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Increased pond depth improves algal productivity and nutrient removal in wastewater treatment high rate algal ponds

Donna L. Sutherland[a,b,*], Matthew H. Turnbull[b], Rupert J. Craggs[c]

[a] National Institute of Water and Atmospheric Research Ltd. (NIWA), PO Box 8602, Christchurch, New Zealand
[b] School of Biological Sciences, University of Canterbury, Christchurch, New Zealand
[c] National Institute of Water and Atmospheric Research Ltd. (NIWA), PO Box 11-115, Hamilton 3200, New Zealand

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ABSTRACT

Depth has been widely recognised as a crucial operational feature of a high rate algal pond (HRAP) as it modifies the amount of light and frequency at which microalgal cells are exposed to optimal light. To date, there has been little focus on the optimisation of microalgal performance in wastewater treatment HRAPs with respect to depth, with advice ranging from as shallow as possible to 100 cm deep. This paper investigates the seasonal performance of microalgae in wastewater treatment HRAPs operated at three different depths (200, 300 and 400 mm). Microalgal performance was measured in terms of biomass production and areal productivity, nutrient removal efficiency and photosynthetic performance. The overall areal productivity significantly increased with increasing depth. Areal productivity ranged from 134 to 200% higher in the 400 mm deep HRAP compared to the 200 mm deep HRAP. Microalgae in the 400 mm deep HRAP were more efficient at NH_4–N uptake and were photosynthetically more efficient compared to microalgae in the 200 mm deep HRAP. A higher chlorophyll-*a* concentration in the 200 mm deep HRAP resulted in a decrease in photosynthetic performance, due to insufficient carbon supply, over the course of the day in summer (as indicated by lower α, P_{max} and oxygen production) compared to the 300 and 400 mm deep HRAPs. Based on these results, improved areal productivity and more wastewater can be treated per land area in the 400 mm deep HRAPs compared to 200 mm deep HRAPs without compromising wastewater treatment quality, while lowering capital and operational costs.

1. Introduction

High rate algal ponds (HRAPs) are an advanced pond first developed in the 1950s for the treatment of wastewater and resource recovery (Oswald and Golueke, 1960) that consist of an open, paddlewheel mixed, shallow, raceway pond. With increased pressure to reduce nutrient loading from wastewater discharges, there has been renewed interest in improving the performance of HRAPs for domestic and agricultural wastewater treatment. HRAPs offer advanced wastewater treatment over traditional waste stabilisation

* *Corresponding author*. School of Biological Sciences, University of Canterbury, Christchurch, New Zealand. Tel.: +64 3 348 8987; fax: +64 3 348 5548.
E-mail addresses: Donna.Sutherland@niwa.co.nz (D.L. Sutherland), Matthew.Turnbull@canterbury.ac.nz (M.H. Turnbull), Rupert.Craggs@niwa.co.nz (R.J. Craggs).

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pond systems (WSPs) by overcoming many of their drawbacks, such as poor and highly variable effluent quality, limited nutrient and pathogen removal (Craggs et al., 2012). Another advantage of HRAPs over WSPs is the resource recovery of algal biomass, for use as fertilizer, protein-rich feed or biofuel, and water as effluent treated to a high standard (Craggs et al., 2012). While the use of HRAPs for biofuel production alone is not yet economical, the coupling of wastewater treatment with biofuel production is considered to be financially viable (Benemann, 2003; Rawat et al., 2011).

Fundamental to the success of both wastewater treatment and biofuel production is the optimisation of microalgal productivity. To further improve the economics of wastewater microalgae biofuel production it is important to achieve the highest yields of algal biomass in the shortest possible time (Grobbelaar, 2010). Even though HRAPs are an established technology, there are opportunities to further enhance microalgal biomass production and wastewater nutrient removal, while reducing capital costs.

Light plays a central role in microalgal productivity, providing the photon energy required in photosynthetic reactions to convert dissolved inorganic nutrients into organic molecules. The effective use of available light by microalgae to maximize photosynthetic efficiency is fundamental for the sustainable and economic production of biofuels (Borowitzka and Moheimani, 2013). Due to the very high algal concentrations in HRAPs light is rapidly attenuated through the water column forming a steep gradient over cm scales. This means that algae at the surface of HRAP are exposed to excessive light, whereas algae at the bottom of HRAP are in near darkness (Grobbelaar et al., 1990). How much light a microalgal cell receives in a HRAP is determined by pond depth, biomass concentration, and turbulence regime. Pond depth and biomass concentration determine the degree of light attenuation, while the turbulence regime determines the frequency at which a cell moves into and out of favourable light conditions.

Despite the fact that depth has been widely recognised as a crucial operation feature for modifying the light environment in HRAPs (Azov and Shelef, 1982; Grobbelaar, 2010), even the most recent literature reviews do not give any clear guidelines for HRAP depths. Optimal depths for HRAPs reported in literature range from 15 to 100 cm (Larsdotter, 2006; Park et al., 2011; Grobbelaar, 2012), while other recommendations include maintaining the HRAP as shallow as possible to provide the maximum amount of light to the algae and limiting pond depths to ensure sufficient light reaches the bottom of the pond (Kroon et al., 1989; Borowitzka, 2005). While a number of studies report on the effects of pond depth on mass cultured algae and cyanobacteria in terms of biomass concentrations and areal productivity, there has been little focus on the optimisation of algal performance in wastewater treatment HRAP. The aim of this study was to investigate the effects of wastewater treatment HRAP depth on the performance of green microalgae with respect to photosynthesis, biomass production and nutrient removal at seasonal scales.

2. Methods

2.1. *High rate algal pond operations and environmental variables*

The study was conducted outdoors at the Ruakura Research Centre Hamilton, New Zealand (37°47′S, 175°190′E). Duplicate treatments of three pond depths (200 mm, 300 mm and 400 mm) were established in identical HRAPs that were 2.2 m long and 1 m wide, with a surface area of 2.23 m^2. The paddlewheels were set to the same rotational speed that resulted in a linear velocity of 0.2 m s^{-1}. This meant that the time for a single blade of the paddlewheel to enter and exit the water varied between depth treatments (4 s for 200 mm, 6 s for 300 mm and 8 s for 400 mm). The HRAPs received primary settled domestic wastewater which was pumped into the ponds every 4 h over a 24 h period. Supplementary carbon was supplied to the ponds in the form of CO_2 gas. The CO_2 addition system consisted of a CO_2 gas cylinder, gas regulator, air pump, gas flow metre and gas diffusers (0–12 L/min range). The CO_2 gas was blended with air (via the air pump) to provide a CO_2 concentration of 1%. The 1% CO_2 was bubbled into the ponds through a gas diffuser placed on the pond bottom just before the paddlewheel. The CO_2 was added to the ponds at a constant flow rate of 1.6 L per minute, regardless of pond depth. At the start of the experiment the HRAPs were inoculated with wastewater algae from an adjacent pilot-scale HRAP (volume 8 m^3), which was dominated (90%) by the colonial green alga *Mucidosphaerium pulchellum* (HC Wood) C. Bock, Proschold & Krienitz. Pond operation parameters are summarised in Table 1.

The environmental variables pH, conductivity, temperature and dissolved oxygen were measured at mid-pond depth

Table 1 – Seasonal pond operation parameters and environmental variables in HRAPs operated at different depths. Data are medians ± standard deviations.

Parameter	Winter			Spring			Summer		
	200 mm	300 mm	400 mm	200 mm	300 mm	400 mm	200 mm	300 mm	400 mm
Sampling months	June–August			September–November			December–February		
Retention time (days)	9	9	9	6	6	6	4	4	4
Daily inflow (L^{-1} d^{-1})	44.4	66.7	88.9	66.7	100	133.3	100	150	200
Pond Temp. (°C)	12.3 ± 2.5	12.2 ± 2.4	12.3 ± 2.4	10.9 ± 3	11.6 ± 2.8	12 ± 2.5	16.0 ± 2.4	16.1 ± 2.1	16.1 ± 1.9
Pond pH	7.5 ± 0.7	7.3 ± 0.9	7.2 ± 0.8	6.7 ± 0.8	6.6 ± 0.9	7.0 ± 0.7	7.5 ± 0.8	7.4 ± 0.6	7.6 ± 0.6
Pond conductivity (μS cm^{-1})	390 ± 154	428 ± 172	512 ± 153	506 ± 303	520 ± 340	576 ± 417	533 ± 104	586 ± 99	590 ± 135
Pond dissolved oxygen (% saturation)	114 ± 13	107 ± 17	106 ± 14	97 ± 18	96 ± 24	92 ± 13	91 ± 27	84 ± 17	77 ± 19