J Appl Phycol (2012) 24:329–337
DOI 10.1007/s10811-012-9810-8

Hectare-scale demonstration of high rate algal ponds for enhanced wastewater treatment and biofuel production

Rupert Craggs · Donna Sutherland · Helena Campbell

Received: 31 July 2011 / Revised and accepted: 2 February 2012 / Published online: 22 February 2012

Abstract High rate algal ponds (HRAPs) are shallow, paddlewheel-mixed open raceway ponds that are an efficient and cost-effective upgrade for the conventional wastewater treatment ponds used by communities and farms the world over. HRAPs provide improved natural disinfection and nutrient removal and can be further enhanced by carbon dioxide (CO_2) addition to promote algal growth which is often carbon limited. This paper discusses the construction and operation of a 5-ha demonstration HRAP system treating primary settled wastewater at the Christchurch wastewater treatment plant, New Zealand. The system consisted of four 1.25-ha HRAPs that were constructed from an existing conventional pond. Algae were harvested from the HRAP effluent in specially designed settlers, which concentrated the algal/bacterial biomass to 1–2% organic solids for conversion to bio-crude oil following dewatering. Performance data from the first 15 months of HRAP operation (without CO_2 addition) are presented. The four demonstration HRAPs had reasonable replication of both treatment performance and algal/bacterial productivity with similar annual average wastewater treatment efficiency (~50% removal of BOD_5, ~87% removal of $fBOD_5$, ~65% removal of ammoniacal-N, ~19% removal of dissolved reactive phosphorus and ~2 log removal of *Escherichia coli*), algal species composition and algal/bacterial biomass production (~8 g m^{-2} day^{-1} volatile suspended solids). These results were in good agreement with the results for pilot-scale HRAP without CO_2 addition in New Zealand. This study provides further indication of the potential for energy efficient and effective wastewater treatment using HRAP, while biofuel conversion of the harvested algal bacterial biomass could provide a valuable niche distributed energy source for local communities.

Keywords Algal biofuel · CO_2 biofixation · Nutrient removal · Open raceway pond

Introduction

The world over, many communities and farms use multiple-pond systems for wastewater treatment (Craggs 2005). These systems have generally performed well in terms of wastewater organic solids removal; however, nutrient removal, algal solids removal and disinfection are highly inconsistent, and the discharge of poor-quality effluents with respect to these parameters may negatively impact the receiving waters (Hickey et al. 1989; Davies-Colley et al. 1995; Craggs et al. 2003). Furthermore, conventional wastewater treatment pond systems are not designed to recover natural resources from wastewater, including energy as biogas, nutrients as algal/bacterial biomass for fertilizer, feed or biofuel use, and water as effluent treated to a consistently high standard. Annual average algal/bacterial productivity in such ponds is typically little more than 2.5 g m^{-2} day^{-1} (volatile suspended solids = ash-free dry weight) (Craggs et al. 2003).

High rate algal ponds (HRAPs) retain the advantages of conventional ponds (simplicity and economy) but overcome many of their drawbacks (poor and highly variable effluent quality, limited nutrient and pathogen removal), and have the added benefit of recovering wastewater nutrients as harvestable algal/bacterial biomass for beneficial use as fertiliser, feed or biofuel. Biofuel conversion of harvested algal/bacterial biomass could provide a valuable niche

R. Craggs (✉) · D. Sutherland · H. Campbell
National Institute of Water and Atmospheric Research Ltd. (NIWA),
PO Box 11-115, Hamilton 3200, New Zealand
e-mail: r.craggs@niwa.co.nz

distributed energy source for local communities. HRAPs are shallow (0.2–0.5 m), continuous raceways around which wastewater is gently circulated by a paddlewheel. HRAPs were developed in the late 1950s for wastewater treatment and resource recovery by Oswald and co-workers (Oswald and Golueke 1960). Algae grow profusely in HRAPs, and daytime photosynthesis can cause dissolved oxygen supersaturation with concentrations of up to 20 g m^{-3}. This photosynthetic oxygenation promotes bacterial oxidation of biodegradable dissolved and particulate organic matter. Nutrient removal in the HRAP is primarily through algal growth and nutrient assimilation (Craggs 2005). The shallow depth of HRAPs enhances the rate of sunlight inactivation of faecal microbes and promotes photo-oxidation of dissolved organic contaminants (Davies-Colley 2005).

Over the last 50 years, full-scale wastewater treatment HRAPs have been built in the USA and several other countries as a component of Advanced Pond Systems (Craggs 2005). The National Institute of Water and Atmospheric Research Ltd. (NIWA) has conducted pilot-scale and full-scale research on HRAPs for the last 13 years to calibrate design and operation to New Zealand conditions, and has shown HRAP to not only provide improved and more consistent wastewater treatment than oxidation ponds, but to have much higher productivity (annual average, ~8 g m^{-2} day^{-1} volatile suspended solids) (Craggs et al. 1998, 2003, 2011). Algal production in HRAP is actually carbon limited due to the low carbon/nitrogen (C/N) ratio of wastewaters (typically 3:1 for domestic wastewater) compared to algal biomass (typically 6:1) (Benemann 2003). Thus, domestic wastewaters contain only half the carbon required to remove all of the nitrogen by assimilation into algal biomass. Carbon limitation in wastewater treatment HRAPs is indicated by elevated daytime pond water pH, resulting from inorganic carbon assimilation causing a shift in the carbonate system equilibrium and release of hydroxide ions which can increase pond water pH to >10.

At a pond water pH of >8.5, the growth of both the wastewater algae and the aerobic heterotrophic bacteria (which degrade the wastewater organic compounds) is increasingly inhibited, in part as a result of high free ammonia concentrations (Azov et al. 1982). Addition of CO_2 to wastewater treatment HRAPs (Fig. 1) would therefore enhance algal production and nitrogen nutrient removal by providing the necessary carbon to stimulate algal growth and reduce pH. Recent research has demonstrated that wastewater treatment performance and algal/bacterial productivity can be further improved through addition of CO_2 (e.g., using flue gas from on-site heat and power generation) to the HRAP water during the daytime to avoid carbon limitation of algal growth (Heubeck and Craggs 2007; Heubeck et al. 2007; Park and Craggs 2010, 2011) and by use of specific operation and management protocols (Park and Craggs 2010). Depending upon local climate conditions, average annual algal/bacterial productivity rates of 12–20 g m^{-2} day^{-1} (volatile suspended solids) may be achieved with CO_2 addition (Park and Craggs 2010; Park et al. 2011).

A major disadvantage of wastewater treatment Advanced Pond Systems is the relatively large land requirement compared with electromechanical treatment systems (e.g. activated sludge) and similar land area to existing two-pond oxidation pond systems. However, HRAP combined with gravity settling pretreatment (e.g. primary clarifier) of raw wastewater (to remove organic solids) and post treatment of HRAP effluent (to remove algal/bacterial biomass), followed by additional effluent polishing if required (Fig. 2) would fit within the footprint of an existing two-pond oxidation pond system. Settled wastewater solids would be anaerobically digested for energy recovery as biogas, and algal/bacterial biomass could be converted to biofuels by the most appropriate method. HRAP systems have lower capital and operating costs than mechanical nutrient removal systems (Downing et al. 2002) and are much easier to operate. HRAP systems provide the co-benefits of enhanced algal production for beneficial use (feed or biofuels), recovery of nutrients for fertilizer use, and offset GHG emissions.

A further advantage of HRAP over oxidation ponds is that the gentle mixing in HRAP promotes the growth of algae that form colonies which can be more easily removed from the pond effluent by gravity settling in simple algal settling ponds or algal harvesters. CO_2 addition to HRAP promotes aggregation/bioflocculation of the colonial algae with bacterial floccs to further enhance algal settling (Park and Craggs 2010). Bioflocculation can also be enhanced by the recycling of a portion of the settled algae in a similar way to sludge recycle in the activated sludge process (Benemann et al. 1980; Park et al. 2011).

Additional treatment (“polishing”) of the algal harvester effluent may be needed to meet specific discharge requirements through use of one or a combination of the following: (a) maturation pond: for further solar-UV disinfection and polishing of the wastewater, and storage before discharge or subsequent re-use; (b) rock filter: for final solids removal, often following a maturation pond; (c) UV disinfection: for disinfection if there is insufficient land area for maturation ponds; (d) membrane filter: to provide a very high-quality effluent, suitable for many re-use applications.

Oswald and Golueke (1960) first proposed the large-scale production of microalgae as a biofuel feedstock using HRAP, with wastewater providing the make-up water and nutrients. Biofuel conversion of algae biomass could involve one or a combination of four main pathways: (1) anaerobic digestion of harvested algae biomass to produce biogas (methane), (2) extraction and transesterification of algae lipid triglycerides to produce biodiesel; (3)

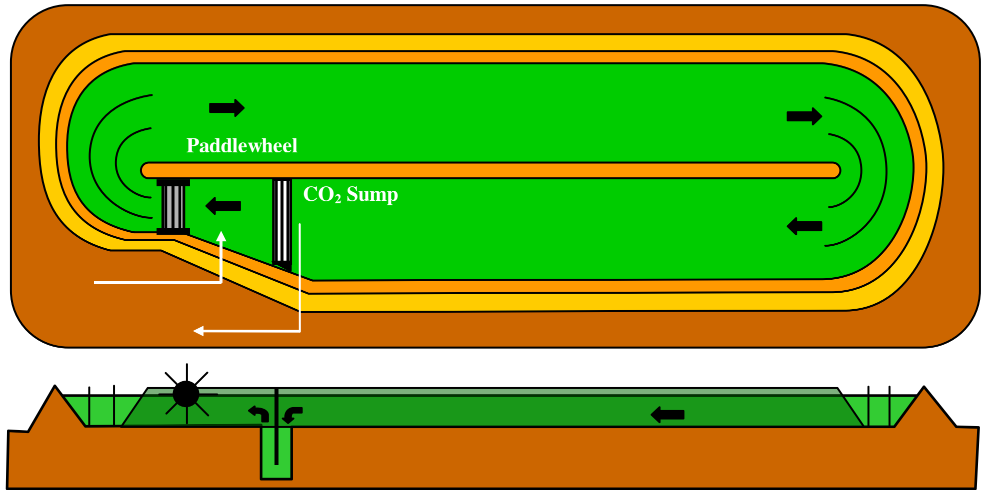

Fig. 1 Schematic diagram of an HRAP with CO_2 addition (plan and elevation view, not to scale)

fermentation of algae carbohydrates to ethanol or butanol; and (4) gasification or other thermochemical conversions of algae, in particular supercritical water reaction to convert wet algal/bacterial biomass to a crude bio-oil (Heubeck and Craggs 2007).

HRAPs fed with nutrient culture medium are used to grow over 90% of worldwide commercial algal production, mainly for high-value food supplements and pigments (Borowitzka and Borowitzka 1988). Photobioreactors (enclosed transparent tubes, bags or similar vessels), although used to grow some high-value algal products, have high capital costs and engineering scale-up limitations that currently make them uneconomical for biofuel applications (Weissman et al. 1988; Sheehan et al. 1998). Even HRAPs, which have much lower capital costs than closed photobioreactors, are probably too expensive to be used for algal biofuel production alone (Oswald and Golueke 1960; Benemann and Oswald 1996; Lundquist et al. 2010). A niche opportunity for community-scale algal biofuel production that might be economical today is where algal production is a by-product from wastewater treatment HRAP, designed for enhanced nutrient removal and disinfection (Benemann 2003).

This paper discusses the design, construction and operation of the world's largest (5 ha) wastewater treatment HRAP system with CO_2 addition and conversion of harvested algal biomass to biofuel. Performance of the system in terms of wastewater treatment (particularly nutrient removal and disinfection) and algal/bacterial biomass production is presented from the first 15 months of operation.

Materials and methods

Christchurch 5-ha demonstration HRAP system The demonstration HRAP system was constructed at the Christchurch wastewater treatment plant, South Island, New Zealand (lat. 43°31′58.73″S, long. 172°42′39.78″E) (Fig. 3). Pond 1 of the existing oxidation pond system was drained, desludged and subdivided by a new 2.8-m-high (4-m crest width) earthen berm to separate off the area in

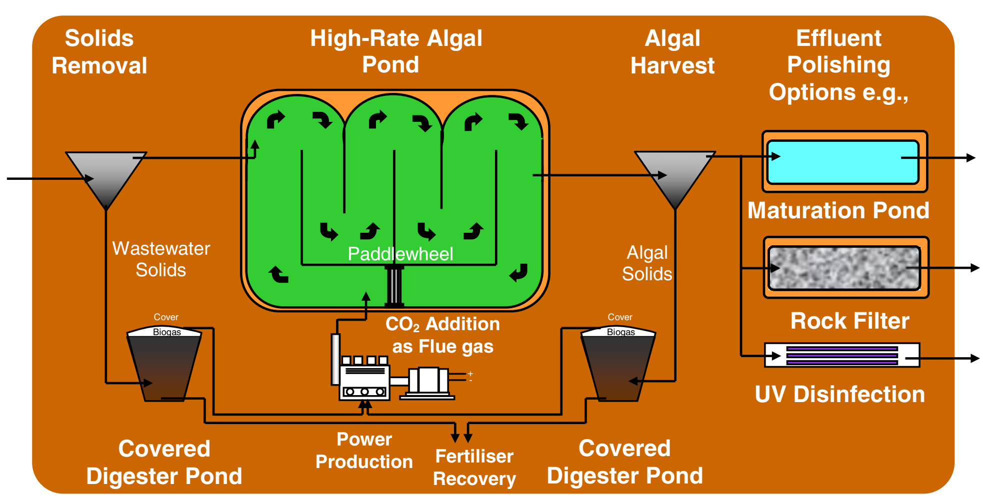

Fig. 2 Schematic diagram concept of a HRAP system with wastewater solids removal pretreatment

Fig. 3 Photograph of one of the Christchurch demonstration HRAPs with an algal harvester

which the 5-ha demonstration HRAP system was constructed. The 5-ha HRAP size was chosen as it is representative of the pond area that would be required for many of the smaller communities in New Zealand and worldwide.

Four adjoining 1.25-ha single-loop raceway HRAPs were formed by earthwork from the floor of the old oxidation pond (Table 1). Laser grading was used to ensure the bottom of the HRAPs was completely level along their length and across their width. Side and channel dividing berms were constructed from compacted earth with internal and external slopes of 2:1 horizontal/vertical. The pond berm slopes were protected against wind and wave erosion and weed growth by a cover of thin (~5 mm) non-woven geotextile that was secured by burying in a trench at the bottom of each berm. The bottom of each HRAP was left unlined to demonstrate cost-effective construction and self-sealing. Two corner deflector baffles (1-mm HDPE membrane supported on ¼ round-treated timber posts) were placed at equal spacing across the channel width and curved around each of the pond corners.

Table 1 Christchurch HRAP and algal harvester design specifications

Pond dimension	HRAP	Algal harvester
Volume (m^3)	4,375	67
Depth (m)	0.35	4.6
Internal berm slope (horiz/vert (1))	2	Vertical and 40°
Surface width (including channel dividing berm) (m)	28	4
Surface length (m)	510	7
Surface area (including channel dividing berm) (m^2)	14,000	28
Freeboard (m)	0.35	–
External slope (horiz/vert (1))	2	–
No. channels across width	2	–

Paddlewheels A single paddlewheel was used to mix the wastewater around each 1.25-ha HRAP at an average horizontal water velocity of 0.2 m s^{-1}, which was sufficient to maintain the algal/bacterial floccs in suspension but minimize suspension of sediment from the pond bottom. Each paddlewheel was 6 m long with eight 0.8-m blades constructed from galvanised steel and painted. The axel bearings were supported on concrete plinths at either end of a concrete-lined paddlewheel station with a shallow curved depression under the paddlewheel that effectively turned it into a positive displacement pump (Fig. 4). The paddlewheels were driven from a direct drive through a gear box by a 3-kW three-phase motor which was controlled by a variable speed controller.

Fig. 4 Photograph of the Christchurch demonstration HRAP paddlewheel

Carbon addition Each HRAP included a CO_2 addition sump to add carbon to the pond water (Fig. 5). CO_2 was taken from the exhaust of the wastewater treatment plant generators and transferred to the HRAP site by a blower through a pipeline. CO_2 addition to each HRAP was controlled by pond water pH-actuated solenoid valves in the gas pipeline that maintained the pH within a range of 7.5–8.5. The CO_2 addition sump (1.0 m wide and 1.5 m deep) spanned the HRAP channel width and was made from concrete. The sump was divided into a downflow and upflow section by a vertical divider baffle. CO_2 was sparged into the downflow side of the sump through six fine bubble tube diffusers.

Influent and effluent The influent wastewater was primary effluent from the wastewater treatment plant which was gravity fed into the HRAP. The influent flow rate to each HRAP (~500 m^{-2} day^{-1}) was controlled by a water level sensor on the pond surface and was confirmed with influent and effluent flow metres. Influent was added to the pond between the CO_2 addition sump and the paddlewheel. Effluent from each HRAP was taken from a standpipe just upstream of the CO_2 addition sump and gently pumped (Tecnicapompe screw impeller pump) into the algal harvester.

Algal harvester The algal harvesters (Fig. 6) were designed with vertical sidewalls, sloping front and back walls in the lamella plate section (to remove the algae from the HRAP effluent) and with a sloping hopper section beneath for storage and further concentration of the settled algal/bacterial biomass before removal through the bottom of the hopper by a helical rotor pump into the harvested algae pipeline (50 mm polyethylene) to the supercritical water reactor (SCWR) for conversion to bio-crude oil (600 m away). Harvester effluent spilled over the weir at the top of the algal harvester and discharged to pond 1 by gravity.

Fig. 5 Photograph of the Christchurch demonstration HRAP CO_2 addition sump

Fig. 6 Photograph of the Christchurch demonstration algal harvester

Bio-crude oil from algae Further dewatering and concentration (up to 30% solids) of the algae was achieved using a centrifuge before conversion to bio-crude oil using a SCWR (Solray Energy, New Zealand). The SCWR mimics processes that may have produced fossil oil by using intense heat (~374°C) and pressure (~22.1 MPa) to disassociate water and degrade organic compounds (Yesodharan 2002). SCWR conversion has similar advantages to anaerobic digestion in that the algal/bacterial biomass does not have to be dried (only a 5–30% solids content is required) as must be done for solvent extraction of lipids, and conversion is of the whole algal/bacterial biomass rather than just the lipid or carbohydrate fraction. Preliminary operation has demonstrated that bio-crude oil is produced with a conversion efficiency of ~30% from which a range of biofuels and other hydrocarbon products (e.g. petrol, diesel, jet fuel and bitumen) could be refined.

Monitoring The performance of each HRAP was determined by measuring the influent and effluent water quality twice per week. Field measurements and water samples were taken from mid-water depth next to the outflow of each HRAP, i.e. the sample was essentially of water about to be discharged from the pond. Measurements were made between 9:00 and 10:00 am NZST since, for most variables,

Table 2 Construction costs of the 5-ha Christchurch demonstration wastewater treatment high rate algal pond system (June 2009)

	Cost NZ $	Cumulative cost NZ $	Cumulative cost NZ $ ha^{-1}	Cumulative cost NZ $ m^{-2}
Pond				
Earthwork	$108,000.00			
Embankment protection	$51,000.00			
End baffles	$26,000.00	$185,000.00	$37,000.00	$3.70
Mixing				
Paddlewheels (inc VSD)	$87,000.00			
Paddlewheel stations	$23,000.00	$295,000.00	$59,000.00	$5.90
CO_2 addition				
CO_2 sumps with baffles	$90,000.00			
CO_2 spargers	$22,000.00	$407,000.00	$81,400.00	$8.14
pH control and valves	$41,000.00	$448,000.00	$89,600.00	$8.96

morning water quality values for HRAP are typically similar to the diurnal median value (Oswald 1991). Field measurements of the pond water temperature and pH, dissolved oxygen (DO), conductivity and turbidity were also made in each pond. Water samples were collected from each pond in 500-mL polypropylene bottles for water quality analysis and 100-mL sterile vials for microbiological analysis. Samples were kept chilled and in the dark prior to analysis at the NIWA Christchurch laboratory within 6 h of collection. The water quality variables that were used to measure the treatment efficiency of the HRAP were analysed according to standard methods (APHA 2008) including: total suspended solids (TSS), volatile suspended solids (VSS), chlorophyll *a*, ammoniacal-N (NH_4-N) and dissolved reactive phosphorus (DRP). Biochemical oxygen demand (BOD_5) without nitrification inhibition, filtered BOD_5 ($fBOD_5$) with reseeding and *Escherichia coli* were analysed by Hill Laboratories, Christchurch.

Results

The four 1.25-ha demonstration wastewater treatment HRAPs were easily constructed from the sediment left after an existing oxidation pond had been drained, dried out and desludged. Cost-effective construction of HRAP embankments was demonstrated using geotextile covered compacted earth berms, and the ponds were successfully filled and operated without the need for an expensive plastic liner. The earthwork ponds were constructed for NZ $3.70 m^{-2}, while total construction costs including the paddlewheel mixing and pH-controlled CO_2 addition were NZ $5.90 m^{-2} and NZ $8.96 m^{-2}, respectively. A breakdown of the essential construction costs for the 5-ha system is given in Table 2. Other costs including those for pipes, valves, pumps, flow measurement and control and real-time pond monitoring have not been included here because they are site specific and will be discussed in a future publication on the techno-economic assessment of the system.

Similar wastewater treatment efficiency and algal/bacterial production was shown by all four demonstration HRAPs

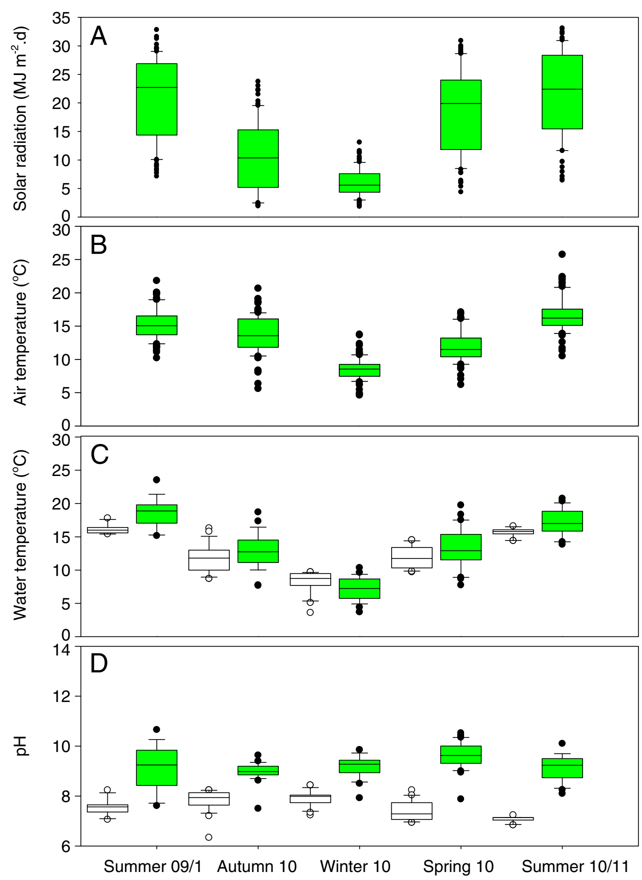

Fig. 7 Ambient conditions (solar radiation, MJ m^{-2} day; air temperature, °C) and influent wastewater and combined HRAP water physical conditions (temperature, °C and pH) measured during the 15 months of operation (December 2009–February 2011). (*box lower boundary*, 25th percentile; *inner line*, median; *upper boundary*, 75th percentile; *whisker below*, 10th percentile; *above*, 90th percentile; *points*, outlying data)

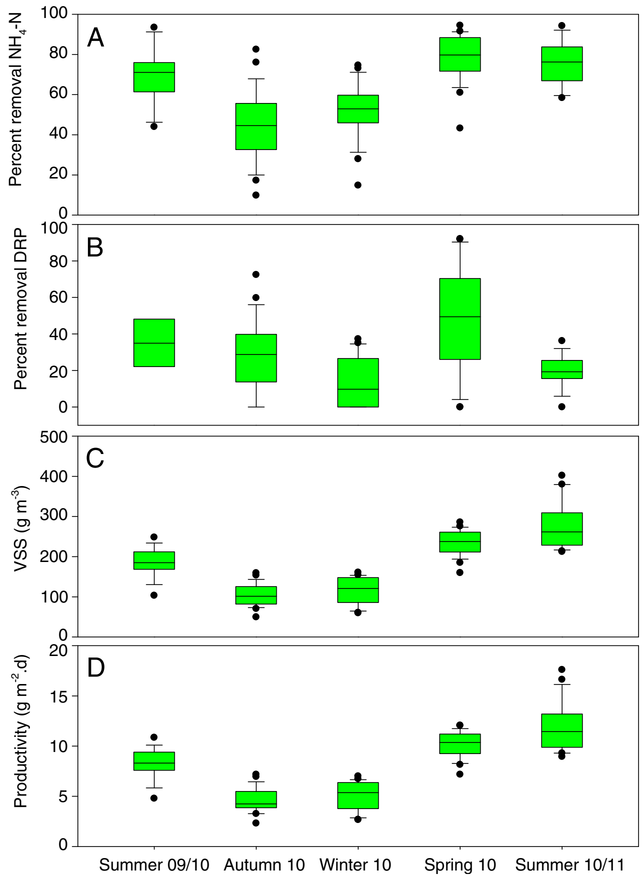

Fig. 8 Percent removal of ammoniacal-N and dissolved reactive phosphorus, volatile suspended solids concentration (g m^{-3}) and algal/bacterial productivity (g m^{-2} day^{-1}) combined for the four replicate HRAPs during the 15 months of operation (December 2009–February 2011) (*box lower boundary*, 25th percentile; *inner line*, median; *upper boundary*, 75th percentile; *whisker below*, 10th percentile; *above*, 90th percentile; *points*, outlying data)

during the initial 15 months of operation as replicates (December 2009–February 2011) (Figs. 7 and 8, Table 3). Morning (9–10 am) HRAP temperatures were 1–2°C cooler than influent water temperature (15.4°C), while HRAP DO levels were nearly saturated (86–98% sat.), and HRAP pH levels were elevated (pH 9.1–9.3) (Fig. 7, Table 3). Wastewater conductivity and alkalinity were both reduced by HRAP treatment, while wastewater BOD_5 concentrations were reduced by 47–52% in the four HRAPs. Removal of $fBOD_5$ was high and consistent between the four HRAPs with all ponds achieving 82–91% removal (Table 3). NH_4-N removal by the four HRAPs was 64–67% while DRP removal was only 14–24% (Fig. 8, Table 3). The HRAP provided efficient disinfection indicated by ~2 log removal of *E. coli* (Table 3).

Populations of colonial algal species naturally developed following initial filling of the HRAP with water from pond 1 of the wastewater treatment plant. Species composition was similar in all four HRAPs which were dominated by

Table 3 Median±standard deviation and percentage removal values of water quality variables in the influent and effluent of the four Christchurch demonstration HRAPs measured during the 15 months of operation (December 2009–February 2011)

Water quality variable	Influent	HRAP 1 effluent		HRAP 2 effluent		HRAP 3 effluent		HRAP 4 effluent	
	Median	Median	% Rem.	Median	% Rem.	Median	% Rem.	Median	% Rem.
Temp. (°C)	15.4±3.2	13.2±4.2		13.1±4.2		13.5±4.3		14.3±4.4	
DO (% sat.)	20.2±23.5	86.2±42.0		98.2±44.0		90.8±42.3		93.4±45.2	
pH	7.6±0.45	9.1±0.99		9.3±0.8		9.2±0.7		9.1±0.64	
Cond. (mS cm^{-1})	920.0±824.0	734.0±182.5	20.2	744.0±151.1	19.1	744.0±168.7	19.1	765.0±174.3	16.8
Alk. (g $CaCO_3$ m^{-3})	195.0±41.2	134.0±32.6	31.3	127.3±33.3	34.7	134.0±26.6	31.3	144.0±30.4	26.2
BOD_5 (g m^{-3})	115.5±71.5	61.5±26.2	46.8	56.0±22.5	51.5	57.5±22.7	50.2	56.0±35.0	51.5
$fBOD_5$ (g m^{-3})	63.0±36.7	5.4±9.0	91.4	10.0±7.2	84.3	5.0±6.9	92.1	11.5±7.8	81.8
Turbidity (NTU)	113.0±108.6	344.5±155.1		328.5±155.7		335.0±156.2		345.5±130.7	
TSS (g m^{-3})	57.7±66.1	200.0±89.4		179.5±89.8		213.4±110.8		225.5±100.5	
VSS (g m^{-3})	47.4±47.9	163.6±74.2		143.6±74.0		163.6±81.8		164.0±82.7	
Chlorophyll *a* (mg m^{-3})	79.1±313.8	2875.8±1894.4		3043.3±2094.9		3122.4±1934.1		2996.8±1702.0	
NH_4-N (g m^{-3})	24.2±9.5	8.6±6.3	64.2	7.9±6.5	67.4	8.6±5.6	5.6	8.6±5.66	64.6
DRP (g m^{-3})	1.92±1.85	1.53±1.23	20.2	1.45±1.29	24.4	1.50±1.23	21.9	1.65±1.54	14.0
E. coli (MPN (100 mL)$^{-1}$)	$1.6\times10^6\pm1.8\times10^6$	$1.2\times10^4\pm4.2\times10^4$	99.3	$4.5\times10^3\pm9.8\times10^3$	99.7	$3.2\times10^4\pm6.1\times10^4$	98.0	$2.0\times10^4\pm1.8\times10^4$	98.8

Micractinium sp. and *Desmodesmus* sp. Algal/bacterial biomass concentrations (measured as VSS) were similar in all four HRAPs ranging between (143 and 163 g m^{-3}). Seasonal variation in algal/bacterial productivity ranged between 4.4 and 11.5 g m^{-2} day^{-1} (Fig. 8). Harvested algal/bacterial biomass with a 1–2% volatile solids content was pumped from the base of the algal harvester to the supercritical water reactor. A higher solids content could be achieved at slower pumping rates.

Discussion

The earthen HRAPs used in this system were economically constructed compared to plastic-lined, often concrete block-walled HRAP used for neutraceutical production. The ~NZ $9 m^{-2} cost including mixing and pH-controlled CO_2 addition is considerably cheaper than current costs for photobioreactors, without taking into account the piping of the influent, effluent and CO_2 which would cost considerably more for the multiple photobioreactor units required per hectare than the single pipelines needed for each 1.25-ha HRAP.

Algal productivity occurred in each of the four HRAPs during the 15 months of operation (December 2009–February 2011) indicated by the nearly saturated morning DO levels (86–98% sat.) although the high morning HRAP pH levels (pH 9.1–9.3) showing that the algal cultures were probably severely carbon limited during the day (Table 3). Mid-afternoon measurements confirmed pH levels as high as pH 11 during sunny periods. Wastewater treatment by the demonstration-scale HRAP was typical of pilot-scale HRAP without CO_2 addition (50% removal of BOD_5, 80% removal of $fBOD_5$ and >60% removal of NH_4-N; see Park and Craggs 2010, 2011). However, given the high daytime pH in the HRAP, it was surprising that more NH_4-N removal by ammonia stripping did not occur as has been previously observed in other pilot-scale systems (e.g. Picot et al. 1991; Garcia et al. 2000). The removal of DRP (14–24%, Table 3) was lower than previously observed (Park and Craggs 2010, 2011) and may have been effected by the low influent concentration, particularly during the latter part of the monitoring period (Fig. 8). The large-scale HRAP provided more efficient disinfection (~2 log removal of *E. coli*) than pilot-scale systems by (~1 log removal of *E. coli*) previously studied (Table 3; Davies-Colley et al. 2003). A possible explanation for the improved disinfection measured in this study is a reduction in short circuiting due to the longer length of the demonstration HRAP raceway channels (~1,000 m compared to ~20 m for the pilot-scale system) enabling greater mixing of influent within the pond volume before completing a circuit.

The colonial algae (*Micractinium* sp. and *Desmodesmus* sp.) that naturally developed in all of the HRAPs are commonly found in wastewater treatment HRAPs the world over (Craggs 2005). The seasonal variation in algal/bacterial biomass production (4.4–11.5 g m^{-2} day^{-1} volatile suspended solids) (Fig. 8) was typical of pilot-scale wastewater treatment HRAP without CO_2 addition (Park and Craggs, 2010).

This study has shown that wastewater treatment HRAPs can be easily constructed within existing oxidation ponds, and the earthen pond bottom can self-seal without the need for expensive plastic liners. The four replicate demonstration HRAPs all had similar wastewater treatment efficiency, algal species composition and productivity, and performance was similar to that previously shown for pilot-scale HRAP without CO_2 addition in New Zealand. These results provide further indication of the potential for energy efficient and effective tertiary-level wastewater treatment using HRAP with harvestable production of algal biomass for biofuel use.

Acknowledgements The authors would like to thank Christchurch City Council, particularly Mark Christison, Mike Bourke and James Feary, for their ongoing support of this project. We also thank George Payne for sourcing and setting up much of the automated control system; Greg Kelly for his assistance with operation and monitoring of the system; and Jason Park for contributing to much of the background research for this study. This research was funded by the New Zealand Foundation for Research Science and Technology, contract C01X0810.

References

APHA (2008) Standard methods for the examination of water and wastewater, 22nd edn. American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC

Azov Y, Shelef G, Moraine R (1982) Carbon limitation of biomass production in high-rate oxidation ponds. Biotech Bioeng 24:579–594

Benemann JR (2003) Biofixation of CO_2 and greenhouse gas abatement with microalgae—technology roadmap. Report no. 7010000926 prepared for the U.S. Department of Energy National Energy Technology Laboratory

Benemann JR, Oswald WJ (1996) Systems and economic analysis of microalgae ponds for conversion of CO_2 to biomass. Final Report. US DOE-NETL No: DOE/PC/93204-T5. Prepared for the Energy Technology Center, Pittsburgh, USA

Benemann JR, Koopman BL, Baker DC, Goebel RP, Oswald WJ (1980) Design of the algal pond subsystem of the photosynthetic energy factory. Final Report for the US Energy Research and Development Administration Contract Number. EX-76-(-01-2548). Report No. 78-4. SERL, Colorado, USA

Borowitzka MA, Borowitzka LJ (eds) (1988) Micro-algal biotechnology. Cambridge University Press, Cambridge, p 390

Craggs RJ (2005) Advanced integrated wastewater ponds. In: Shilton A (ed) Pond treatment technology. IWA scientific and technical report series. IWA, London, pp 282–310

Craggs RJ, Green FB, Oswald WJ (1998) Advanced integrated wastewater pond systems (AIWPS): potential application in New Zealand. Proc NZWWA Ann Conf pp 56–62

Craggs RJ, Davies-Colley RJ, Tanner CC, Sukias JPS (2003) Advanced ponds systems: performance with high rate ponds of different depths and areas. Water Sci Technol 48:259–267

Craggs RJ, Heubeck S, Lundquist TJ, Benemann JR (2011) Algae biofuel from wastewater treatment high rate algal ponds. Water Sci Technol 63:660–665

Davies-Colley RJ (2005) Pond disinfection. In: Shilton A (ed) Pond treatment technology. IWA scientific and technical report series. IWA, London, pp p100–136

Davies-Colley RJ, Hickey CW, Quinn JM (1995) Organic matter, nutrients and optical characteristics of sewage lagoon effluents. NZ J Mar Freshwat Res 29:235–250

Davies-Colley RJ, Craggs RJ, Nagels JW (2003) Disinfection in a pilot-scale advanced pond system (APS) for domestic sewage treatment in New Zealand. Water Sci Technol 48:102– 108

Downing JB, Bracco E, Green FB, Ku AY, Lundquist TJ, Zubieta IX, Oswald WJ (2002) Low cost reclamation using the advanced integrated wastewater pond systems technology and reverse osmosis. Water Sci Technol 45:117–125

García J, Mujeriego R, Hernández-Mariné M (2000) High rate algal pond operation strategies for urban wastewater nitrogen removal. J Appl Phycol 12:331–339

Heubeck S, Craggs RJ (2007) Resource assessment of algae biomass for potential bio-energy production in New Zealand. NIWA Report HAM2007-157 for the New Zealand Energyscape Program for Scion Ltd.

Heubeck S, Craggs RJ, Shilton A (2007) Influence of CO_2 scrubbing from biogas on the treatment performance of a high rate algal pond. Water Sci Technol 55:193–200

Hickey CW, Quinn JM, Davies-Colley RJ (1989) Effluent characteristics of domestic sewage lagoons and their potential impacts on rivers. NZ J Mar Freshwat Res 23:585–600

Lundquist TJ, Woertz IC, Quinn NWT, Benemann JR (2010) A realistic technology and engineering assessment of algal biofuel production, Energy Biosciences Institute, University of California, Berkeley, California, October. Ascension Publishing

Oswald WJ (1991) Introduction to advanced integrated wastewater ponding systems. Water Sci Technol 24:1–7

Oswald WJ, Golueke CG (1960) Biological transformation of solar energy. Adv Appl Microbiol 2:223–262

Park JBK, Craggs RJ (2010) Wastewater treatment and algal production in high rate algal ponds with carbon dioxide addition. Water Sci Technol 61:633–639

Park JBK, Craggs RJ (2011) Nutrient removal in high rate algal ponds with CO_2 addition. Water Sci Technol 63:1758–1764

Park JBK, Craggs RJ, Shilton AN (2011) Wastewater treatment high rate algal ponds for biofuel production. Biores Technol 102:35–42

Picot B, El Halouani H, Casellas C, Moersidik S, Bontoux J (1991) Nutrient removal by high rate pond system in a Mediterranean climate (France). Water Sci Technol 23:1535–1541

Sheehan J, Dunahay T, Benemann J, Roessler P (1998) A look back at the U.S. Department of Energy's aquatic species program—biodiesel from algae. National Renewable Energy Laboratory, Golden, CO, 80401 NERL/TP-580-24190

Weissman JC, Goebel P, Benemann JR (1988) Photobioreactor design: comparison of open ponds and tubular reactors. Bioeng Biotechnol 31:336–344

Yesodharan S (2002) Supercritical water oxidation: an environmentally safe method for the disposal of organic wastes. Current Sci 82:1112–1122