THE WEALTH IN BREWERY EFFLUENT – WATER AND NUTRIENT RECOVERY USING ALTERNATIVE TECHNOLOGIES

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ABSTRACT

High rate algal ponding (HRAP) and constructed wetland (CW) technology was used to remove nutrients from brewery effluent, thus recovering water and producing algal biomass. The HRAP/CW system was effective in reducing chemical oxygen demand (COD) from ca. 150 mg/L to below 75 mg/L, and ammonia from 30 mg/L to below 1 mg/L. The HRAP was initially inconsistent in phosphate removal, but phosphate levels within discharge standards were achieved in the combined HRAP/CW system. The HRAP/CW system was ineffective at removing chloride from the effluent, which persisted at levels of 200-500 mg/L. Hydraulic retention time in the HRAP was reduced from 13 to 3.8 days by optimising flow rate for maximal ammonia removal. The HRAP/CW was highly resilient to variations in effluent quality. The recovered water was successfully used to produce hydroponic lettuce and fish, and harvested algae were made available for potential use as a fish feed ingredient.

KEYWORDS

Algal ponding; constructed wetland; beneficiation; industrial effluent remediation

INTRODUCTION

Effluent disposal is an increasingly costly liability for industry. Breweries produce a substantial effluent stream, rich in organic matter originating from the brewing process. In some breweries this is sent to municipal sewage works after reduction of chemical oxygen demand (COD) by means of anaerobic digestion. South Africa's largest brewer, The South African Breweries (SAB) Ltd, uses about 10.5-million m^3 of water per annum at one of its breweries, and approximately 70 % of this is discharged as waste water. This effluent is typically treated at a cost to industry and usually off-site so the option of reuse is often not available. Technologies, such as high-rate algal ponds (HRAP) and constructed wetlands (CW) offer an alternative to conventional treatment methods and, due to their low-tech nature, can be operated on-site which makes recovered water available for reuse. The aim of our research was to adapt HRAP and CW systems to recover water, culture single cell algae in the process, and demonstrate the potential for downstream reuse in aquaculture and hydroponics systems.

This work was carried out in partnership with SAB Ltd at the Ibhayi Brewery near Port Elizabeth. SABMiller Ltd is implementing a comprehensive set of sustainability objectives which include: working towards zero waste operations; making beer with less water (the group average is 4.56 L water per litre of beer); and reducing its energy and carbon footprint (currently 12.7kg CO_2/hL beer). The unique aspect of the project was the sequencing and integration of effluent treatment technologies, which resulted in a novel approach to the way industrial effluent was processed and a novel approach to the way constituents were made available for reuse and beneficiation.

MATERIALS AND METHODS

Experimental system

The integrated algal ponding system (IAPS) included the brewery's existing anaerobic digester (AD), and a research-scale primary facultative pond (PFP; 17 m^3), two series of HRAP systems (5.4 m^3 per series) and a CW. Brewery effluent was anaerobically digested by consortia of bacteria in the AD, which broke down complex organic molecules into CO_2 and methane. This reduced the effluent's chemical oxygen demand (COD) and re-mineralised nitrogen and phosphorous locked up in the organic-rich waste. The effluent water was gravity fed from the AD into the PFP where a broad spectrum of bacterial activity and opportunistic algal growth took place further reducing the organic load of the effluent stream. The effluent stream left the PFP via a splitter box where it was divided into two even steams, which pass into one of two HRAP systems where most of the algal assimilation took place (Figure 1A). Treated effluent left the HRAP by gravity into a sump (i.e. post-IAPS) where it was stored prior to being introduced into the constructed wetland (CW; Figure 1B). Post-CW effluent was then used as a water source for aquaculture (i.e. fish production) or hydroponics (i.e. vegetable production) and the algae is harvested and used as a feed ingredient for pelleted fish feed.

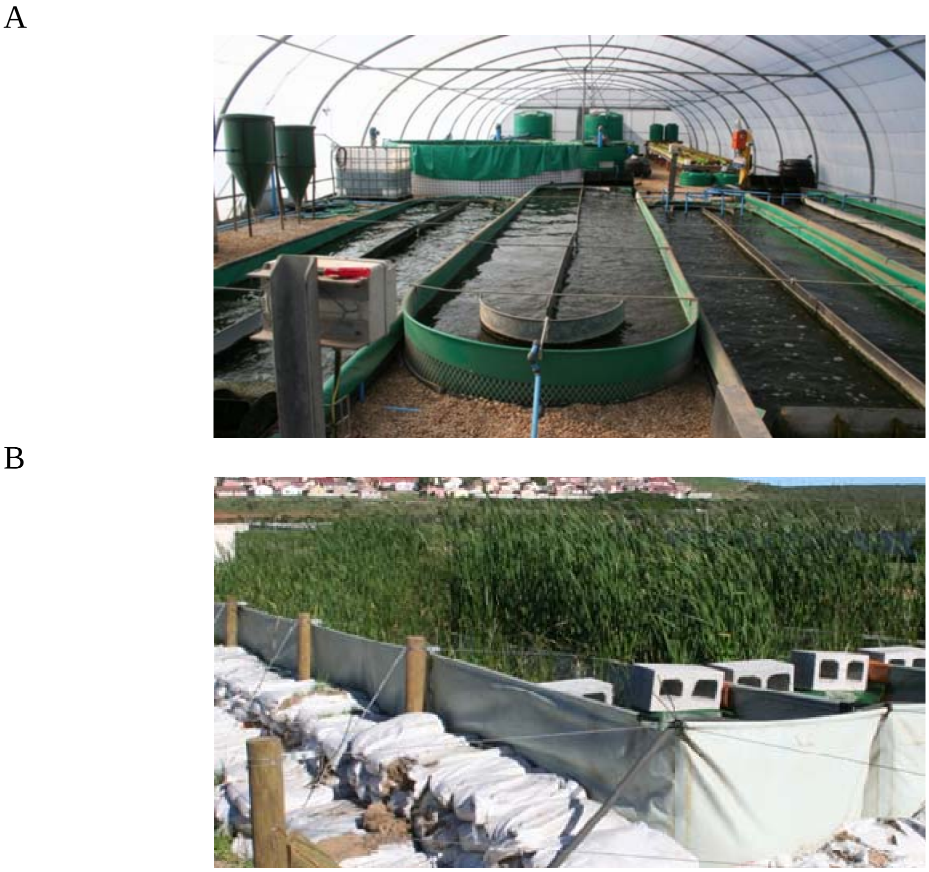

Figure 1 (A) The high rate algal ponding system with primary facultative pond, and hydroponic system in the background and (B) the constructed wetland.

The aquaculture system was divided into two separate systems, each with eight tanks (0.56 m^3 $tank^{-1}$), a vortex clarifier (2.5 m^3), a mechanical bead filter, a biological filter (3.5 m^3) and circulated with an electronic pump (1.1 kW). One of the systems was run using a conventional, municipal water source and the second used treated brewery effluent. There were also two hydroponic systems, each with a sump (500 L) a header tank (260 L) and four separate growing bays (12 m bay^{-1}). One of the systems was run using a conventional, municipal water source and inorganic fertiliser and the second used treated brewery effluent, supplemented with some inorganic fertiliser.

Effluent data collection

The performance of the HRAP system was monitored for one year, from May 2009 to June 2010, to determine its efficiency in reducing post-AD COD, ammonia, phosphate, and chloride concentrations. Nitrite and nitrate were also included during the course of the study. Effluent samples were taken three times a week post-AD, post-PFP and post-HRAP. They were measured spectrophotometrically using Selectech test-kits. The pH and temperature of the samples were measured using a Hanna hand held probe. The flow rate through the HRAP was maintained at a constant rate (480 L day^{-1}) until April 2010, when it was incrementally increased to determine the maximum flow rate the HRAP can handle without washing out the algae and maintain reducing ammonia below 3 mg/L post-HRAP. The CW (42 m^3) was included downstream of the HRAP in February 2010 to polish the final effluent and samples were measured pre- and post-CW three times a week.

The South African National Government's Department of Water and Environmental Affairs (DWEA) general limits for discharge of industrial effluent into a natural water source were used as a general bench-mark to assess the efficiency of nutrient removal of the system (DWEA [1]).

Use of treated effluent for fish and vegetable production

Mozambique tilapia *Oreochromis mossambicus* were stocked into both aquaculture systems (i.e. the system that contained treated effluent and the control) and their survival and condition was monitored. Tanks were checked daily for fish mortalities. Condition factor was calculated using Equation 1:

$$CF = W/L^3 \times 100 \qquad (1)$$

where CF is the condition factor, W is weight (g) and L is length (mm), after one month. Similarly, the growth of vegetables in both hydroponic systems (i.e. the system that contained treated effluent and the control) were compared.

RESULTS AND DISCUSSION

High rate algal pond (HRAP) and constructed wetland (CW) performance

Initially, COD levels post- HRAP were similar to those of the effluent received from the AD (Figure 2A). The high concentration of algal biomass under the slow effluent throughput regime was believed to be responsible for the persistently high COD levels; however, once HRAP flow rates were optimised and the wetland added (April-June 2010), COD levels were reduced from ca. 140 mg/L to close to or below DWEA general limit of 75 mg/L (Figure 2B). Gaigher et al. [2] observed a similar drop, reducing brewery effluent COD to around 100 mg/L using algae and macrophytes. As the DWEA COD general limit excludes the algal cell contribution to COD (DWEA [1]), the COD levels post-HRAP where reduced by a further 36 % by filtering the samples to 0.45 µm (Figure 3). Furthermore, the constructed wetland was effective in reducing COD levels by a further 25 % (Figure 2C). As the wetland matures it will probably reduce COD further since mature wetlands have been shown to reduce COD of municipal waste by 90 % (Kivaisi [4]) and 94 % (Shrestha et al. [6]) and winery effluent by 98 % (Shepherd et al. [5]).

The HRAP was highly efficient at removing nitrogen from the effluent. Ammonia entered the system at between 30 and 60 mg/L and was reduced to 0.1 – 1.0 mg/L, even at the increased flow rates through the system during April 2010 (Figure 3). The rate of ammonia removal observed here was similar to that in other work (Idelovitch & Michail [3]). There was very little variation in post-HRAP ammonia levels, indicating that the system was very resilient to changes in effluent quality, as well as seasonal effects of light and temperature. The post HRAP ammonia levels were consistently below the DWEA general discharge limit of 6 mg/L indicating that the HRAP system achieved the required water quality objective for ammonia (Figure 3A). The wetland was effective in further reducing the post-HRAP ammonia levels (Figure 3B). When the flow rate optimisation trial was conducted in April, post-HRAP ammonia levels rose to 6 mg/L in mid-April (as the algal system reached its limit; see Figure 3 wetland inlet), but the wetland remained effective in reducing the levels to well within the DWEA general limit (Figure 3).

Nitrite and nitrate were not detected in the HRAP system prior to April 2010, since the algal cells directly assimilated the ammonia and no nitrification was observed; Gaigher et al. [2] observed nitrite and nitrate levels as low 0.001 mg/L in brewery effluent treated using algal ponds. During April 2010 in the current study, however, when flow rates were increased through the HRAP and algal cells began to thin out, measurable levels of nitrite and nitrate were observed as a result of bacterial activity converting the excess ammonia to nitrite and then nitrate. The April optimisation trial showed that the wetland was highly effective in lowering the post-HRAP levels of nitrite and nitrate (Figures 4A and 4B). The levels of nitrite and nitrate leaving the HRAP and wetland never exceeded the DWEA general limit of 15 mg/L (DWEA [1]). Overall, HRAP and wetland technologies can be considered efficient at nitrogen removal from brewery effluent.

Phosphate levels in the post-AD effluent were lowered significantly by the HRAP during the autumn and spring months, but very little was removed during the winter (Figure 5). From March 2010 onwards, the phosphate levels in the brewery effluent dropped to well below the DWEA discharge general limit of 10 mg/L (DWEA [1]). The addition of the wetland in February 2010 further enhanced the capability of the system to remove phosphate; however, the efficiency of the wetland in phosphate removal cannot be quantified until phosphate is once again present in the effluent. Despite investigations into the sources of phosphate in the effluent from the brewery, the reason for its disappearance remains unknown. The average efficiency of phosphate removal from domestic and industrial wastewater by constructed wetlands is 40 % (Vymazal [7]) and phosphorus in brewery effluent was reduced by 75 % in a similar algal ponding system (Gaigher et al. [2]) which means that, should phosphate rise to previous levels, the HRAP and wetland should bring phosphate to within DWEA discharge standards.

The HRAP process and wetland were not effective at lowering either chloride or electrical conductivity, which are indicators of the amount of total dissolved salts in the effluent. Over the monitoring period, the levels of chloride and conductivity either remained unchanged, or increased through the HRAP and wetland due to evaporative losses – particularly during the summer months (Figures 6 and 7). During the winter months, and during the period of increased flow rate (April 2010), chloride and conductivity levels were effectively unchanged through the HRAP/wetland system (Figures 6 and 7). The high chloride/conductivity in the effluent may pose a problem for certain forms of water re-use, and the gradual accumulation of chloride limits 100 % water recycling. The problem could be addressed by reducing the use of chloride products in the brewing/cleaning process.

The HRAP system increased the post-AD pH from 7.4 – 8.0 to around 9.5 due to the photosynthetic activity of the algae (Figure 8A). The wetland was effective in reducing the pH to between 8.3 and 9 (Figure 8B); however, its efficiency at reducing pH has increased as the wetland has matured. It is thus possible that the wetland might reduce pH further as it matures. The DWEA discharge standard for pH is 5.5-9.5, so post-HRAP pH is largely within these limits and post-wetland effluent is already well within the limit (DWEA [1]) and similar to other studies (Gaigher et al. [2]).

High rate algal pond (HRAP) and constructed wetland (CW) effluent quality compared to that of a conventional activate sludge (AS) system

The efficiency of the brewery's activated sludge (AS) unit was compared to the high rate algal pond (HRAP) and constructed wetland (CW) for key water quality parameters. In general, the performance of the HRAP/wetland system was much more consistent (i.e. reduced range) that the AS, and for certain parameters (ammonia and nitrate) it much more efficient in reducing the overall levels to within DWEA discharge standards (Table 1). Both systems had a common effluent source, i.e. the Ibhayi Brewery anaerobic digester (AD). The AD and AS data were made available by SAB Ltd, and only data collected between 1/05/2009 to 31/03/2010 were used in this exercise in order to compare directly with HRAP performance data for the same period. In addition, data collected after the wetland was commissioned (6/04/2010 to 30/06/2010) were included.

The pH level increase in the HRAP system was higher than that of the AS system due to the photosynthetic activity of the algae. However, the mean pH after the wetland was within the DWEA general limit of 9.5 (Table 1A). Unlike the AD and AS, pH in the wetland and HRAP was not adjusted/maintained by chemical dosing. The HRAP and wetland were more effective at removing nitrate than the AS, with AS values substantially higher than the DWEA general limit for discharge into a water resource (Table 1D). The most striking differences between the AS and the HRAP/wetland system are the extreme ranges recorded in the AS, compared to the relatively narrow ranges observed in the HRAP/ wetland for all parameters (Table 1). This indicates that the HRAP/ wetland system is more stable and resilient to variations in effluent quality as well as environmental variation. Furthermore, the HRAP and wetland data included periods when HRAP system manipulations took place to determine performance limits, as well as the period when the wetland was first commissioned. This would explain the ranges in Table 1; when operating optimally, the ranges are likely to be reduced further.

Flow rate optimisation

High rate algal pond (HRAP) optimisation

During April 2010, the flow rate through the high rate algal ponding (HRAP) system was incrementally increased to determine the maximum effluent volume that it could treat. To achieve this, the flow rate was increased in one of the high rate algal pond (HRAP) systems, while the flow in the second system remained unchanged to act as a “control” for comparison. The system temperature was approximately 25ºC during this period with sunny, hot weather.

The increased flow rates (Table 2) reduced the retention time in the primary facultative pond (PFP) from 18 days to 9 days, while the retention time in the HRAP was reduced from 13.3 days to 3.8 days (Table 2). The system was pushed to 2000 L/d but it crashed and was unable to maintain low ammonia levels at this flow (Figure 9), since the algal/bacterial cells were washed out faster than they could reproduce. The optimum flow rate for the HRAP system, under this set of environmental conditions was thus 1400 L/d which is equivalent to a retention time of 3.8 days. The total time taken to treat brewery effluent through the PFP and HRAP under these current conditions was thus reduced from 31 to 13 days (Table 2 and Figure 9).

Ammonia concentration was recorded as an indicator to evaluate the success of the HRAP at increased flow rates, and was compared to that of the control HRAP. Ammonia remained well below the maximum concentration for effluent discharge into a river system, even when the flow rate was increased from ~450 L/d to ~780 and then ~1400 L/day, but the system became less efficient when increased to ~2000 L/day (Figure 9).

Constructed wetland (CW) optimisation

The wetland had only been running since the beginning of March 2010 and was subsequently still maturing, and its efficiency is likely to increase considerably. A preliminary analysis was carried out on the efficiency of the wetland between May and June 2010, where the optimal length of wetland required to reduce brewery effluent to within DWEA general limits at a flow rate of 135±8.9 L/h (n = 40; during day light hours), i.e. the average flow rate that was used between May and June 2010, was determined.

The change in pH and ammonia levelled off within 13 m of linear wetland, i.e. within one quarter of the total length of the wetland’s gravel bed (Figures 11A and 11B) with both parameters well within DWEA general limits for the discharge of wastewater into a water resource. Nitrate continued to level off down the length of the raceway at a constant rate, with almost all the nitrate removed by the end of the raceway (Figure 21C); however, nitrate levels were within DWEA general at all times. The rate of COD reduction levelled off after about 26 m, i.e. halfway down the length of the wetland (Figure 10D), at which point mean COD levels were also within the DWEA general limits.

In summary, the wetland need not be more than half of its current length to treat effluent at a rate of 135±8.9 L/h during daylight hours.

Resilience of a combined high rate algal pond (HRAP) and constructed wetland (CW) system

The main advantages of the HRAP and wetland are their robust resilience to changes in the environment, minimal human intervention and low (almost negligible) energy and carbon footprint. In over a year of continual operation (January 2009 – June 2010), the HRAP system proved highly resilient to seasonal variations, changes in effluent quality, flow rate and occasional shocks. Significantly, the HRAP system has never failed. The stability of the HRAP and wetland relies entirely on natural biological balances in these systems, and not on human intervention (e.g. chemical dosing) in response to changes in the brewery effluent. The only energy used in the HRAP is the very small load to run the paddlewheel; for both the wetland and the HRAP, the rest of the energy needed to run the system is derived directly from the sun.

The system remained stable a malfunction of automated pH adjustment system of the anaerobic digester, an unplanned word dump, and algal cell washout during the optimisation trials.

Hydroponic and fish production in treated brewery effluent

Project Eden demonstrated that the recycled brewery effluent, treated in the HRAP and constructed wetland systems, was suitable for the hydroponic culture of lettuce. There were no apparent differences in lettuce grown using conventional inorganic fertilisers and those grown in treated brewery effluent (Figure 11). Similarly, there were no mortalities in either of the aquaculture systems during the trials, i.e. 100 % survival rate in both the control and the brewery effluent treatments. There were no significant differences in the condition factor (i.e. a measure of how “fat” or “thin” a fish is) of fish cultured in the municipal water control and treated brewery effluent, with a combined mean condition factors of 1.94±0.11 (Student’s t-test; p = 0.37).

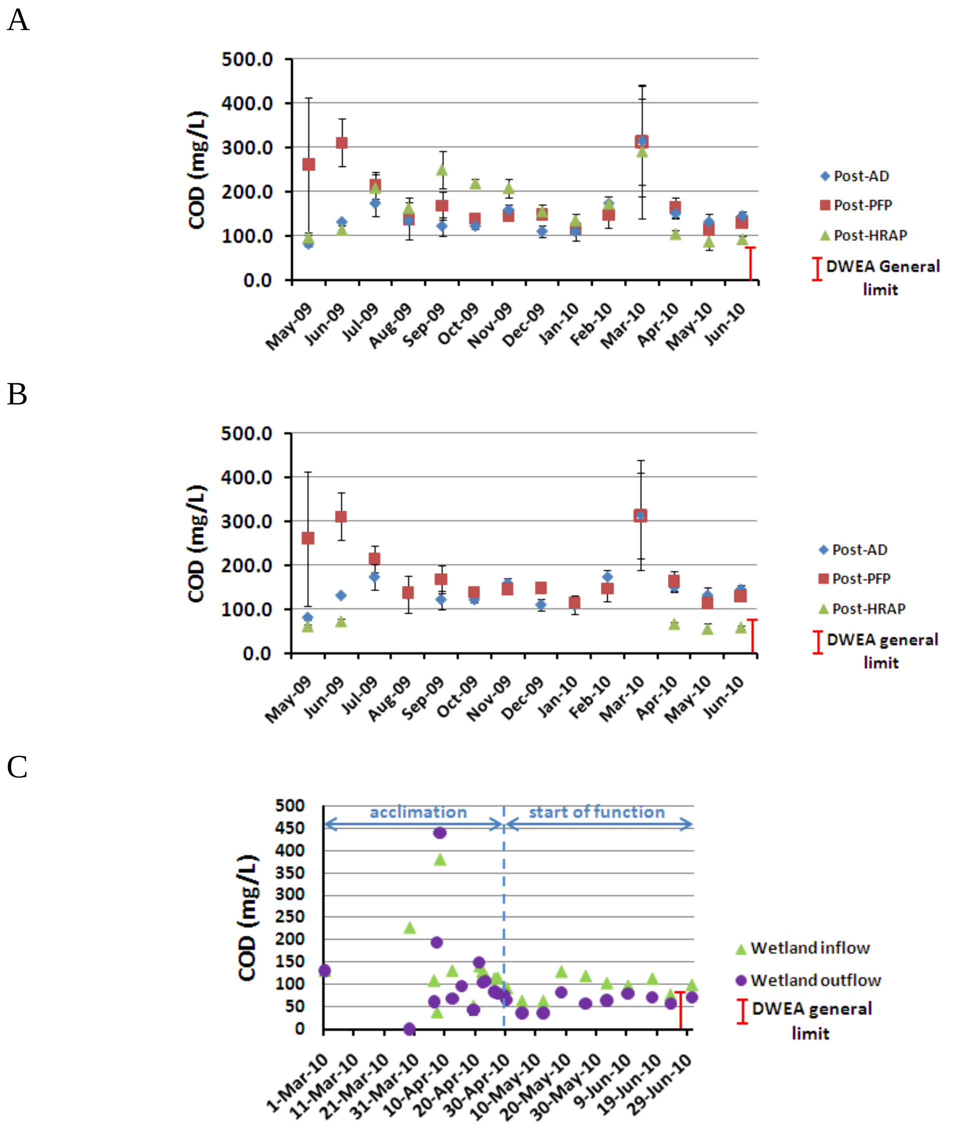

Figure 2 Mean (± standard error) monthly chemical oxygen demand (COD) of brewery effluent in the anaerobic digester (AD), the primary facultative pond (PFP), and post high rate algal ponding (post-HRAP) system filtered to (A) 8 µm and (B) 0.45 µm, and (C) COD reduction in the wetland (raw data). DWEA – Department of Water and Environmental Affairs.

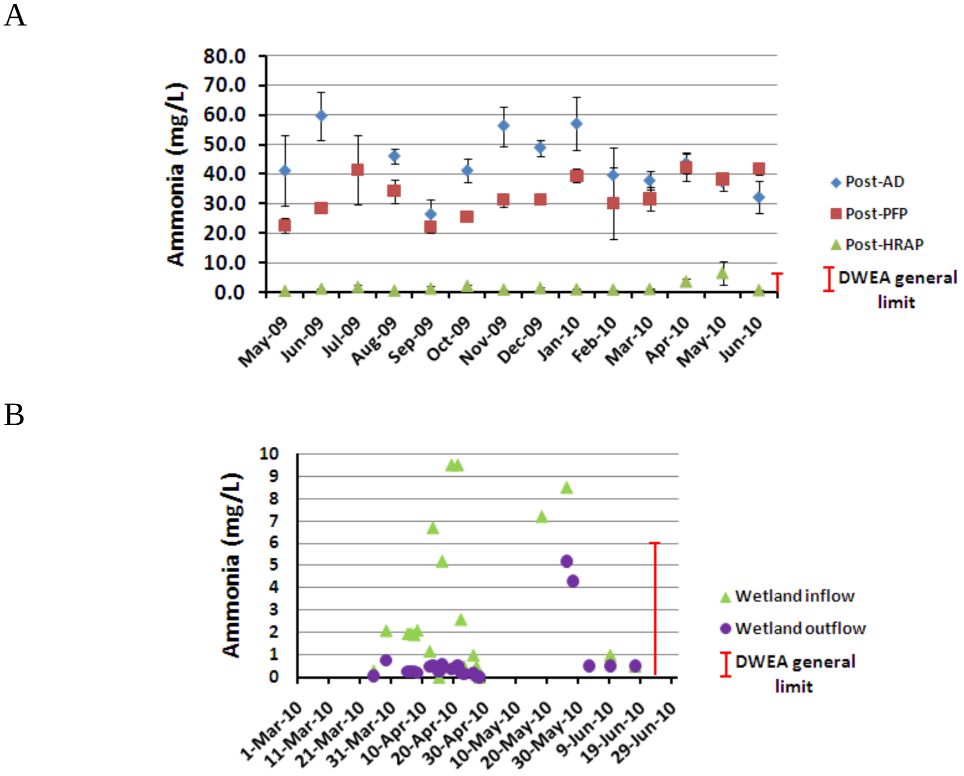

Figure 3 (A) Mean (± standard error) monthly ammonia concentration (mg/L) in treated brewery effluent post anaerobic digestion (post-AD), post primary facultative ponding (post-PFP) and post high rate algal ponding (post-HRAP) system and (B) in the constructed wetland.

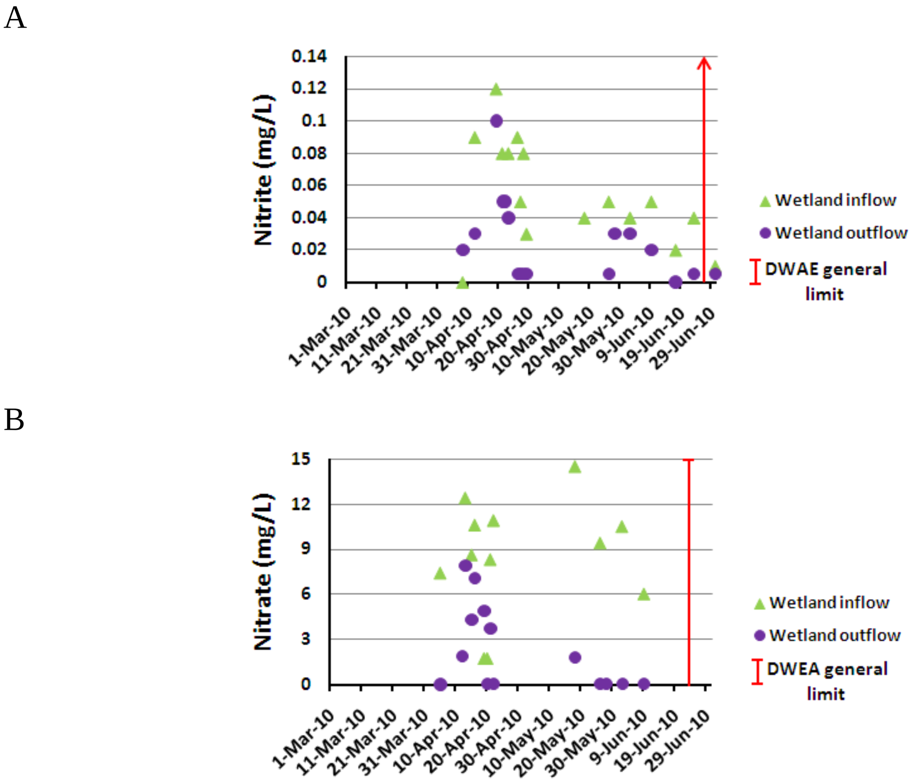

Figure 4 (A) Nitrite and (B) nitrate reduction in the constructed wetland.

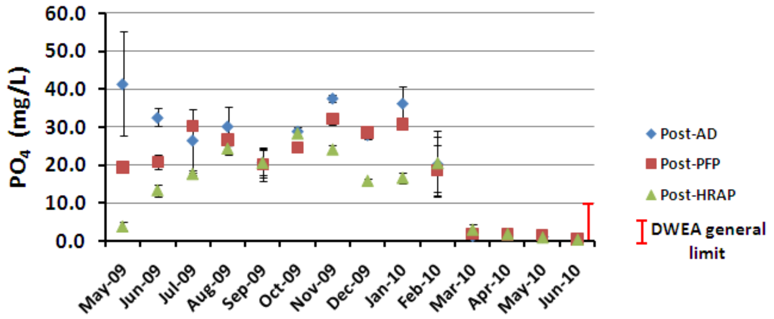

Figure 5 Mean (± standard error) phosphate concentration (mg/L) in treated brewery effluent post anaerobic digestion (post-AD), post primary facultative ponding (post-PFP) and post high rate algal ponding (post-HRAP) system.

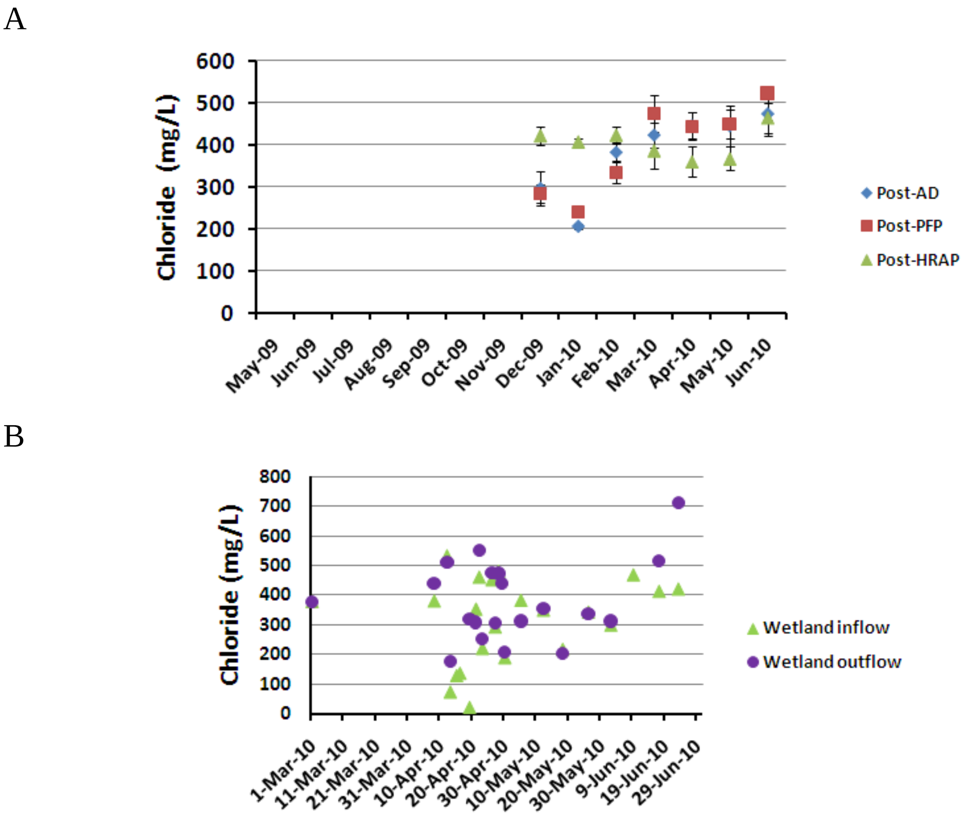

Figure 6 (A) Chloride concentration (mg/L) in treated brewery effluent post anaerobic digestion (post-AD), post primary facultative ponding (post-PFP) and post integrated algal ponding system (post-HRAP), and (B) chloride concentration in the wetland.

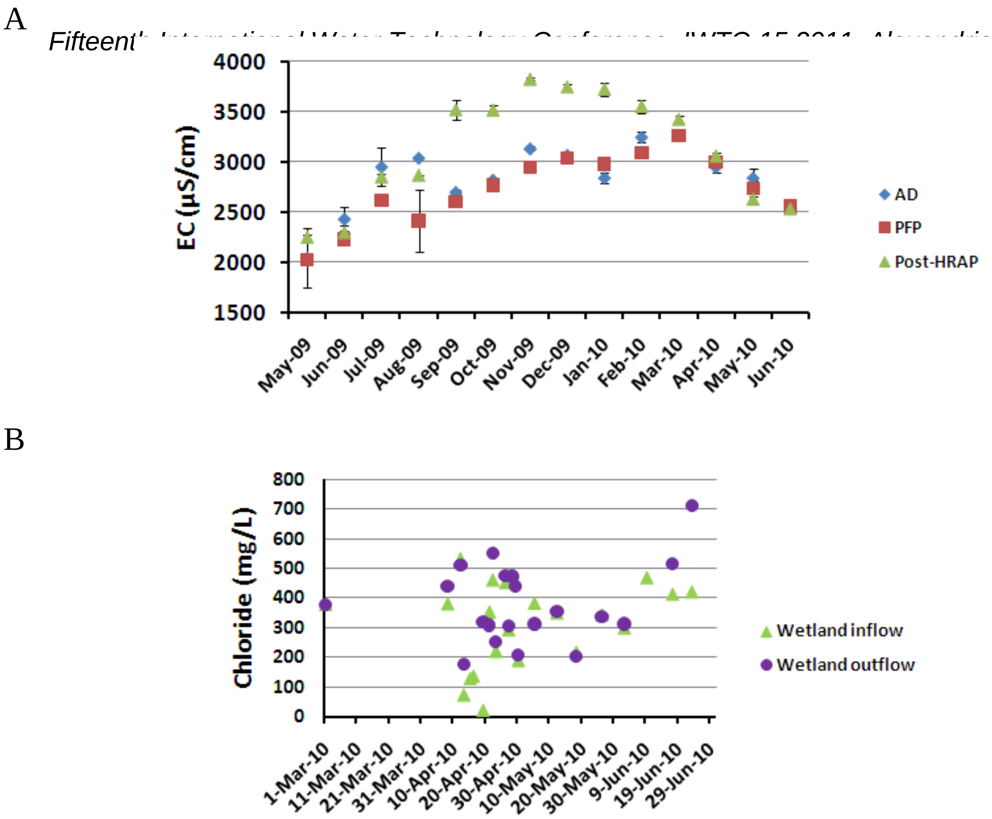

Figure 7 (A) Electrical conductivity (EC) of treated brewery effluent in the anaerobic digester (AD), primary facultative pond (PFP), post high rate algal ponding system (post-HRAP) and (B) in the constructed wetland.

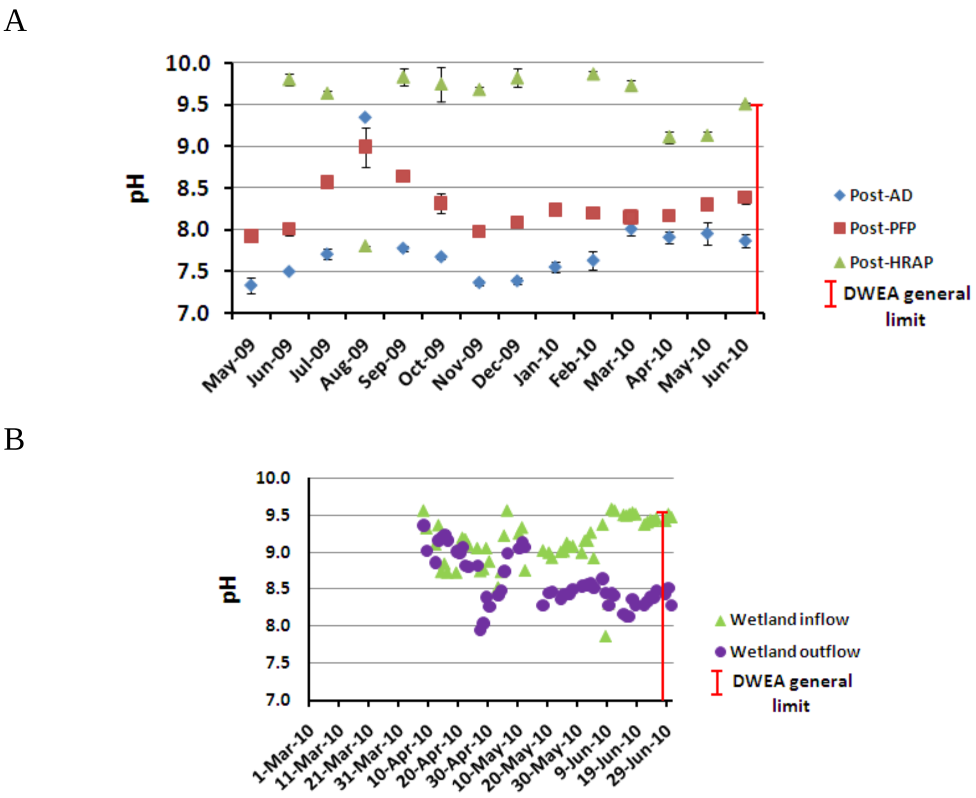

Figure 8 (A) The pH of treated brewery effluent post anaerobic digestion (post-AD), post primary facultative ponding (post-PFP) and post high rate algal ponding system (post-HRAP), and (B) the pH entering and leaving the wetland.

Table 1 Mean (and range) temperature, pH, chemical oxygen demand (COD), ammonia, nitrate and electrical conductivity recorded in the Ibhayi brewery anaerobic digester (AD) and the activated sludge (AS) clarifier over flow, and post-HRAP from 1/05/2009 to 31/03/2010*, and post-wetland from 6/04/2010 to 30/06/2010**, together with the Department of Water and Environmental Affairs (DWEA) general authorisation limits[1].

		AD outflow		AS		Post-HRAP		Post-wetland*		DWEA	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Min	Max
Temp	°C	30.6	(6.9 - 39.3)	-		19.3	(10.0 - 29.7)	19.0	(12.2 - 22.6)	-	-
pH		7.2	(5.82 - 13.82)	8.0	(6.53 - 9.97)	9.8	(6.6- 10.5)	8.6	(8.0 - 9.8)	5.5	9.5
COD	mg/L	215.2	(0.04 - 1105)	103.5	(8 - 870)	181.2	(83 -742)	96.7	(36 - 440)	-	75.0
Ammonia	mg/L	44.2	(0.32 - 195)	2.0	(0.06 - 98)	1.0	(0.02 - 4.0)	0.8	(0.03 - 0.6)	-	6.0
Nitrate	mg/L	-		22.2	(0.36 - 62)	under range		2.5	(0.05 - 7.9)	-	15.0
EC	uS/cm	2795	(1020 - 11200)	2534	(1220 - 92000)	3411	(2088 - 3975)	2863	(1990 - 5539)	700	1500
TDS	mg/L	1417	(373 - 16200)	1252	(140 - 4300)	-		-		-	-
TSS	mg/L	-		-		-		-		-	25.0

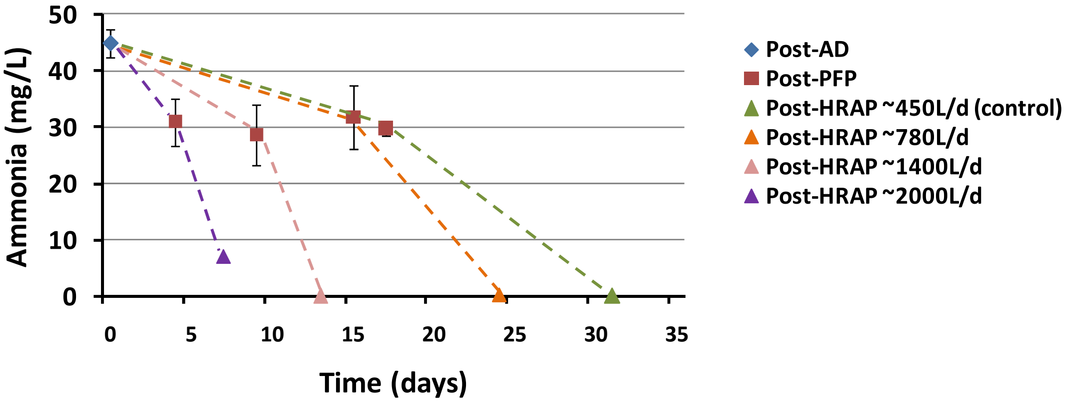

Figure 9 Mean ammonia concentration recorded in post-anaerobic digester (AD) brewery effluent, post-primary facultative pond (PFP) and post-high rate algal ponds (HRAP) through which brewery effluent flowed at either 450 to 620 L/d (i.e. control flow of ~50 L/h) or at elevated flow rates of firstly ~780 L/d and then 1400 L/d and then to ~2000 L/d.

Table 2 Mean rate (L/h) that brewery effluent flowed into the primary facultative pond (PFP) and both high rate algal pond (HRAP) systems. The flow rate of effluent into one HRAP system remained unchanged at ~50 L/d; with the exception that effluent was allowed to flow through that system for 12 rather than 8 h/d (i.e. control treated 410 to 620 L/d). The flow into the second HRAP was increased to treat ~780 L/d for two weeks and then to ~1400 L/d and then to ~2000 L/d.

	Flow rate (L/h)	**Effluent treated (L/d)**	**Effluent retention time (d)**
PFP (pre-optimisation)	116	931	18.6
PFP (1/3-15/3)	148	1182	14.6
PFP (17/3-19/3)	248	1982	8.7
HRAP-control (1/3-15/3)	51	411	13.3
HRAP-control (17/3-19/3)	51	620	8.8
HRAP-780L/d (1/3-15/3)	98	784	6.9
HRAP-1400L/d (17/3-19/3)	118	1414	3.8
HRAP-2000L/d	170	2000	System crashed 2.7

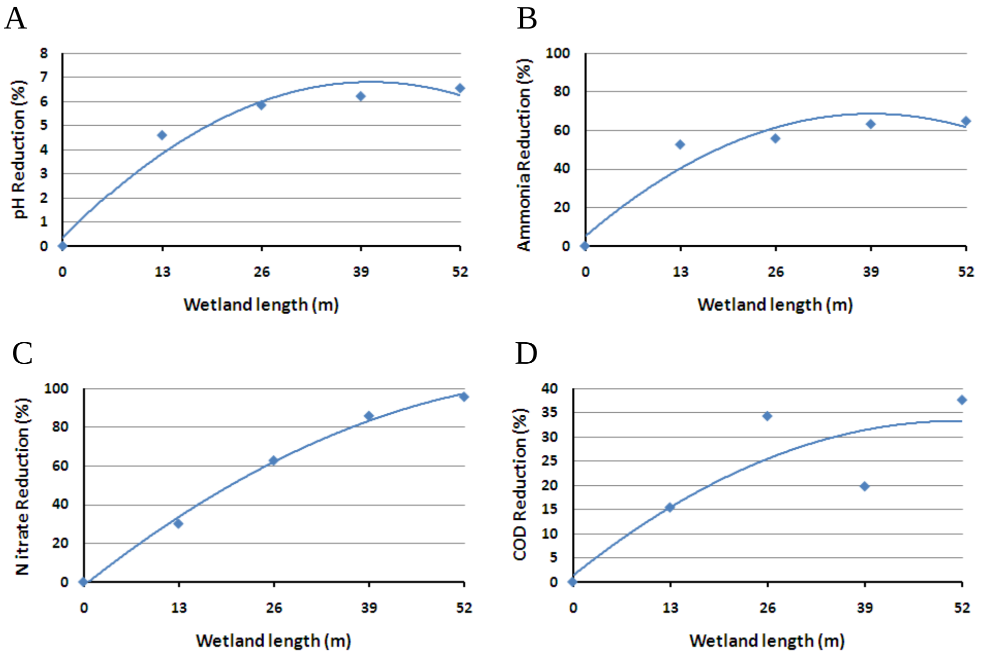

Figure 10 The reduction of (A) pH, (B) ammonia, (C) nitrate and (D) chemical oxygen demand (COD – filtered to 8 µm; i.e. not all algae removed from sample) down the length of a wetland at a flow rate of 135±8.9 L/h.

Figure 11 Lettuce grown in treated brewery effluent supplemented with inorganic fertiliser and lettuce grown in municipal water using conventional inorganic fertiliser (control) in the hydroponic system.

CONCLUSION

The high rate algal ponding and the constructed wetland systems proved effective in treating most effluent parameters to Department of Water and Environmental Affairs general limits for the discharge of industrial effluent into a natural water resource (DWEA [1]). The system was highly efficient at nitrogen removal (ammonia, nitrite and nitrate) with a ten-fold reduction, which brought these parameters consistently within the DWEA general discharge limit of 6 mg/L for ammonia and 15 mg/L for nitrite and nitrate. Similarly, the pH and COD of the effluent treated in the system fell within the DWEA general limits (DWEA [1]). The HRAP system was inconsistent in its removal of phosphate, with absorption efficiency decreasing through the 2009 winter months, but it remained within the general discharge limit of 10 mg/L (DWEA [1]).

The recovered water was suitable for hydroponic lettuce production, and fish were successfully cultured in the treated effluent, which again demonstrates the system’s ability to clean effluent. Furthermore, algae was harvested from the HRAP system and successfully used as an ingredient in fish feed.

The way forward includes low cost, low maintenance, low energy, environmentally sustainable technologies to treat industrial effluent. Furthermore, the technology used here was low-tech and easily maintained making it possible for industries to treat their own effluent and thus recover water and nutrients for onsite reuse or for use in downstream industries or making it suitable for discharge into a natural water resource with negligible environmental impact.

The system has been successfully developed and tested on a pilot scale by SAB Ltd. Rhodes University, in partnership with SAB Ltd, are considering demonstrating the value of these alternative methods of effluent treatment on a commercial-scale.

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