WORLD-FIRST WASTEWATER ALGAL BIO-CRUDE OIL DEMONSTRATION

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ABSTRACT

The world's largest wastewater treatment High Rate Algal Pond (HRAP) system with conversion of harvested algal biomass to biofuel has been constructed at the Christchurch (Chch) Wastewater Treatment Plant and will be operated over two years to demonstrate wastewater treatment performance. This paper describes HRAP wastewater treatment technology and the associated co-benefits, discusses the design, construction and operation of the Chch HRAP system and presents preliminary data on wastewater treatment efficiency and algal productivity from the first summer of operation. The 5 ha HRAP demonstration system was constructed within an existing oxidation pond. Four adjoining 1.25 ha single loop raceway HRAPs were formed by earthwork and the bottom of the HRAP was left unlined to demonstrate cost-effective construction and self-sealing. Each HRAP included a paddlewheel, CO_2 addition sump, and had an algal harvester with inflow pump and harvested algae pump. Preliminary results from the first summer of operation without CO_2 addition showed that the four replicate demonstration HRAPs had similar wastewater treatment efficiency (~66% removal BOD_5; ~86% removal of $fBOD_5$; ~76% removal ammoniacal-N removal and ~35% removal of DRP); algal species composition and productivity (equivalent to >30 t ha^{-1}.y). Harvested algal biomass had a solids content of ~1% volatile solids. These preliminary results show reasonable replication of treatment performance and algal productivity between the four demonstration HRAP and were similar to previous results for pilot-scale HRAP with CO_2 addition during NZ summer conditions; and further indicate the potential for energy efficient and effective tertiary-level wastewater treatment using HRAP.

KEYWORDS

Wastewater, Treatment, CO_2, High Rate Algal Pond, Algae, Biofuel, Bio-crude oil

1 INTRODUCTION

The world's largest wastewater treatment High Rate Algal Pond (HRAP) system with conversion of harvested algal biomass to biofuel has been constructed at the Christchurch Wastewater Treatment Plant and will be operated over two years to demonstrate wastewater treatment performance (particularly nutrient removal and disinfection) and algal productivity. The efficiency and economics of conversion of algal biomass harvested from the HRAP System to bio-crude oil by Super Critical Water technology developed by Christchurch company Solray Energy Ltd will also be determined. High Rate Algal Ponds (HRAP) retain the advantages of conventional ponds (simplicity and economy) but overcome many of their drawbacks (poor and inconsistent effluent quality, limited nutrient and pathogen removal), and have the added benefit of recovering nutrients into harvestable algal biomass for beneficial use as fertiliser, feed or biofuel. Biofuel conversion of harvested algal biomass could provide a valuable niche distributed energy source for local communities. This paper describes HRAP wastewater treatment technology and the associated co-benefits, discusses the design, construction and operation of the Chch HRAP system and presents preliminary data on wastewater treatment efficiency and algal productivity from the first summer of operation.

1.1 OXIDATION PONDS

Many of New Zealand's communities and farms use two-stage oxidation pond systems for wastewater treatment (NZMWD, 1974; NZDEC, 2006). 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 effluent discharged to receiving waters is often of poor quality with respect to these parameters (Hickey et al., 1989; Davies-Colley et al., 1995; Craggs et al., 2003). Furthermore, oxidation pond systems are not designed to optimise the recovery of natural resources from wastewater, including energy as biogas, nutrients as algal biomass for biofuel use and water as effluent treated to a consistently high standard. Typical algal productivity in oxidation ponds is little more than 10 tonnes/ha.y (ash free dry wt) (Craggs et al., 2003).

1.2 COMMERCIAL ALGAL PRODUCTION SYSTEMS AND ALGAL BIOFUEL

HRAP 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 & 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 & Golueke, 1960; Benemann & Oswald, 1996). A niche opportunity for community-scale algal biofuel production that could be economical today, is where algal production is a by-product from wastewater treatment HRAP, designed for enhanced nutrient removal and disinfection (Benemann, 2003).

2 HIGH RATE ALGAL PONDS (HRAP)

HRAPs are shallow (0.2-0.5 m), continuous raceways around which wastewater is gently circulated by a paddlewheel. HRAP were developed in the late 1950s for wastewater treatment and resource recovery by Oswald and co-workers (Oswald & Golueke, 1960). Algae grow profusely in HRAP 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 (ammoniacal-N and dissolved reactive phosphorus; DRP) removal in the HRAP is primarily through algal growth and nutrient assimilation (Craggs, 2005). The shallow depth of HRAP enhances the rate of sunlight inactivation of faecal microbes, and promotes photo-oxidation of dissolved organic contaminants (Davies-Colley, 2005).

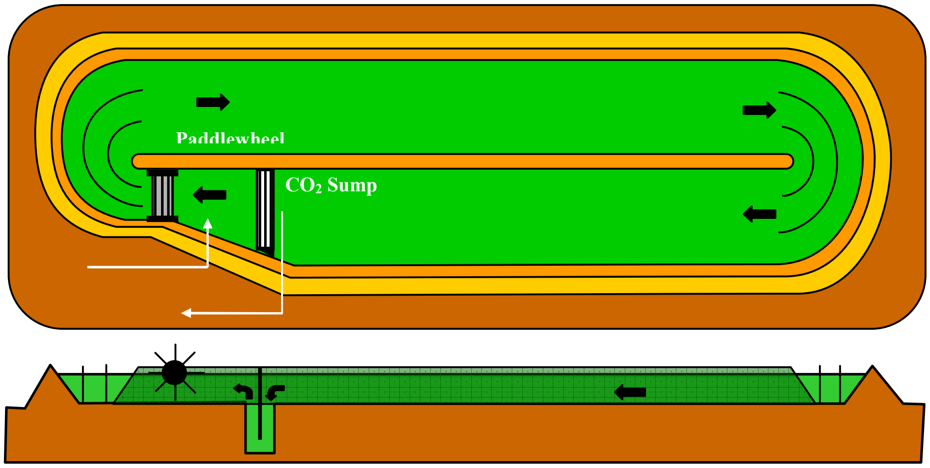

Figure 1: Schematic Diagram of a High Rate Algal Pond (HRAP) with CO_2 addition (Plan and elevation view, not to scale)

Over the last 50 years full-scale wastewater treatment HRAP have been built in the USA and several other countries as a component of Advanced Pond Systems (Craggs, 2005). NIWA has conducted pilot-scale and full-scale research on HRAP 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 (~30 tonnes/ha.y ash free dry wt) (Craggs et al., 1998; Craggs et al., 2003; Craggs et al., 2010). However, algal production in HRAP is severely carbon-limited due to the low 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 the use of bicarbonate ions as a CO_2 source for algal photosynthesis, releasing hydroxide ions which can increase pond water pH to >10.

At pond water pH of >8.5 the growth of both 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 (Figure 1) would therefore enhance algal production and nitrogen nutrient removal by stimulating algal growth. Recent research has demonstrated that wastewater treatment performance and algal 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 & Craggs, 2007; Heubeck et al., 2007; Park & Craggs, 2010a; b) and by use of specific operation and management protocols (Park et al., 2010). Depending upon local climate conditions, average annual algal productivity rates of 45 - 60 tonnes/ha/y may be achieved.

A major disadvantage of wastewater treatment Advanced Pond Systems is the relatively large land requirement compared with electromechanical treatment systems (e.g. activated sludge), however High Rate Algal Ponds 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 biomass), followed by additional effluent polishing if required (Figure 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 biomass could be converted to biofuels by the most appropriate method. HRAP systems have lower capital and operating costs than mechanical nutrient removal systems 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 fertiliser use, and offset GHG emissions.

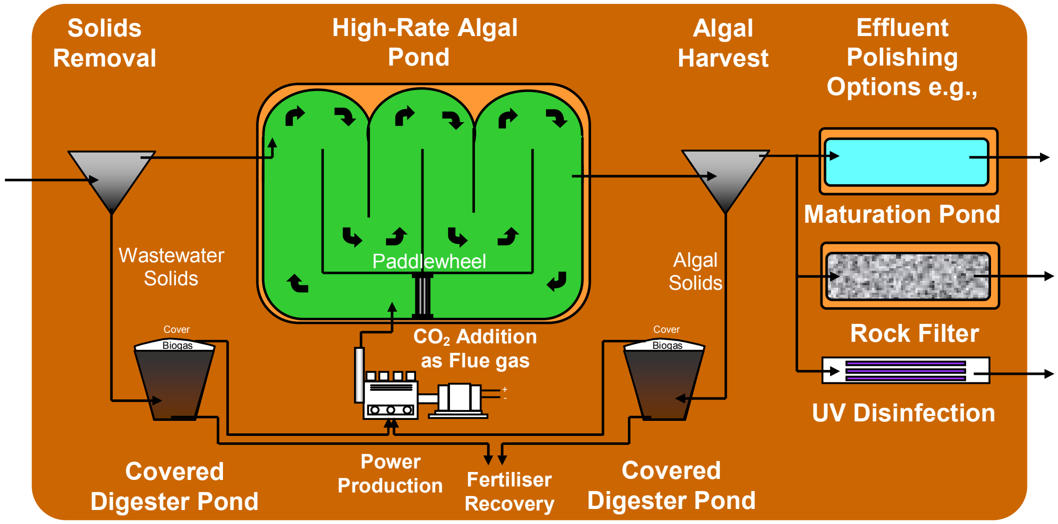

Figure 2: Schematic diagram concept of a HRAP system with wastewater solids removal pretreatment

2.1 ALGAL HARVEST

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 harvest tanks. CO_2 addition to HRAP promotes aggregation / bioflocculation of the colonial algae with bacterial floccs to further enhance algal settling. Bioflocculation can also be enhanced by 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., 2010).

2.2 FURTHER EFFLUENT POLISHING

Additional treatment ("polishing") of the Algal Harvester effluent may be needed to meet specific discharge requirements though 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 reuse; (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.

2.3 ALGAL BIOFUEL CONVERSION

Oswald and Golueke (1960) first proposed the large-scale production of microalgae as a biofuel feedstock using HRAPs, 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) Fermentation of algae carbohydrates to ethanol or butanol and (4) Gasification or other thermochemical conversions of algae, in particular super-critical water reaction to convert wet algal biomass to a crude bio-oil (Heubeck & Craggs, 2007).

3 CHRISTCHURCH 5 HA DEMONSTRATION HRAP SYSTEM

The demonstration HRAP system was constructed at the Christchurch wastewater treatment plant, South Island New Zealand (Latitude: 43°31′ S Longitude: 172°37′ E) (Figure 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 bund to separate off the area in 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. The remaining area of Pond 1 was restored to WWTP operation as a maturation pond, receiving secondary effluent and operated at a water depth of ~1.3 m.

Figure 3: Photograph of one of the Christchurch Demonstration HRAP with Algal Harvester

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 the pond corners.

Table 1: Christchurch HRAP and Algal Harvester Design Specifications

Pond Dimension	HRAP	Algal Harvester
Volume (m^3)	4375	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)	14000	28
Freeboard (m)	0.35	-
External slope (horiz : vert (1))	2	-
No. channels across width	2	-

3.1 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, which was sufficient to maintain the algal colonies 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 (Figure 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.

Figure 4: Photograph of the Christchurch Demonstration HRAP Paddlewheel

3.2 CARBON ADDITION

Each HRAP included a CO_2 addition sump to add carbon to the pond water (Figure 5). CO_2 was taken from the exhaust of the 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 injection sump (1.0 m across 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.

Figure 5: Photograph of the Christchurch Demonstration HRAP CO_2 addition sump

3.3 INFLUENT AND EFFLUENT

The influent wastewater was gravity fed from the primary effluent pipeline at the WWTP and sometimes from the inflow area of the WWTP Pond 1 (secondary effluent) or a combination of the two. The influent flow rate was controlled by a water level sensor on the surface of each HRAP. The flow rate to each HRAP was ~500 m^3 d^{-1} and was confirmed with influent and effluent flow meters. Influent was added to the pond between the paddlewheel and the CO_2 addition sump. 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.

3.4 ALGAL HARVESTER

The algal harvesters (Figure 6) were designed with vertical side-walls, 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 biomass before removal through the bottom of the hopper by a helical rotor pump into the harvested algae pipeline (50 mm PE) to the SCWR (600 m away). Harvester effluent spilled over the weir at the top of the algal harvester and flowed to Pond 1 by gravity.

Figure 6: Photograph of the Christchurch Demonstration Algal Harvester

3.5 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 Super Critical Water Reactor (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 biomass does not have to be dried (5-30% solids) and conversion is of the whole algal 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 fuels and other hydrocarbon products (e.g. petrol, diesel, jet fuel and bitumen) could be refined. At the opening of the demonstration project, a lawn mower was operated with 100% bio-petrol that had been refined from bio-crude oil produced from algae harvested from the effluent of the four demonstration HRAPs.

3.6 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 in the surface water 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, morning water quality values are typically similar to the diurnal median value (Oswald, 1991). Field measurements of the pond water temperature and pH, 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 hours of collection. The water quality variables that were used to measure the treatment efficiency of the HRAP were analysed according to standard methods (APHA, 2005). Analyses were made of: Total Suspended Solids (TSS); Volatile Suspended Solids (VSS); Chlorophyll *a*; Ammoniacal-N (NH_4-N); Dissolved Reactive Phosphorus (DRP). Biochemical Oxygen Demand (BOD_5) without nitrification inhibition and filtered BOD_5 ($fBOD_5$) with reseeding were analysed by Hill laboratories, Christchurch.

4 RESULTS AND DISCUSSION

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 berms was demonstrated using geotextile covered compacted earth and the ponds were successfully filled and operated without the need for an expensive plastic liner. The HRAP system was opened on 20th November 2009 will be operated for two and a half years. Preliminary results of wastewater treatment efficiency of the four demonstration HRAPs during the first summer of operation (1st December – 28th February) are shown in Table 2 which compares median values of water quality variables in the influent and HRAP effluents.

Morning (9-10 am) HRAP temperature was very similar to influent water temperature (18-19°C), whereas HRAP DO levels were saturated (100-116% sat.) indicating a healthy algal population; and HRAP pH levels were elevated (pH 9.3-9.6) showing that the algal culture was probably severely carbon limited during the day (Table 2). Wastewater conductivity and alkalinity were both reduced by HRAP treatment, with reduction in ammoniacal-N concentration accounting for some of the reduction in conductivity. Wastewater BOD_5 concentrations were reduced by 64-70% in the four HRAP. Removal of $fBOD_5$ was very high and consistent between the four HRAP with all ponds achieving 85-88% removal (Table 2). Removal of nutrients in the four HRAP was typical of pilot-scale HRAP without CO_2 addition, with 73-79% ammoniacal-N removal and 20-49% DRP removal (Table 2) (Park & Craggs 2010a; b).

Table 2: Median and percentage removal values of water quality variables in the influent and effluent of the four Chch demonstration HRAP measured during NZ summer (1st December - 28th February) conditions

Water Quality Variable	Influent	HRAP1 Effluent		HRAP2 Effluent		HRAP3 Effluent		HRAP4 Effluent	
	Median	Median	% Rem.	Median	% Rem.	Median	% Rem.	Median	% Rem.
Temp. (°C)	19.0	18.7		18.3		18.8		19.1	
DO (% sat.)	8.5	99.9		116.2		104.0		111.1	
pH	7.6	9.3		9.6		9.5		9.3	
Cond. (mS cm^{-1})	855	651	23.9	666	22.1	657	23.2	671	21.6
Alk. (g $CaCO_3$ m^{-3})	221.5	166.2	24.9	147.2	33.5	152.5	31.2	181.5	18.1
BOD_5 (g m^{-3})	205.0	60.5	70.5	62.5	69.5	65.5	68.1	74.5	63.7
$fBOD_5$ (g m^{-3})	90.0	13.0	85.6	12.5	86.1	11.3	87.5	12.5	86.1
NH_4-N (g m^{-3})	31.0	7.8	74.5	6.4	79.3	6.9	77.6	8.4	72.8
DRP (g m^{-3})	4.7	3.3	30.2	2.4	48.5	2.7	43.8	3.8	19.6
Turbidity (NTU)	288	410		505		485		523	
TSS (g m^{-3})	143.3	209.1		244.7		288.8		270.3	
VSS (g m^{-3})	117.6	162.8		187.2		198.0		190.8	
Chlorophyll *a* (mg m^{-3})	56	2764		3471		4449		3369	

Populations of colonial algal species naturally developed following initial filling of the HRAP with water from Pond 1 of the WWTP. Species composition was similar in all four HRAP which were dominated by *Micractinium* sp. and *Desmodesmus* sp. Algal/bacterial biomass concentrations (measured as VSS) were similar in all four HRAP ranging between (163 and 198 g m^{-3}) and were used to calculate algal productivity. This algal productivity under summer conditions is equivalent to 30 t ha^{-1}.y (Figure 7) and is typical of pilot-scale HRAP without CO_2 addition.

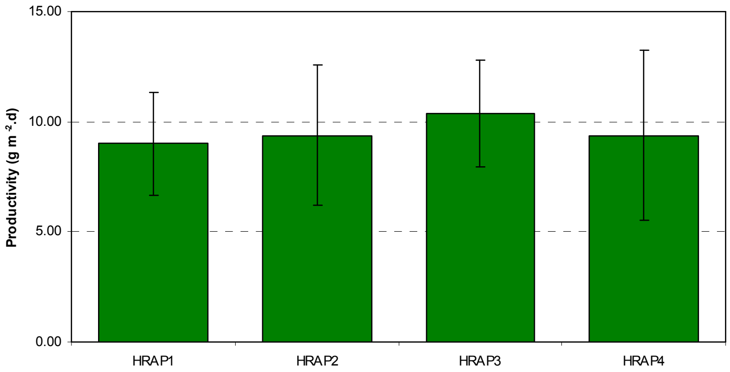

Figure 7: Algal productivity in the four Christchurch demonstration HRAP without CO_2 addition measured during NZ summer (1st December - 28th February) conditions (Median +/- standard deviation)

Harvested algal biomass with a 1% VS content was pumped from the base of the algal harvester to the SCWR and higher solids content could be achieved at slower pumping rates.

5 CONCLUSIONS

Wastewater treatment HRAPs were easily constructed from earth within an existing oxidation pond and were shown to 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 was similar in the four replicate demonstration HRAPs.

Harvested algal biomass had a solids content of ~1% VS.

These preliminary results show reasonable replication of treatment performance and algal productivity between the four demonstration HRAP and were similar to previous results for pilot-scale HRAP with CO_2 addition during NZ summer conditions; and further indicate the potential for energy efficient and effective tertiary-level wastewater treatment using HRAP.

ACKNOWLEDGEMENTS

The authors would like to thank Christchurch City Council, particularly Mark Christison, Mike Bourke and Franz Resl for their ongoing support of this project. We also thank Greg Kelly for his assistance with operation and monitoring of the system. This research was funded by the Foundation for Research Science and Technology.

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