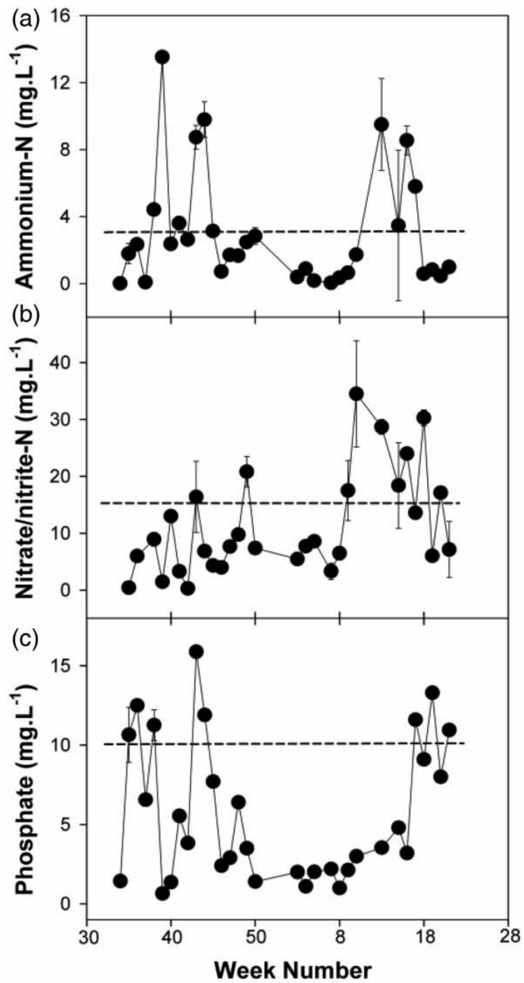

Figure 4 | Nutrient content and composition of treated water from the IAPS at point of discharge. (a) Phosphate, (b) nitrate/nitrite-N and (c) ammonium-N concentrations in composite samples harvested weekly over a 24 h period for 8 months were determined using test kits as described in the 'Materials and methods' section. Stippled line indicates the General Limit Values for each parameter. Data presented are the average of duplicate measurements.

ammonium-N (Figures 4(a)–4(c)). Indeed, calculation of the mean values (±standard deviation) for all determinations in the sampling window indicates that the final effluent from the IAPS routinely contained phosphate-P $= 5.3 \pm 2$, nitrate/nitrite-N $= 12.4 \pm 4$ and ammonium-N $= 2.9 \pm 1$ mg L^{-1} (Table 1).

Figure 5 shows the total faecal coliform count in the final effluent from the IAPS. After week 3 (2013), there was a dramatic increase in CFUs in the treated water, caused by short circuiting due to incorrect positioning of the inlet pipe from ASP A. Consequently, partially treated water from HRAOP A was not detained in HRAOP B for sufficient time to allow for disinfection. However, following correct positioning of the inflow, CFUs of coliforms returned to levels acceptable for discharge. Thus, disinfection is dependent upon full function and correct operation of IAPS.

Table 1 presents the mean values for all data collected to determine water quality of the final effluent from the IAPS in relation to the General Authorization standards for discharge to a water course and compares these data to those obtained after passage of the effluent through three different TTUs. Clearly, water quality of the final IAPS effluent does not fully comply with the required limits for discharge. Tertiary treatment was carried out in parallel using an MPS, SSF and CRF and, although each unit received a fraction of the total IAPS final effluent, indications are that CRF and SSF were the more effective water polishing methodologies. This, coupled with an apparent lower land

Table 1 | Summary data on water quality of the effluent from the IAPS before and after tertiary treatment either by an MPS, SSF, or CRF. Also shown are the General Authorization limits for discharge to a water course (DWA 2010). Data for effluent quality were determined on a per week interval over a period of 8 months

		Water quality of final effluent			
Parameter	**General Authorization limit**[a]	**IAPS**	**IAPS + MPS**	**IAPS + SSF**	**IAPS + CRF**
pH	5.5–9.5	9.4 ± 1	9.9 ± 0.5	8.3 ± 0.7	8.0 ± 0.4
Dissolved oxygen (mg L^{-1})	>2	5.5 ± 1	13.5 ± 3.6	6.0 ± 2.5	12.6 ± 1.4
EC (mS m^{-1})	70 mS m^{-1} above intake to a maximum of 150 mS m^{-1}	107.8 ± 19	94.5 ± 47.1	95.4 ± 48.3	100.1 ± 12.6
COD (mg L^{-1})[b]	75	72.2 ± 13	72.0 ± 10.1	59.3 ± 12.2	62.1 ± 4.4
Nitrate/nitrite-N (mg L^{-1})	15	12.4 ± 4	4.0 ± 1.9	6.7 ± 2.5	5.1 ± 1.7
Ammonium-N (mg L^{-1})	3	2.9 ± 1	0.5 ± 0.5	2.3 ± 0.9	0.3 ± 0.1
Phosphate (mg L^{-1})	10	5.3 ± 2	4.3 ± 1.7	1.4 ± 0.6	0.5 ± 0.2
TSS (mg L^{-1})	25	34.5 ± 13	22.1 ± 12.3	19.3 ± 8.5	19.5 ± 9.8
Total coliforms (CFU 100 mL^{-1})	1,000	>1,000	<1,000	<1,000	<1,000

[a]General Authorizations in terms of Section 39 of the National Water Act (Republic of South Africa Water Act 1998).
[b]After removal of algae.

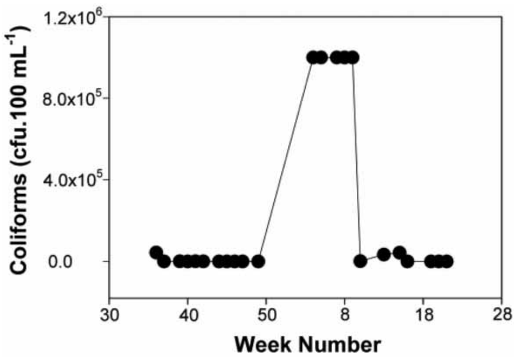

Figure 5 | Estimation of faecal coliforms in treated water from the IAPS at point of discharge. Composite samples were harvested weekly over a 24 h period for 8 months. Data are the mean of three independent determinations.

requirement suggests that these two tertiary treatment processes might be appropriate for use in combination with IAPS although other tertiary treatment processes such as a constructed wetland or reed beds still need investigation.

DISCUSSION

IAPS as a sewage treatment technology is a derivation of the Algae Integrated Wastewater Pond System (AIWPS®) developed by Oswald, who is credited as the pioneer of algae pond technology (Ludwig *et al.* 1951). Oswald initially focused on the relationship between algae and bacteria in sewage treatment (Oswald *et al.* 1955). Later, he coined the term photosynthetic oxygenation (Oswald *et al.* 1957) and used this concept to describe the aeration effect caused by algae on treated water (Ludwig *et al.* 1951; Ludwig & Oswald 1952; Oswald *et al.* 1953, 1955). By 1957, Oswald had established the HRAOP which amalgamated sewage remediation via biological oxygenation and nutrient removal (Oswald *et al.* 1955, 1957), and which eventually led to the fully developed AIWPS® (Oswald *et al.* 1957).

The IAPS used in this study is similar in design to Oswald's 'AIWPS® Secondary Process', which typically produces a final effluent that does not comply with environmental discharge standards (Green *et al.* 1995b) and was designed and constructed without final polishing, e.g. a maturation pond. Thus, and at best, the final effluent generated by this IAPS can only be described as a 'secondary treated' water. It may seem surprising that a demonstration IAPS would be commissioned that did not produce an effluent compliant with standards. However, the IAPS pilot in question was configured as an aside to the Belmont Valley WWTW and commissioned for research and demonstration purposes only, with raw sewage sourced directly from an off take immediately after the inlet works and the final treated water discharged via the municipal WWTW to MP, and the detail of its implementation and operation are recounted elsewhere (Mambo *et al.* 2014).

The present study was carried out to evaluate IAPS as a technology for municipal sewage treatment and to determine whether the quality of the treated water was of a standard suitable for discharge to the environment. Results confirm (as might have been expected) that water quality of the IAPS final effluent operated under the conditions used, which are according to original design specifications (Rose *et al.* 2002), does not meet the standard for discharge in terms of both TSS and COD. Even so, levels of nitrate/nitrite-N, ammonium-N and phosphate-P, and DO and EC are all within the General Authorization limits (Republic of South Africa Water Act 1998).

Apoptosis, the commonest phenotype of programmed cell death (PCD), has recently been elegantly demonstrated in microalgae and shown to cause the release of organic nutrients which are used by others in the population as well as co-occurring bacteria for growth (Orellana *et al.* 2013). As determined by these authors, a significant proportion of the algae population ($55\% \pm 15$) can undergo PCD at night after daytime growth. It is distinctly possible therefore that the elevated TSS and COD of water from an IAPS is due to algal PCD in the HRAOP and ASP, suggesting that settled algae be removed as quickly as possible. Furthermore, the incorporation of an appropriate TTU (i.e. MPS, SSF or CRF) to consistently reduce levels of both TSS and COD will allow for discharge to a water course. From the present study, CRF was more effective than either an MPS or SSF. Land availability notwithstanding, it is recommended that either CRF or SSF be further explored for possible incorporation as part of the design and process flow of IAPS destined for the commercial scale treatment of municipal sewage.

Disinfection remains a major concern and faecal coliform count increased during the course of sampling which negatively impacted the quality of the treated water produced by the IAPS. This is perhaps not unexpected considering system design and strongly supports the conclusion by Craggs *et al.* (2012) that additional treatment of the algae harvester effluent (i.e. outflow from the ASP) requires polishing to meet specific discharge standards. Furthermore, and during the course of the present investigation, short circuiting caused by incorrect influent pipe positioning into HRAOP B aggravated the coliform count. Once pipe placement was rectified there was a dramatic decline in coliforms present in the final effluent from week 13 onwards emphasising the disinfection potential of HRAOP B. Thus correct configuration and operation of the IAPS at all times is vital for effective waste water treatment.

In conclusion the work described here set out: (1) to determine the water quality of the IAPS effluent over an extended operating period; (2) to demonstrate compliance with the South African General Limit Values for discharge of up to 2,000 m^3 of waste water on any given day into a water resource that is not a listed water resource; and (3) to evaluate the contribution of tertiary treatment on levels of $COD_{filtered}$ and TSS in the treated water. Notwithstanding several design and operational constraints, it is concluded based on the presented data that:

- physicochemical characteristics including pH, DO and EC of the IAPS effluent comply with the General Limit Values for discharge, and that introduction of tertiary treatment to further reduce both TSS and $COD_{filtered}$ is essential;
- nutrient characteristics of the IAPS effluent comply with the General Limit Values for discharge and that addition of tertiary treatment will ensure that phosphate-P, nitrate/nitrite-N and ammonium-N concentrations are routinely below the limit values of 10, 15 and 3 mg L^{-1} respectively;
- a reduction in faecal coliforms in the treated water to comply with the General Limit Values for discharge is guaranteed only when the system is correctly operated (i.e. correct retention of the effluent in HRAOP B) and with an appropriate TTU.

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