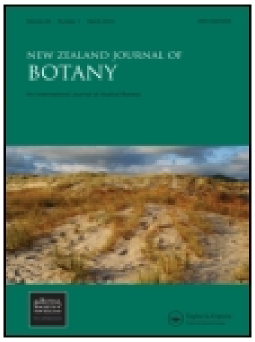

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RESEARCH ARTICLE

High rate algal pond systems for low-energy wastewater treatment, nutrient recovery and energy production

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High rate algal pond (HRAP) systems provide opportunities for low-energy wastewater treatment and energy recovery from wastewater solids, as well as biofuel production from the harvested algal biomass. The wastewater is pretreated using covered anaerobic ponds or gravity settlers and covered digester ponds which remove and digest the wastewater solids. The effluent is then treated in shallow gently mixed HRAP which efficiently breakdown the dissolved organic matter. The algae assimilate wastewater nutrients to provide both secondary and partial tertiary-level treatment. HRAP also provide more efficient natural disinfection. HRAP performance can be further enhanced by bubbling CO_2 into the pond during the day to promote algal growth when it is often carbon-limited. This paper discusses the design and operation and performance of HRAP systems and their application for economical, low-energy upgrade of conventional wastewater treatment ponds combined with energy recovery and biofuel production.

Keywords: biogas; covered anaerobic ponds; digester; disinfection; high rate algal ponds; nutrient removal

Introduction

Wastewater treatment ponds provide opportunities for low-energy wastewater treatment and energy recovery from wastewater solids, as well as biofuel production from the harvested algal biomass (Oswald & Golueke 1960; Benemann & Oswald 1996; Craggs et al. 2011). Worldwide many thousands of communities, industries and farms use two-stage pond systems for wastewater treatment (e.g., in New Zealand, NZMWD 1974; NZDEC 2006). These systems are cost-effective, require little maintenance and generally perform well in terms of the removal of wastewater organic solids. However, nutrient (N, P) removal, algal solids removal and disinfection are highly inconsistent, and the discharge of poor-quality effluents may negatively impact 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 optimize the recovery of natural resources from wastewater, including energy as biogas, water as effluent treated to a consistently high standard, and nutrients as algal/bacterial biomass for fertilizer, feed or biofuel use. Annual average algal/bacterial productivity in conventional facultative ponds is typically little more than 2.5 g m^{-2} d (ash free dry weight), but when this biomass accumulates it can exert a considerable organic load on receiving waters (Davies-Colley et al. 1995; Craggs et al. 2003). Communities, industries and farmers face a considerable financial burden if they replace or upgrade existing pond systems using 'mechanical' treatment systems such as packaged activated sludge plants. Thus there is a critical need for a cost-effective alternative upgrade option for pond systems. Since there has already been considerable investment in pond technology, it makes good

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*Corresponding author. Email: r.craggs@niwa.co.nz economic sense to upgrade treatment by making use of existing pond infrastructure.

High rate algal pond (HRAP) systems provide a particularly cost-effective approach as a pond-based retrofit, while also being cost competitive for new waste treatment facilities. HRAP systems incorporate many improvements on conventional wastewater treatment ponds. They require similar or less land area, virtually eliminate sludge disposal, produce little odour and are capable of consistently providing a higher degree of nutrient removal and disinfection. Moreover, HRAP systems are much easier to operate and are more economical than mechanical treatment systems and have the co-benefits of enhancing algal production for beneficial use (feed or biofuel), recovering wastewater nutrients for fertilizer use and offsetting greehouse gas emissions.

HRAP systems are a development of advanced integrated wastewater pond systems (AIWPS) that were developed by Oswald and co-workers at the University of California at Berkeley from the late 1950s. (Oswald 1991; Green et al. 1995; Oswald 1996; Craggs 2005). Several systems are operating in northern Californian cities today, such as St Helena (constructed in 1967) and Hilmar (constructed in 2000) (Fig. 1). HRAP systems are a 'quantum leap' over conventional ponds because they integrate ecological engineering principles and incorporate many different (physical, chemical and microbiological) natural treatment processes. The diversity of natural treatment processes that occurs in the different components of the system enables HRAP systems to be much more resilient and robust than mechanical treatment. HRAP systems essentially consist of four main unit processes arranged in series (e.g., Fig. 2):

1. wastewater solids removal and subsequent ambient temperature anaerobic digestion;
2. aerobic treatment by sunlight-powered algal growth on the supernatant;
3. algal removal and subsequent conversion to biofuel; and
4. further polishing of the treated effluent as required.

Wastewater solids removal and anaerobic digestion

Wastewater solids can either be settled and digested in covered anaerobic ponds (Fig. 3), or concentrated in a gravity settler (primary clarifier) and subsequently digested in covered digester ponds (Fig. 4). These simple ambient temperature digesters provide low-cost, but efficient anaerobic digestion.

Covered anaerobic ponds

Covered anaerobic ponds (CAP) are deep to promote the sedimentation of wastewater solids and anaerobic decomposition to methane. The surface of the pond is covered to prevent odour release and collect biogas for energy recovery. Conventional anaerobic ponds are widely used for the treatment of agricultural, industrial and municipal wastewaters (McGrath & Mason 2004; Park & Craggs 2007). Anaerobic ponds are simple, usually unheated anaerobic digesters operating in the psychrophilic temperature range (below 35 °C), with operating temperature varying with ambient temperature. Below 35 °C, volatile solids (VS) reduction and biogas production rates decrease almost linearly with decreasing temperature (Henze 1995), thus anaerobic ponds require a longer solids retention time than expensive, mixed, heated (mesophilic, c. 35 °C) digesters to achieve the same VS reduction (Stevens & Schulte 1977; Cullimore et al. 1985).

Conventional anaerobic ponds in New Zealand have been primarily designed for VS and biochemical oxygen demand $(BOD)_5$ reduction through the sedimentation of wastewater solids with typically > 70% removal of total solids (TS) and > 80% removal of VS achieved (Heubeck et al. 2010). These anaerobic ponds are uncovered, allowing biogas (comprising primarily of CH_4 and CO_2) to escape to the atmosphere, contributing to greenhouse gas and odour emissions. Annual average biogas methane production by New Zealand pig and dairy farm CAPs based on the VS loading (0.22–0.26 m^3 CH_4/kg VS_{added}) is similar to that of mesophilic digesters, although CAP methane production shows a pronounced seasonal variation (Park and Craggs 2007; Craggs et al. 2008; Heubeck et al. 2011).The long solids retention times (1–5 years) of CAPs

Figure 1 Photographs of St Helena and Hilmar advanced integrated wastewater pond systems in northern California, USA. Courtesy of Tryg Lundquist.

Figure 2 Photograph of a covered anaerobic HRAP system in the Waikato, New Zealand.

compared with mesophilic digesters (10–20 days) appears to fully compensate for the lower operating temperature and lack of mixing.

Earth-sealed perimeter covers are used to capture and store the biogas produced by the CAP. Various plastic membrane materials can be used as cover materials [including high-density polyethylene (HDPE) and polypropylene]. The cover does not require in-built flotation, but an array of weight pipes is needed for rainwater guidance. Rainwater is

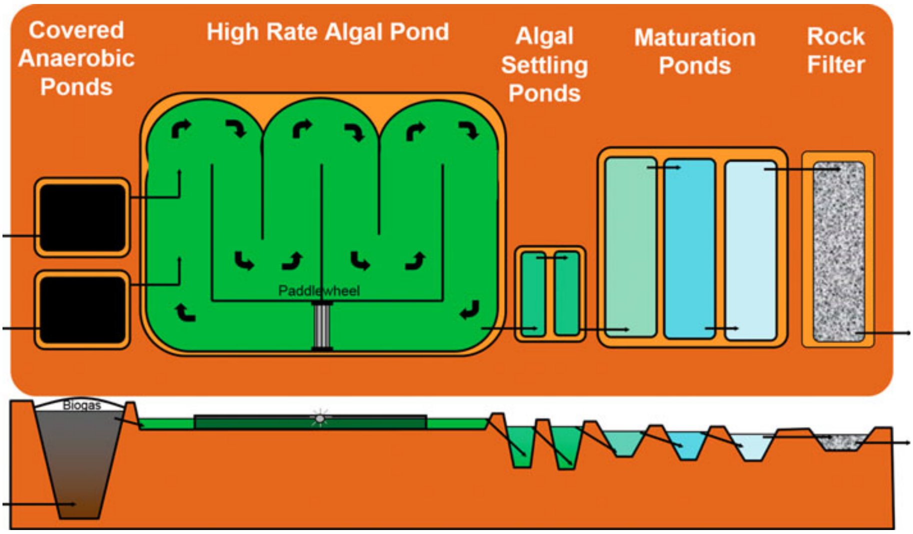

Figure 3 Schematic diagram of a high rate algal pond system with HRAP, CAP, algal settling ponds, maturation ponds and rock filter.

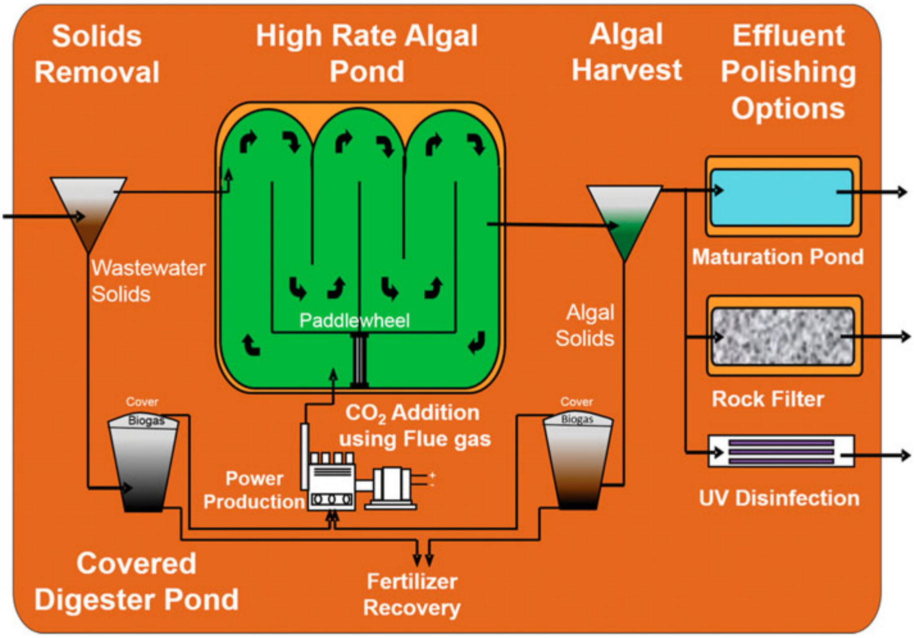

Figure 4 Schematic diagram of an HRAP system with CO_2 addition.

removed from the cover by a float-switch-operated submersible pump. Biogas draw-off from the cover is accomplished using a 100 mm perforated poly (vinyl chloride) (PVC) pipeline around the pond perimeter under the cover, connected through the cover to a centrifugal gas blower that extracts the biogas for use.

Covered digester ponds

Wastewater solids are transferred from a gravity settler (primary clarifier) to the covered digester pond (CDP). For larger systems, solids transfer may be continuous, but for smaller systems, transfer every hour or even every four hours is adequate. CDPs are designed in a similar way to CAPs except that they have a much smaller volume as the wastewater solids have been separated from the wastewater in the gravity settler and/or the algal solids have been concentrated in an algal harvest tank (see below). CDPs are designed to gradually fill over time so, unlike CAPs, have an increasing liquid volume (and depth). The floating pond surface cover must be designed to accommodate the variable water level. Once full, the supernatant digestate is removed, but the settled wastewater and/or algal solids can remain in the pond for many years to digest fully. Both the supernatant digestate and digested solids have value as a liquid fertilizer and soil amendment, respectively.

Uses of biogas

Biogas methane has an energy content of 33.8 MJ m^{-3} (0.67 kg) CH_4 at standard temperature and pressure (equivalent to c. 1 L of petrol) and can be used directly for heating (9.39 kWh_{heat} m^{-3} CH_4) or electricity generation at 30% conversion efficiency (2.82 kWh_e m^{-3} CH_4 and simultaneous heat generation c. 4.70 kWh_{heat} m^{-3} CH_4). This power can be used to displace the electricity requirements of the wastewater treatment plant, with any surplus exported to the grid (though this would require additional capital investment for transformers, line upgrades, etc.). Biogas can also be cleaned (desulfurized, stripped of CO_2), dried and compressed (> 20 MPa) for export into natural gas pipelines or use as a transport fuel. Much of the purification (removal of dust CO_2 and H_2S) could be achieved by scrubbing with HRAP water (Conde et al. 1993; Mandeno et al. 2005).

High rate algal ponds

The supernatant from CAPs or gravity settlers is treated in a HRAP. HRAP are shallow, paddlewheel mixed, raceway ponds that were developed for wastewater treatment and resource recovery in the late 1950s by Oswald and colleagues (Oswald & Golueke 1960; Benemann et al. 1980b; Oswald 1988a,b; Craggs 2005). Organic loading rate, depth, hydraulic retention time and horizontal mixing velocity are the main operational control variables for HRAP. Depending on climate, the maximum organic loading rate of HRAP is between 100 and 150 kg BOD_5 ha^{-1} d. HRAP depth is dependent on wastewater clarity (typically 0.2–0.6 m) and in temperate climates, hydraulic retention time varies seasonally (3–4 d in summer and 7–9 d in winter). Paddlewheel mixing (typically 0.15–0.30 m s^{-1}) causes turbulent eddies that provide a vertical mixing component within the pond so that algal cells are intermittently exposed to sunlight. Paddlewheel mixing (Fig. 5) also selects for colonial algal species that are usually outcompeted in facultative ponds as the colonies settle faster than unicellular algae in quiescent water.

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/bacterial biomass for beneficial use as fertilizer, feed or biofuel. HRAP efficiently collect sunlight energy and convert it into algal biomass and photosynthetic oxygen production to promote aerobic bacterial decomposition of the remaining dissolved organic matter in the wastewater. Daytime algal photosynthesis in the HRAP can cause supersaturation of dissolved oxygen with concentrations of over 20 g m^{-3}. HRAP paddlewheels have only one-tenth of the energy requirement of mechanical aeration,

Figure 5 Photograph of a HRAP paddlewheel, Christchurch, New Zealand.

which is very energy intensive. The HRAP algae assimilate the wastewater nutrients (ammoniacal-N and phosphate that might otherwise cause eutrophication of receiving waters) to provide both secondary and partial tertiary-level treatment (Oswald 1988a; Craggs 2005). HRAP provide more efficient natural disinfection than conventional wastewater treatment ponds, since the shallow depth enhances the rate of sunlight inactivation of faecal microbes, and promotes photo-oxidation of dissolved organic contaminants (Davies-Colley 2005). Algal photosynthesis raises the daytime pH of the HRAP which contributes to nutrient removal by promoting the volatilization of ammonia and precipitation of phosphates.

HRAP biomass is typically composed of 70–90% algae, with the balance mainly made up of bacteria and detritus with some invertebrates, fungi and viruses (Benemann et al. 1980b; Azov et al. 1982; Lundquist 2008). HRAP tend to select for algal strains that thrive under the diurnally varying conditions for sunlight, temperature, pH and dissolved O_2 (Weissman et al. 1988). The annual biomass productivity of wastewater treatment HRAPs without CO_2 addition at moderate latitudes and Mediterranean climates is typically 30 t ha^{-1} y (ash free dry wt), which is 2–3 times higher than the annual productivity of conventional facultative ponds (10–15 t ha^{-1} y; Benemann et al. 1980b; Craggs et al. 1998, 2003, 2011).

CO_2 addition

HRAP performance, particularly nutrient removal and algal production, is often depressed by severe daytime carbon limitation, indicated by high pond water pH levels (typically above 10), due to the photosynthetic uptake of CO_2 and bicarbonate (Oswald 1988a; Garcia et al. 2000; Craggs 2005; Kong et al. 2010; Park & Craggs 2010). Carbon limitation is due, in part, to the low C : N ratio of wastewaters (typically 3:1 to 4:1 for municipal wastewater) compared with algal biomass (typically 6:1, ranging from 10:1 to 5:1 depending on whether N is limiting or not; Benemann et al. 1980a; Lundquist et al. 2008). Thus, domestic wastewaters contain insufficient C to remove all the N (and P) by direct assimilation into algal biomass. More importantly, C limitation, and the concomitant rise in pond water pH above 8.5, severely depresses the growth rates and productivity of algae (Weissman & Goebel 1987; Kong et al. 2010), although, by using available bicarbonate, some algal species are able to grow (with low productivity) even above pH 10. The inhibition of algal growth at high pH in wastewater treatment HRAP might also be due in part to high levels of free ammonia at high pH (Azov & Goldman 1982; Azov et al. 1982; Konig et al. 1987). Further, intense photosynthesis in HRAPs also increases daytime dissolved O_2 levels, typically to 200–300% saturation. Supersaturation of oxygen promotes bacterial degradation of wastewater organic compounds, however, it can inhibit algal productivity, particularly at high pH and carbon limitation (Weissman et al. 1988). High pond pH, above c. 8.5, can also inhibit the growth of aerobic heterotrophic bacteria that oxidize wastewater organic matter to CO_2 (Craggs 2005).

Addition of CO_2 to wastewater treatment HRAPs (Fig. 6) increases the carbon availability and enables pond water pH to be maintained at an optimum (pH 7.5–8.5) for both algae and bacteria. The annual average biomass productivity of wastewater treatment HRAPs can potentially be doubled with CO_2 addition to 16–20 g m^{-2} d (Heubeck et al. 2007; Park & Craggs 2010, 2011). CO_2 addition also promotes nutrient removal by assimilation into algal biomass. A local source of CO_2 for wastewater treatment HRAPs can be found in CO_2-rich flue gas from use of biogas captured in the CAP or CDP to produce electricity (Eisenberg et al. 1981; Benemann 2003).

Algal removal

The colonial microalgal species that predominate in HRAP (e.g., *Scenedesmus* sp., *Micractinium* sp., *Actinastrum* sp., *Pediastrum* sp., *Dictyosphaerium* sp. and *Coelastrum* sp.) naturally settle by gravity when removed from the mixing of the HRAP into simple algal settling ponds or shorter hydraulic retention time algal harvest tanks (Benemann et al. 1980b; Oswald 1988a; Banat et al. 1990; Green et al. 1996; Wells 2005; Heubeck et al. 2007; Park

Figure 6 Photograph of the Christchurch demonstration HRAP CO_2 addition sump showing dividing baffle and CO_2 addition manifold pipe.

& Craggs 2010). Removal efficiency is improved by bioflocculation/aggregation of the algal colonies when CO_2 is added to the HRAP or a portion of the settled algae is recycled back to the HRAP in a similar way to sludge recycle in the activated sludge process (Benemann et al. 1980b; Eisenberg et al. 1981; Park & Craggs 2010).

Algal settling ponds and algal harvest tanks

Algal settling ponds enable natural settling of the algal biomass and provide storage for the periodic recovery of the settled algae. Algal harvest tanks (Fig. 7) are engineered to promote efficient gravity settling using lamella plates and secondary thickening of settled algae to

1–3% solids. Settled algal biomass is removed continuously or daily (for small systems) to avoid deterioration of the harvested algae before beneficial use.

Algal biomass use

The algal biomass can be recovered for fertilizer use because it is rich in nitrogen, phosphorus and potassium. Algal biomass also has potential to be used as animal feed, converted to biofuel or used as a substrate for the chemical industry. Biofuel conversion of wastewater-grown algal/bacterial biomass could provide a valuable niche distributed energy source for local communities and was first proposed by Oswald & Golueke (1960). The simplest biofuel option to apply at wastewater treatment HRAP is anaerobic digestion in CDPs either separately or in combination with wastewater solids.

Further treatment

Depending upon the requirements for effluent discharge water quality, further polishing of the HRAP system effluent may be required. One or a combination of the following may be used:

- maturation ponds, to provide further solar-UV disinfection and polishing of the wastewater, and enable effluent storage before discharge or subsequent reuse (Oswald 1990, 1991; Craggs 2005);
- rock filter, to reduce effluent solids levels following a maturation pond;
- UV disinfection, to replace maturation ponds if there is insufficient land;
- membrane filter, to provide a very high-quality effluent for reuse.

Treatment performance

HRAP systems can be used to provide more effective aerobic treatment (oxidation of wastewater

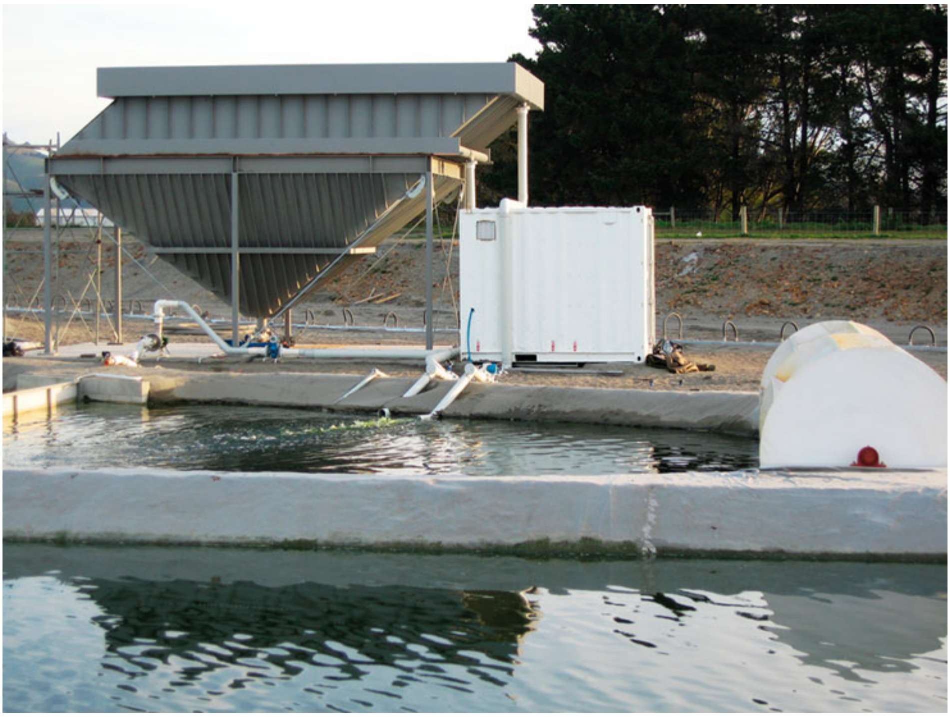

Figure 7 Photograph of the Christchurch demonstration algal harvester tank containing lamella plates.

organic compounds, BOD) and improved removal of nutrients, faecal indicators and algal biomass than facultative pond systems. Moreover, HRAP systems are much more cost-effective and energy efficient than electromechanical wastewater treatment technologies, providing an equivalent level of wastewater treatment. Over the last 12 years, National Institute of Water and Atmospheric Research Ltd has developed and evaluated HRAP systems under New Zealand conditions and has calibrated the design and operation of the system (Fig. 8). HRAP systems consistently provide higher effluent quality than conventional pond systems by: (1) removal of wastewater solids (TSS), and particulate BOD through settling and anaerobic digestion in anaerobic ponds; (2) complete anaerobic digestion reducing sludge handling to annual removal; (3) natural disinfection with minimal the use of artificial UV treatment; and (4) high nutrient removal (particularly of potentially toxic ammonia).

HRAP systems can be designed to treat wastewater to all but the most stringent discharge requirements. The typical effluent quality of HRAP systems with and without CO_2 addition compared with conventional wastewater pond systems treating domestic sewage is given in Table 1.

Improved phosphorus removal

HRAP systems effluent phosphorus concentrations can be reduced by the addition of low levels of chemical flocculant to the HRAP effluent before the algal settling pond/algal harvest tank. Chemical flocculant addition leads to an improvement in most HRAP systems effluent quality variables (Table 2).

Reduced footprint

Replacing the CAP with a primary sedimentation tank followed by an algal digester pond, the algal settling ponds with algal harvest ponds and maturation ponds with UV disinfection, would almost half the footprint of HRAP systems, enabling them to be installed at many more wastewater treatment plants.

Figure 8 Photograph of the 5 ha HRAP system operating at Christchurch, New Zealand.

Table 1 Typical effluent quality of HRAP systems (with MP and rock filter) with and without CO_2 addition compared with conventional wastewater treatment ponds in New Zealand.

Water quality variable	Conventional WSP		HRAP systems + MP + rock filter		HRAP systems with CO_2 addition	
	Median	95 percentile	Median	95 percentile	Median	95 percentile
BOD_5 ($g\ m^{-3}$)	< 40	< 110	< 15	< 50	< 15	< 40
TSS ($g\ m^{-3}$)	< 80	< 150	< 15	< 60	< 15	< 40
NH_4-N ($g\ m^{-3}$)	< 10	< 30	< 5	< 20	< 2	< 10
TKN ($g\ m^{-3}$)	< 20	< 50	< 10	< 40	< 5	< 15
DRP ($g\ m^{-3}$)	< 10	< 15	< 5	< 10	< 2	< 5
TP ($g\ m^{-3}$)	< 10	< 15	< 7	< 15	< 5	< 10
E. coli (MPN/100 mL)	< 40 000	< 400 000	< 100	< 1000	< 100	< 1000

Table 2 Typical effluent quality of HRAP systems (with MP and rock filter) and P flocculation.

Water quality variable	HRAP systems + MP + rock filter + P flocculation	
	Median	95 percentile
BOD_5 ($g\ m^{-3}$)	< 10	< 30
TSS ($g\ m^{-3}$)	< 10	< 30
NH_4-N ($g\ m^{-3}$)	< 4	< 15
TKN ($g\ m^{-3}$)	< 5	< 15
DRP ($g\ m^{-3}$)	< 1	< 5
TP ($g\ m^{-3}$)	< 2	< 10
E. coli (MPN/100 mL)	< 100	< 1000

Economics of HRAP systems

Capital and operating costs of HRAP systems for secondary wastewater treatment (BOD_5 removal) are estimated to be only one quarter to one third those of electromechanical secondary-level activated sludge treatment (Green et al. 1995; Downing et al. 2002). Similar or even lower ratios would likely apply in comparing tertiary treatment (nutrient removal) with the HRAP systems to electromechanical systems that achieve nutrient removal.

The capital and operating costs of algal production and harvesting in HRAP systems are essentially fully covered by the wastewater treatment function, with biofuels a relatively minor co-product, which does not significantly impact the overall system economics. 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). 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 fertilizer use, and offset greenhouse gas emissions.

Environmental benefits of HRAP systems

Beyond economics, algal wastewater treatment with co-production of biofuels has fewer environmental impacts (‘footprint’) in terms of land, water, energy and fertilizer use than schemes for algal biomass production exclusively for biofuels (Borowitzka 1999, 2005; Benemann 2003; Tampier 2009; Clarens et al. 2010). The environmental benefits, from greenhouse gas abatement and sustainability in general, also strongly favour HRAP systems compared with electromechanical treatment processes (typically advanced activated sludge systems). Algal biofuel production from wastewater treatment HRAP with CO_2 addition abates greenhouse gas emissions by several mechanisms (Benemann 2003; Lundquist et al. 2010): (1) reduction in energy use (mostly electricity and greenhouse gas emissions from fossil fuel use for generation); (2) substitution of biofuels for fossil fuels (such as biogas-generated electricity) offsets greenhouse gas emission from fossil fuel use for generation; (3) use of recovered wastewater nutrients and carbon in algal biofuel residues as fertilizer offsets greenhouse gas emissions associated with nitrogenous fertilizer production and phosphate rock mining.

Conclusions

Municipal wastewater treatment using HRAP systems with CO_2 addition, and with algal biofuels as co-products provides the potential for energy-efficient and effective tertiary-level wastewater treatment at significantly lower costs compared with electromechanical technologies. Wastewater enriched with biogas or flue gas CO_2 is an excellent growth medium (water, nutrients and buffering) for naturally occurring algae. Bioflocculation of algal biomass followed by settling is a very promising low-cost approach to algal harvesting. Of the several pathways to convert harvested algal biomass to biofuel, anaerobic digestion of algal biomass along with the settled wastewater solids would be the easiest to apply as the capital and operation costs of anaerobic digestion and biogas use infrastructure would be funded by the wastewater treatment plant. Harvesting algae from wastewater treatment HRAP effluent enables recovery of wastewater nutrients that can be recycled as fertilizer after biofuel conversion. Wastewater treatment HRAP also provide GHG abatement from a combination of low-energy wastewater treatment, renewable fuel production and fertilizer recovery.

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