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REVIEW

Mini-review: high rate algal ponds, flexible systems for sustainable wastewater treatment

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Abstract Over the last 20 years, there has been a growing requirement by governments around the world for organisations to adopt more sustainable practices. Wastewater treatment is no exception, with many currently used systems requiring large capital investment, land area and power consumption. High rate algal ponds offer a sustainable, efficient and lower cost option to the systems currently in use. They are shallow, mixed lagoon based systems, which aim to maximise wastewater treatment by creating optimal conditions for algal growth and oxygen production—the key processes which remove nitrogen and organic waste in HRAP systems. This design means they can treat wastewater to an acceptable quality within a fifth of time of other lagoon systems while using 50% less surface area. This smaller land requirement decreases both the construction costs and evaporative water losses, making larger volumes of treated water available for beneficial reuse. They are ideal for rural, peri-urban and remote communities as they require minimum power and little on-site management. This review will address the history of and current trends in high rate algal pond development and application; a comparison of their performance with other systems when treating various wastewaters; and discuss their potential for production of added-value products. Finally, the review will consider areas requiring further research.

Keywords Algae · High rate algal ponds · Wastewater · Wastewater treatment

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Introduction

In recent years, there has been an increase in interest and research regarding high rate algal ponds (HRAP). This has largely been driven by their potential to grow large amounts of algae from which value-added products may be derived, rather than by their potential application to more sustainable wastewater treatment. The mini-review specifically focusses on the application of HRAPs for wastewater treatment and considers the secondary benefit of biomass production and utilisation, while also identifying knowledge gaps and the need for future research.

High rate algal ponds, past, present and future

HRAPs were developed at the University of California in the middle of the twentieth century while investigating the use of algal biomass for wastewater treatment (Oswald et al. 1957; Oswald and Golueke 1960). The term 'high-rate pond' was first used by Oswald (1963) to describe open raceway ponds that differ from other pond systems in that they aim to maximise their algal biomass concentration to increase their wastewater treatment efficiency (Fig. 1) (Bahlaoui et al. 1997). Since their initial development in the USA, HRAPs have been operated in many countries including Israel (Shelef and Azov 1987), France (Picot et al. 1991), Morocco (El Hamouri 2009), the United

Fig. 1 Two high rate algal ponds at Melbourne Water Western Treatment Plant, Australia designed by the authors and fed anaerobic and facultative lagoon treated domestic wastewater

Kingdom (Fallowfield and Garrett 1985b), Spain (García et al. 2008), Australia (Young et al. 2016), China and New Zealand (Craggs et al. 2003a). Due to their reliance on algal photosynthesis, they are better suited and more easily operated in arid, semi-arid and tropical climates (Garcia et al. 2006; Sahoo and Seckbach 2015). They have been used to treat a variety of wastes including domestic (Chen et al. 2003), tannery (Rose et al. 1996), dairy (Craggs et al. 2003b) and piggery (Fallowfield and Garrett 1985a).

HRAPs are considered a low-cost wastewater treatment system compared to conventional electromechanical systems with construction costs typically ~70% less than activated sludge systems, the major wastewater treatment system in the USA (DOE 2016). Operation cost is also reduced for HRAP as they require substantially less energy than activated sludge systems (Shilton et al. 2008; Woertz et al. 2009; Craggs et al. 2011). This reduction in energy not only reduces cost but also reduces greenhouse gas emissions making them an option to improve the sustainability of wastewater treatment trains (Acién et al. 2016). Due to their low-cost and simple operation HRAPs are ideal for operation for rural, peri-urban and remote communities when land availability is not constrained (Garcia et al. 2006; Acién et al. 2016; DOE 2016). Currently, these communities largely employ waste stabilisation ponds (WSP) as low-cost wastewater treatment systems. Using the descriptions in Buchanan (2014), an infrastructure and associated cost comparison between an in series facultative—maturation pond HRAP and a five cell WSP system, commonly used in rural South Australia, was undertaken (Table 1). The scenario assumed a population served of 700 persons with a flow of 140 l per person per day equalling a total wastewater flow of 100 kl d^{-1}. Given these assumptions, the cost of constructing the HRAP system was 39.2% of the WSP when operated at a depth of 0.32 and 47.5% when operated at a depth of 0.43 m.

There has been extensive research into the ability of HRAPs to treat standard wastewater parameters (Table 2). Reported 5-day biological oxygen demand (BOD_5) removal rates range between 22–93.4% with a median of 59% (Banat et al. 1990; El Hamouri et al. 1995; Craggs et al. 2003a; El Hafiane and El Hamouri 2005; Buchanan 2014; Young et al. 2016). The removal of nitrogen and ammonium is considered to be mainly through incorporation into algal biomass and pH-dependent ammonia volatilisation with limited nitrification having been reported as well (Cromar et al. 1996; Garcia et al. 2000; Craggs et al. 2003a). The reported removal of total nitrogen ranges between 26.6–75.7% with a median of 61.23% (Shelef et al. 1982; Banat et al. 1990; Picot et al. 1991, 1992; Chen et al. 2003; Craggs et al. 2003a; El Hafiane and El Hamouri 2005; Park and Craggs 2011) and ammonium removal ranges between 21.89–94% with a median 77% (Wood et al. 1989; Banat et al. 1990; Picot et al. 1991, 1992; El Hamouri et al. 1995; Craggs et al. 2003a; El Hafiane and El Hamouri 2005; Park and Craggs 2011; Buchanan 2014; Sutherland et al. 2014a). The two main mechanisms of phosphorus removal are thought to be through incorporation into the algal biomass and pH-dependent precipitation. Reports of total phosphorus removal ranges between 10.48–97.2% with a median of 42.73% (Shelef et al. 1982; Picot et al. 1991, 1992; Chen et al. 2003; El Hafiane and El Hamouri 2005; El Hamouri 2009; Sutherland et al. 2014a) and orthophosphate

Table 1 Comparison of the estimated infrastructure and associated costs of an in series, five cell facultative—maturation waste stabilisation pond system and an HRAP based on the descriptions by Buchanan (2014). The scenario assumed a population served of 700 persons with a flow of 140 l per person per day equalling a total wastewater flow of 100 m^{-3} d^{-1}. Assumptions made for HRAP pond design were external earth walls; 1:3 internal batter; internal plastic curtain walls; square shape—made for calculation simplicity and an HDPE liner buried 1.5 m all sides. A buffer tank was included in the HRAP design to manage short-term peak stormwater flows and prevent flushing out of the active biomass. Pricing used for earthworks was \$12 m^{-3} and for installed plastic was \$15 m^{-2} based on 2011 estimates with all prices in Australian dollars. The evaporation rate used was based on the pan evaporation rates typically experienced in South Australia, 1.8–2 m

Design parameters	High rate algal pond		Waste stabilisation pond
Pond depth (m)	0.32	0.43	1.2
Freeboard (m)	0.2	0.25	0.8
Surface area (m^2)	2500	3100	6000
Surface area as percentage of WSP (%)	41.6	47	100
Annual evaporative loss (m^3)	4500	5580	10,800
Evaporative loss as percentage of treated water (%)	12.3	15.3	29.6
Top dimensions (m)	51.7	57.9	81.1
Bottom dimensions (m)	50.0	55.7	77.5
Internal volume (m^3)	1348	2197	12,169
Liner area (m^2)	2831	3525	6816
Curtain area (m^2)	104	151	504
Earthworks as percentage of WSP (%)	11.1	18.1	100
Estimated construction costs	A\$	A\$	A\$
HDPE liner	44,030	55,139	109,801
Earthworks	16,82	26,362	146,023
Paddlewheel assembly	20,000	20,000	
Buffer tank	20,000	20,000	
Total construction	100,211	121,501	255,825
HRAP costs as a percentage of those for the WSP	39.2%	47.5%	100.0%

removals range between −3.75–71% with a median of 21.2% (Wood et al. 1989; Picot et al. 1991, 1992; El Hamouri et al. 1995; Chen et al. 2003; Craggs et al. 2003a; Buchanan 2014; Sutherland et al. 2014a). Disinfection in HRAPs is believed to be mainly dependent on solar irradiance (Craggs et al. 2004), pond depth and pH (Buchanan et al. 2011b) or all three (Fallowfield et al. 1996). Considering that depth influences the exposure of pond volume to solar radiation, and pH is influenced by algal photosynthesis which in turn is influenced by solar radiation exposure, it could be theorised that overall these studies suggest depth is the main factor on disinfection in HRAP. Reported $\log_{10}$ reduction values for *Escherichia coli* in HRAPs range between 1 and 3.01 $\log_{10}$ *E. coli* MPN 100 ml^{-1} with a median of 1.4 $\log_{10}$ *E. coli* MPN 100 ml^{-1} (Craggs et al. 2003a; Davies-Colley et al. 2003, 2005; El Hafiane and El Hamouri 2005; Buchanan 2014; Young et al. 2016). There is limited information on the removal of heavy metals by HRAPs, but the few existing studies point towards effective removal mainly through adsorption in algal and microbial biomass (Rose et al. 1998; Toumi et al. 2000). .

Algal biomass concentration is maximised by creating an environment conducive to photosynthesis through maximising the pond volume's exposure to solar radiation by shallow ponding and mixing (Rawat et al. 2011). Operational depths of HRAPs range between 0.2 and 0.8 m with the most common being ~0.3 m (Craggs et al. 2003a; Park and Craggs 2011). Gentle mixing is predominantly carried out by a paddlewheel at surface water velocities between 0.15 and 0.3 m s^{-1} (Sutherland et al. 2015). Increasing algal biomass concentration increases wastewater treatment efficiency as it increases the mutual breakdown of organic waste by algae and bacteria (Craggs et al. 2004; El Hamouri 2009). This results in HRAP providing faster treatment than non-mixed pond systems and as such HRAP systems can operate at shorter hydraulic retention times (HRT) or have higher organic loading rates (Green et al. 1996; Buchanan 2014) with typical HRT ranging between 4 and 10 days (Picot et al. 1992). The high rates of algal

Table 2 Dimensions, location and operating conditions of high rate algal ponds treating various wastewaters and their reported removals of standard wastewater parameters

Author	Wastewater	Length (m)	Width (m)	Surface area (m^2)	Depth (m)	HRT (days)	Removal						
							Coordinates	BOD_5 (%)	Total nitrogen (%)	Ammonia (%)	Total phosphorous (%)	Orthophosphate (%)	*E. coli* LRV (*E. coli* MPN 100 ml^{-1})
Banat et al. (1990)	Facultative treated domestic wastewater	10	5	–	0.45	5	29.37, 47.97	90.37	59.65	90	–	–	–
El Hamouri et al. (1995)	Grease/sand trap and anaerobic pond treated domestic wastewater	–	–	3023	0.4	4.2	Latitude 30.55	32	–	78.92	–	53.05	–
El Hamouri et al. (1995)	Grease/sand trap and anaerobic pond treated domestic wastewater	–	–	3023	0.4	4.2	Latitude 30.56	45.13	–	21.89	–	30.51	–
Buchanan (2014)	Septic tank treated domestic wastewater	–	–	192	0.32	4.5	−34.14, 140.14	93.4	–	69.8	–	18.9	1.741
Buchanan (2014)	Septic tank treated domestic wastewater	–	–	208	0.43	6.4	−34.14, 140.15	92.5	–	73.5	–	21.2	2.079
Buchanan (2014)	Septic tank treated domestic wastewater	–	–	226	0.55	9.1	−34.14, 140.16	90.2	–	61.1	–	6.5	1.977
Buchanan (2014)	Facultative treated domestic wastewater	–	–	192	0.32	4.5	−34.14, 140.17	72	–	72	–	0.1	2.52
Buchanan (2014)	Facultative treated domestic wastewater	–	–	208	0.43	6.4	−34.14, 140.18	59	–	83	–	0.1	2.12

Table 2 (continued)

Author	Wastewater	Length (m)	Width (m)	Surface area (m^2)	Depth (m)	HRT (days)	Removal						
							Coordinates	BOD_5 (%)	Total nitrogen (%)	Ammonia (%)	Total phosphorous (%)	Orthophosphate (%)	*E. coli* LRV (*E. coli* MPN 100 ml^{-1})
Buchanan (2014)	Facultative treated domestic wastewater	–	–	226	0.55	9.1	−34.14, 140.19	51	–	35	–	0.02	3.01
Young et al. (2016)	Septic tank treated domestic wastewater	–	–	200	0.32	5	−34.14, 140.20	91.76	–	–	–	–	2.13
Shelef et al. (1982)	Bar-screened domestic wastwater	–	–	120	0.4	3.4	–	–	75.2	–	95.7	–	–
Shelef et al. (1982)	Bar-screened domestic wastwater	–	–	120	0.5	4.25	–	–	62.8	–	93.6	–	–
Shelef et al. (1982)	Bar-screened domestic wastwater	–	–	120	0.35	2.9	–	–	72.7	–	95.2	–	–
Shelef et al. (1982)	Bar-screened domestic wastwater	–	–	120	0.25	2	–	–	83.3	–	97.2	–	–
Picot et al. (1992)	Facultative treated domestic wastewater	13.4	3.6	48	0.35	8	43.42, 3.59	–	34.33	66.16	24.49	8.28	–
Chen et al. (2003)	Settling tank treated wastewater	–	–	–	0.3	8	31.70, 122.37	–	75.2	80.4	47.5	43.5	–
Chen et al. (2003)	Settling tank treated wastewater	–	–	–	0.3	4	31.70, 122.38	–	75.7	93.6	40.7	38.2	–
Park and Craggs (2011)	Anaerobic digested domestic wastewater	–	–	31.8	0.3	8	−37.78, 175.32	–	26.6	74.29	–	–	–
Wood et al. (1989)	Settling tank treated wastewater	22	11	–	0.4	–	−25.75, 28.19	–	–	73.76	–	32.7	–

Table 2 (continued)

Author	Wastewater	Length (m)	Width (m)	Surface area (m^2)	Depth (m)	HRT (days)	Removal						
							Coordinates	BOD_5 (%)	Total nitrogen (%)	Ammonia (%)	Total phosphorous (%)	Orthophosphate (%)	*E. coli* LRV (*E. coli* MPN 100 ml^{-1})
Picot et al. (1992)	Primary pond treated domestic wastewater	12.4	3.8	–	0.35	8	Latitude 43.00	–	30.54	92	31.58	71	–
Picot et al. (1992)	Primary pond treated domestic wastewater	12.4	3.8	–	0.35	4	43.42, 3.59	–	47.81	94	44.76	71	–
Sutherland et al. (2014a)	Primary treated domestic wastewater	–	–	12,500	0.35	7	−43.53, 172.68	–	–	47	37	–	–
Sutherland et al. (2014)	Primary treated domestic wastewater	–	–	12,500	0.35	9	−43.53, 172.69	–	–	53	22	–	–
Sutherland et al. (2014a)	Primary treated domestic wastewater	–	–	12,500	0.35	7	−43.53, 172.70	–	–	79	49	–	–
Sutherland et al. (2014a)	Primary treated domestic wastewater	–	–	12,500	0.35	5.5	−43.53, 172.71	–	–	77	20	–	–
El Hafiane and El Hamouri (2005)	Step up-flow anaerobic reactor and gravel filter treated domestic wastewater	–	–	790	0.35	3	33.98, −6.87	22	86	86	66	59	1.23
Craggs et al. (2003a)	Primary pond treated domestic wastewater	20.3	4.2	85	0.45	7.5	−37.30, 175.50	54.55	51.95	91	15.32	−3.75	1.42

Table 2 (continued)

Author	Wastewater	Length (m)	Width (m)	Surface area (m^2)	Depth (m)	HRT (days)	Removal							
							Coordinates	BOD_5 (%)	Total nitrogen (%)	Ammonia (%)	Total phosphorous (%)	Orthophosphate (%)	*E. coli* LRV (*E. coli* MPN 100 ml^{-1})
Craggs et al. (2003a)	Primary pond treated domestic wastewater	30.5	4.2	128.1	0.3	7.5	−37.30, 175.50	54.55	57.96	85	10.48	13.75	1.49
Davies-Colley et al. (2003)	Domestic wastewater	–	–	–	0.3	7.5	−37.30, 175.50	–	–	–	–	–	1
Davies-Colley et al. (2005)	Anaerobic digester treated domestic and laboratory wastewater	–	–	–	–	8	−37.78, 175.32	–	–	–	–	–	1
Davies-Colley et al. (2005)	Anaerobic digester treated domestic and laboratory wastewater	–	–	–	–	8	−37.78, 175.32	–	–	–	–	–	1

photosynthesis also produce high concentrations of dissolved oxygen and high pH levels which both fluctuate diurnally (Craggs et al. 2004). During peak solar radiation, dissolved oxygen concentrations can reach supersaturation, and pH levels can reach as high as 11 (Norvill et al. 2016).

As solar energy is the main energy source for HRAPs, the influence of depth and light attenuation on their wastewater treatment performance and biomass productivity has garnered research. Sutherland et al. (2014b) compared three pilot-scale HRAPs operated at different depths, 0.2, 0.3, 0.4 m. There was no significant difference between the depths in the removal of ammonia and orthophosphate relative to inflow, but in regards to the total amount of ammonia removed and algal productivity, the 0.4 m outperformed the other depths. Buchanan (2014) studied the influence of depth on the wastewater treatment performance of a full-scale HRAP. The HRAP was operated at three different depths, 0.32, 0.43, 0.55 m, while treating two different strengths of wastewater either septic tank treated domestic wastewater or the same wastewater further treated by a facultative pond. When treating septic tank treated wastewater the 0.43 m depth slightly outperformed the 0.32 m depth, and both outperformed the 0.55 m depth. When treating the facultative pond effluent, the 0.32 m depth had the best performance based on BOD_5 and *E. coli* removal while the 0.43 m depth had the best performance when removing ammonia. The results from both studies suggest that the optimal depth for a HRAP acting as a secondary wastewater treatment system is ~0.4 m and the results presented by Buchanan (2014) suggest the optimal depth for a HRAP acting as a tertiary wastewater treatment system is 0.32 m when removal of BOD_5 and *E. coli* are a priority and 0.43 m when ammonia removal is a priority. When interpreting these results, it should be considered that both these studies had limitations with Sutherland et al. (2014b) acknowledging that the light climate would be different in full-scale HRAPs and Buchanan (2014) only being able to run a single HRAP at a time meaning the different depths experienced different weather conditions. Ideally, to properly understand the effect of depth, two full-scale HRAPs should be operated concurrently at different depths while fed the same wastewater.

Comparison of high rate algal pond performance with other treatment systems

HRAPs have been considered as a replacement for other low-cost systems, mainly WSPs. However, before wide-scale replacement of WSP can occur, further comparisons of conventional wastewater treatment systems and HRAPs should be made under varied operational and geographic conditions. The comparison is made difficult as the performance of both systems can be affected by their specific location meaning that compared systems must be geographically close. This can be difficult to arrange, and consequently, there are only a few studies comparing their performance in this way (Picot et al. 1992; Toumi et al. 2000; El Hamouri et al. 2003; Buchanan et al. 2011a; Buchanan 2014). These studies have shown HRAPs have equal or better removal of standard wastewater parameters, with the one exception of orthophosphate removal in Buchanan (2014). The HRAPs also showed equal performance in the removal of pathogens and better performance in the removal of heavy metals (Picot et al. 1992; Toumi et al. 2000; El Hamouri et al. 2003; Buchanan et al. 2011a; Buchanan 2014). Toumi et al. (2000) demonstrated when compared to a facultative pond a HRAP was 1.3 times more efficient at removing zinc, ten times more efficient at removing copper and twice as efficient at removing lead.

This equivalence in treatment is significant because of the reduced time HRAPs take to achieve it—requiring at least 80% less HRT. This reduction in HRT means HRAPs have less standing volume than WSPs. Consequently, they are significantly smaller with estimated reductions in size of 40% (El Hamouri et al. 2003) and 60% (Buchanan 2014). This has two benefits, firstly construction costs, in particular, earthworks, are reduced with Buchanan (2014) estimating a reduction of 25–50%, and secondly, less treated effluent is lost by evaporation because of the reduction in surface area. This decrease in evaporative loss is of particular importance due to substantial reuse of wastewater for irrigation particularly in less affluent areas which commonly experience high evaporation loss (Jimenez 2007). It has been estimated the reduction in evaporative loss can be up to 90% (Buchanan et al. 2011a; Buchanan 2014). HRAPs have also been demonstrated to supersede WSPs in several further operational parameters: HRAPs do not require desludging; do not experience thermal stratification and hydraulic short-circuiting and produce higher concentrations of algal biomass which can be utilised (Fallowfield and Garrett 1985b; Cromar et al. 1996).

A notable disadvantage of HRAPs compared to WSPs is their requirement for a paddlewheel to mix the system, which can make it more difficult to operate the system where access to electricity is difficult. While there is no real solution to this problem, it is partially mitigated by the energy requirement being low so a small generator could be used (Shilton et al. 2008; Shoener et al. 2014). An ideal solution is to power the paddlewheel using solar panels, but the current cost would be prohibitive to the communities that would benefit the most, although it is predicted that in the near future there will be large drops in prices (Pinner and Rogers 2015).

Arbib et al. (2013) compared the wastewater treatment performance of an experimental HRAP to an experimental photobioreactor. The photobioreactor outperformed the HRAP in the removal of all standard wastewater parameters and produced a higher concentration of algal biomass (Arbib et al. 2013). Undermining this performance is the severe biofouling the photobioreactor experienced causing cessation of the experiment: something a HRAP would not experience (Arbib et al. 2013). It should also be considered that photobioreactors cost substantially more to construct and operate as well as being more challenging to up-scale, all of which limit their application compared to HRAPs (Munoz and Guieysse 2006).

Potential for production of added value products

The use of the wastewater-grown algal biomass for the production of value-added products has long been seen as a major attraction of HRAPs (Oswald and Golueke 1960; Shelef et al. 1982). Potential uses for the algal biomass include biofuel, animal feed, pigment production and fertiliser (Christenson and Sims 2011; Craggs et al. 2011). The low quality of the biomass, the potential contamination of the biomass by pathogens in the wastewater and the difficulty in maintaining monocultures in an open system mean that HRAP biomass is most suitable for biofuel production (Brennan and Owende 2010; Leu and Boussiba 2014; Shukla et al. 2017). For this reason, and the increasing interest in alternate renewable transport fuel options to replace fossil fuels the use of HRAP biomass has overwhelmingly focused on biofuel production (Pulz 2001; Brennan and Owende 2010; Leu and Boussiba 2014). This interest in using algal biomass as a source for creating biofuels has long been of interest, and this can be seen in the yearly publication and patents on algal biofuels following in-trend with the price of oil (US$) (Fig. 2). Large-scale production of algal biofuels is hindered by the high cost of production especially when compared to fossil fuel petroleum. It is thought that coupling biofuel production with wastewater treatment will reduce the cost (Driver et al. 2014). Essentially, the HRAP is used as a ready built low-cost reactor and wastewater as a low-cost feedstock for algae (Chen et al. 2015). While theoretically, this coupling seems ideal where wastewater is transformed into biofuel and treated effluent for reuse, there are still many limitations to this application (Sutherland et al. 2015; Doma et al. 2016). Reliable and cheap harvesting is considered by many to be the most important limitation to the utilisation of the algal biomass to produce biofuels or any other added-value product with harvesting estimated to cost up 50% of the algal biomass (Greenwell et al. 2009; Hwang

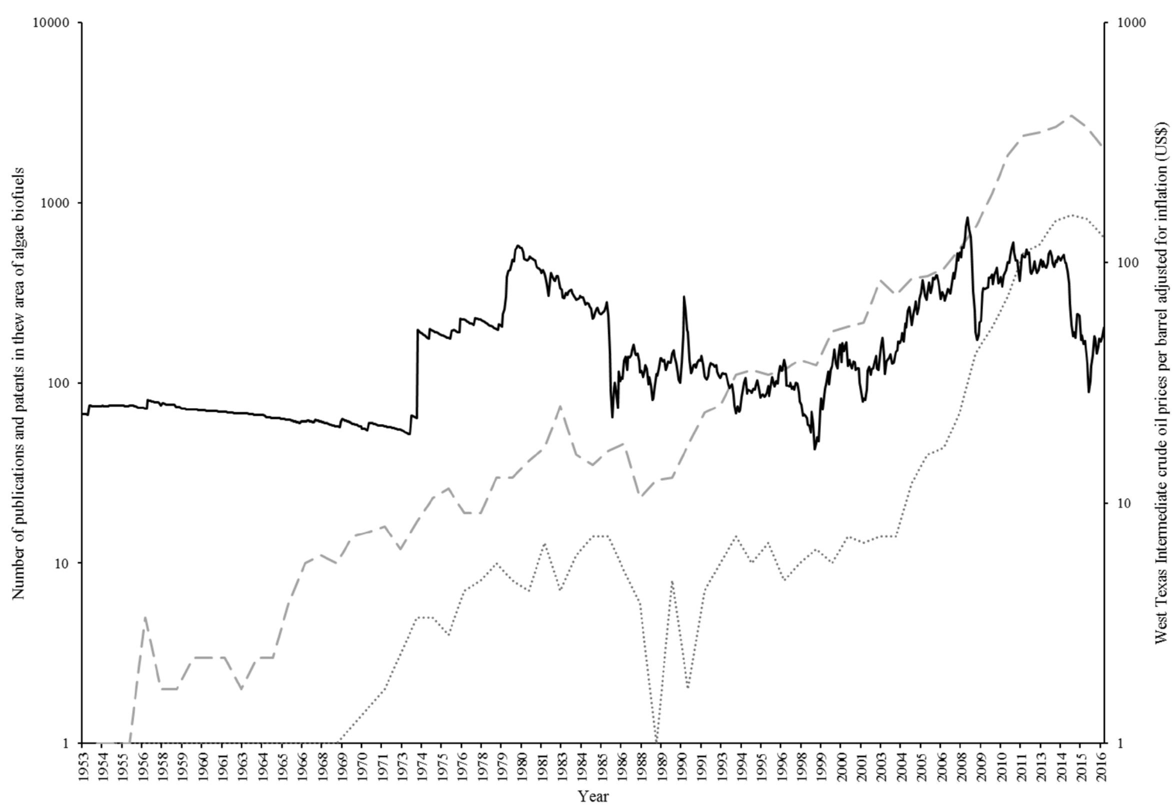

Fig. 2 The number of patents (--) and publications (•••) on algae biofuels and the West Texas Intermediate crude oil prices per barrel adjusted for inflation (US$) (Macrotrends 2017) (–) both on the logarithmic scale between 1953 and 2016

et al. 2016). The algal phyla that populate wastewater treating HRAPs, typically microalgae, are challenging to harvest due to their small cell size, <20 µm, similar density to water, 1.08–1.13 g ml^{-1}, and strong negative charge (Park et al. 2011). Out of the most well-known methods, sedimentation and flocculation are generally considered the most promising options as they are relatively cheap, simple to operate and easy to up-scale (Milledge and Heaven 2013). Flocculation involves the addition of chemicals that triggers single-celled microalgae to aggregate into flocs that are more easily removed (Pahazri et al. 2016). Historically, the flocculants commonly used were metal salts, such as iron(III) chloride and alum, and cationic polymers such as chitosan and cationic starch (Pittman et al. 2011; Vandamme et al. 2013). There are difficulties with these flocculants the former with contamination of the biomass and the latter being influenced by pH and ionic conditions: cost can also be a limiting factor (Pittman et al. 2011; Vandamme et al. 2013). Flocculation involving the use of microorganisms and their products, bioflocculation, can involve the use of other algae, bacteria and fungi. Bioflocculation avoids chemical contamination to the biomass and has been promising but has yet to be proven outside of laboratory settings (Van Den Hende et al. 2011; Manheim and Nelson 2013; Wrede et al. 2014; Muradov et al. 2015). Sedimentation involves the use of gravitational forces to settle the algae from the liquid phase and is simple and relatively cheap method but has problems associated with reliability and speed (Milledge and Heaven 2013). Settling reliability can differ greatly between algae species, and it is thought selecting for more readably settable algal species may increase harvestability (Milledge and Heaven 2013). A novel way to do this has been recycling a portion of algal biomass harvested by sedimentation to increase yields in future harvests is another promising method that while demonstrated effectively in pilot-scale HRAPs has yet to be demonstrated in large-scale HRAPs (Park et al. 2013, 2015; Gutiérrez et al. 2016). Park and Craggs (2014) found recycling 10% of the daily algal biomass in a pilot HRAP dominated by the rapidly settling *Pediastrum boryanum* increased subsequent harvests settleability by 25% and biomass productivity by 40%.

Another major limitation to the utilisation of wastewater-grown algal biomass in HRAPs is the productivity achieved is well below the theoretical maximum of 50–60 g m^{-2} day^{-1} (Christenson and Sims 2011; Sutherland et al. 2015). Due to the high pH, it is believed algal growth in wastewater is carbon limited and providing additional carbon would increase productivity (Craggs et al. 2012). The most popular solution to this problem has been adding carbon to the HRAPs as carbon dioxide via flue gas, which has the bonus of reducing greenhouse gas emissions and as a consequence potentially earning tax and carbon credits (Munoz and Guieysse 2006; DOE 2016). There have been several studies on the effect carbon dioxide addition has on algal biomass productivity in HRAPs, and while some results have been promising, the interpretation is hampered by the experiments being laboratory based or using pilot-scale systems (Heubeck et al. 2007; de Godos et al. 2010; Van Den Hende et al. 2011), not having adequate controls (Park and Craggs 2010, 2011; Craggs et al. 2012) or using pure carbon dioxide which is lacking chemicals present in flue gas that may be toxic to algae (Chen et al. 2015; de Godos et al. 2016). Even if it were clear such addition substantially increased algal biomass, such systems would be limited in location to where suitable flue gas can be added, estimated to be <10% of flue gas emitting infrastructure in the USA, as transport of the gas is prohibitively expensive (Lundquist et al. 2010). Increasing productivity through the selection of high producing strains or genetic modification have also been considered, but there are problems in maintaining monocultures through predation/parasitism and more competitive wild strains (Christenson and Sims 2011; Sutherland et al. 2015).

Areas for further research

Increasing beneficial reuse of treated wastewater requires minimising the risk to the public of exposure to pathogenic microorganisms. Excluding *E. coli* and faecal indicators, there is a lack of information on the disinfection of many prominent pathogens and indicator organisms in large-scale, fully operational HRAPs. The only investigation into the removal of other bacteria by a HRAP was in a pilot-scale system which did show effective removal of the indicator organisms *Staphylococcus* spp. and *Clostridium perfrigens* (García et al. 2008). There is a notable absence of studies on the removal of pathogenic viruses. However, two studies on virus indicator organisms both showed effective removal (Davies-Colley et al. 2005; Young et al. 2016).

Research is also needed on the removal of pathogenic protozoa in full-scale HRAPs. Young et al. 2016 attempted using aerobic spore-forming bacteria as surrogate indicators of protozoa, the result was inconclusive and suggested they were unsuitable indicators for lagoon systems. Arkai et al. (2001) investigated the removal of *Cryptosporidium parvum* oocysts in a semi-permeable bag using a pilot-scale HRAP and showed removals of >98%. Studies on the removal of helminths have shown HRAPs perform removal, but primary treatment seems to be the main contributor (El Hamouri et al. 1994; El Hamouri et al. 1995; El Hamouri 2009). Given the extra treated effluent HRAPs produce for reuse, it is particularly important to determine their removal capabilities for the reference pathogens listed in *The World Health Organization Guidelines for the Safe*

Use of Wastewater Excreta and Greywater Volume II: Wastewater use in Agriculture (2006). These are *Campylobacter* spp. for bacteria, rotavirus/norovirus for viruses, *Cryptosporidium* spp. for protozoa and *Ascaris lumbricoides* for helminths (WHO 2006; Mara et al. 2010).

Emerging contaminants are a wide-ranging group of primarily organic compounds that have recently been acknowledged as potentially posing a hazard to human and environmental health. As they are a recent problem, there have been few studies on the removal of emerging contaminants by HRAPs (de Godos et al. 2012; Matamoros et al. 2015). de Godos et al. (2012) measured the removal of the antibiotic tetracycline in a pilot scale 24 L HRAP and found a removal of 69 ± 1%. Matamoros et al. (2015) measured the removal of 26 emerging contaminants including pesticides, pharmaceuticals, plasticisers and personal care products in a pilot scale 470 l HRAP. They recorded removal efficiencies ranging from 0 to 99% depending on the chemical, season and HRT. They also performed an ecotoxicological risk assessment which showed following treatment the remaining concentration of chemicals had no acute toxicity risk (Matamoros et al. 2015). Both studies agreed that the major contributors to the HRAPs removal of emerging contaminants were photodegradation and biodegradation. Suggesting research on the removal of emerging contaminants in full-scale HRAPs is necessary as the light climate would be expected to be different due to the difference in size of the pilot systems employed in previous studies and relative influence of the paddlewheel.

Conclusion

HRAPs present an alternative, or at least augmentative adjunct to current wastewater treatment systems which are costly to install, maintain and often unsuitable due to space and location constraints. HRAPs may provide a more flexible system with many of the advantages of a bioreactor, control over operational parameters, without the requirements of maintaining sterility and laboratory formulated feedstocks (Oswald 1963; Araki et al. 2001; Park and Craggs 2014; Sutherland et al. 2014b; Macrotrends 2017).

References

Acién FG, Gómez-Serrano C, Morales-Amaral M, Fernández-Sevilla J, Molina-Grima E (2016) Wastewater treatment using microalgae: how realistic a contribution might it be to significant urban wastewater treatment? Appl Microbiol Biotechnol 100:9013–9022

Araki S, Martın-Gomez S, Bécares E, De Luis-Calabuig E, Rojo-Vazquez F (2001) Effect of high-rate algal ponds on viability of *Cryptosporidium parvum* Oocysts. Appl Environ Microbiol 67:3322–3324

Arbib Z, Ruiz J, Álvarez-Díaz P, Garrido-Pérez C, Barragan J, Perales JA (2013) Long term outdoor operation of a tubular airlift pilot photobioreactor and a high rate algal pond as tertiary treatment of urban wastewater. Ecol Eng 52:143–153

Bahlaoui M, Baleux B, Troussellier M (1997) Dynamics of pollution-indicator and pathogenic bacteria in high-rate oxidation wastewater treatment ponds. Water Res 31:630–638

Banat I, Puskas K, Esen I, Al-Daher R (1990) Wastewater treatment and algal productivity in an integrated ponding system. Biol Wastes 32:265–275

Brennan L, Owende P (2010) Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products. Renew Sustain Energy Rev 14:557–577

Buchanan AN (2014) Comparing the performance of a high rate algal pond with a waste stabilisation pond in rural South Australia. Flinders University, Adelaide

Buchanan N, Cromar N, Bolton N, Fallowfield H (2011a) Comparison of a high rate algal pond with a 'standard'secondary facultative waste stabilisation pond in rural South Australia. Paper presented at the international water association small sustainable solutions for water conference, Venice, 18th – 22nd April, 2011

Buchanan N, Cromar N, Bolton N, Fallowfield H (2011b) The disinfection performance of a high rate algal pond (hrap) at kingston-on-murray, South Australia. Paper presented at the International Water Association's 9th specialist group conference on waste stabilisation ponds, Adelaide, South Australia, 1–3 August, 2011

Chen P, Zhou Q, Paing J, Le H, Picot B (2003) Nutrient removal by the integrated use of high rate algal ponds and macrophyte systems in China. Water Sci Technol 48:251–257

Chen G, Zhao L, Qi Y (2015) Enhancing the productivity of microalgae cultivated in wastewater toward biofuel production: a critical review. Appl Energy 137:282–291

Christenson L, Sims R (2011) Production and harvesting of microalgae for wastewater treatment, biofuels, and bioproducts. Biotechnol Adv 29:686–702

Craggs R, Davies-Colley R, Tanner C, Sukias J (2003a) Advanced pond system: performance with high rate ponds of different depths and areas. Water Sci Technol 48:259–267

Craggs R, Tanner C, Sukias J, Davies-Colley R (2003b) Dairy farm wastewater treatment by an advanced pond system. Water Sci Technol 48:291–297

Craggs RJ, Zwart A, Nagels JW, Davies-Colley RJ (2004) Modelling sunlight disinfection in a high rate pond. Ecol Eng 22:113–122

Craggs R, Heubeck S, Lundquist T, Benemann J (2011) Algal biofuels from wastewater treatment high rate algal ponds. Water Sci Technol 63:660–665

Craggs R, Sutherland D, Campbell H (2012) Hectare-scale demonstration of high rate algal ponds for enhanced wastewater treatment and biofuel production. J Appl Phycol 24:329–337

Cromar N, Fallowfield HJ, Martin N (1996) Influence of environmental parameters on biomass production and nutrient removal in a high rate algal pond operated by continuous culture. Water Sci Technol 34:133–140

Davies-Colley R, Craggs R, Nagels J (2003) Disinfection in a pilot-scale advanced pond system (APS) for domestic sewage treatment in New Zealand. Water Sci Technol 48:81–87

Davies-Colley R, Craggs R, Park J, Sukias J, Nagels J, Stott R (2005) Virus removal in a pilot-scale advanced pond system as indicated by somatic and F-RNA bacteriophages. Water Sci Technol 51:107–110

de Godos I, Blanco S, García-Encina PA, Becares E, Muñoz R (2010) Influence of flue gas sparging on the performance of high rate algae ponds treating agro-industrial wastewaters. J Hazard Mater 179:1049–1054

de Godos I, Muñoz R, Guieysse B (2012) Tetracycline removal during wastewater treatment in high-rate algal ponds. J Hazard Mater 229:446–449
de Godos I, Arbib Z, Lara E, Rogalla F (2016) Evaluation of high rate algae ponds for treatment of anaerobically digested wastewater: effect of CO_2 addition and modification of dilution rate. Bioresour Technol 220:253–261
DOE (2016) National Algal Biofuels Technology Review
Doma HS, El-Liethy MA, Abdo SM, Ali GH (2016) Potential of using high rate algal pond for algal biofuel production and wastewater treatment. Asian J Chem 28:399
Driver T, Bajhaiya A, Pittman JK (2014) Potential of bioenergy production from microalgae. Curr Sustain Renew Energy Rep 1:94–103
El Hafiane F, El Hamouri B (2005) Anaerobic reactor/high rate pond combined technology for sewage treatment in the Mediterranean area. Water Sci Technol 51:125–132
El Hamouri B (2009) Rethinking natural, extensive systems for tertiary treatment purposes: the high-rate algae pond as an example. Desalin Water Treat 4:128–134
El Hamouri B, Khallayoune K, Bouzoubaa K, Rhallabi N, Chalabi M (1994) High-rate algal pond performances in faecal coliforms and helminth egg removals. Water Res 28:171–174
El Hamouri B et al (1995) The performance of a high-rate algal pond in the Moroccan climate. Water Sci Technol 31:67–74
El Hamouri B, Rami A, Vasel J (2003) The reasons behind the performance superiority of a high rate algal pond over three facultative ponds in series. Water Sci Technol 48:269–276
Fallowfield H, Garrett M (1985a) The photosynthetic treatment of pig slurry in temperate climatic conditions: a pilot-plant study. Agric Wastes 12:111–136
Fallowfield H, Garrett M (1985b) The treatment of wastes by algal culture. J Appl Bacteriol 59:187S-205S
Fallowfield HJ, Cromar N, Evison L (1996) Coliform die-off rate constants in a high rate algal pond and the effect of operational and environmental variables. Water Sci Technol 34:141–147
Garcia J, Mujeriego R, Hernandez-Marine M (2000) High rate algal pond operating strategies for urban wastewater nitrogen removal. J Appl Phycol 12:331–339
Garcia J, Green B, Lundquist T, Mujeriego R, Hernández-Mariné M, Oswald W (2006) Long term diurnal variations in contaminant removal in high rate ponds treating urban wastewater. Bioresour Technol 97:1709–1715
García M, Soto F, González JM, Bécares E (2008) A comparison of bacterial removal efficiencies in constructed wetlands and algae-based systems. Ecol Eng 32:238–243
Green FB, Bernstone L, Lundquist T, Oswald W (1996) Advanced integrated wastewater pond systems for nitrogen removal. Water Sci Technol 33:207–217
Greenwell H, Laurens L, Shields R, Lovitt R, Flynn K (2009) Placing microalgae on the biofuels priority list: a review of the technological challenges. J R Soc Interface. doi:10.1098/rsif.2009.0322
Gutiérrez R, Ferrer I, González-Molina A, Salvadó H, García J, Uggetti E (2016) Microalgae recycling improves biomass recovery from wastewater treatment high rate algal ponds. Water Res 106:539–549
Heubeck S, Craggs R, 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
Hwang J-H, Church J, Lee S-J, Park J, Lee WH (2016) Use of microalgae for advanced wastewater treatment and sustainable bioenergy generation. Environ Eng Sci 33:882–897
Jimenez B (2007) Helminths (Worms) eggs control in wastewater and sludge. In: International symposium on new directions in urban water management, pp. 12–14
Leu S, Boussiba S (2014) Advances in the production of high-value products by microalgae industrial. Biotechnology 10:169–183
Lundquist TJ, Woertz IC, Quinn N, Benemann JR (2010) A realistic technology and engineering assessment of algae biofuel production. Energy Biosci Inst 1:1–178
Macrotrends (2017) Crude Oil Prices—70 Year Historical Chart. http://www.macrotrends.net/1369/crude-oil-price-history-chart. Accessed 14 January 2017
Manheim D, Nelson Y (2013) Settling and bioflocculation of two species of algae used in wastewater treatment and algae biomass production. Environ Prog Sustain Energy 32:946–954
Mara D, Hamilton A, Sleigh A, Karavarsamis N (2010) Discussion paper: options for updating the 2006 WHO guidelines WHO, FAO, IDRC, IWMI
Matamoros V, Gutiérrez R, Ferrer I, García J, Bayona JM (2015) Capability of microalgae-based wastewater treatment systems to remove emerging organic contaminants: a pilot-scale study. J Hazard Mater 288:34–42
Milledge JJ, Heaven S (2013) A review of the harvesting of micro-algae for biofuel production. Rev Environ Sci Bio/Technol 12:165–178
Munoz R, Guieysse B (2006) Algal–bacterial processes for the treatment of hazardous contaminants: a review. Water Res 40:2799–2815
Muradov N et al (2015) Fungal-assisted algal flocculation: application in wastewater treatment and biofuel production. Biotechnol Biofuels 8:24
Norvill ZN, Shilton A, Guieysse B (2016) Emerging contaminant degradation and removal in algal wastewater treatment ponds: identifying the research gaps. J Hazard Mater 313:291–309
Oswald W (1963) The high-rate pond in waste disposal. Dev Ind Microbiol 4:112–125
Oswald WJ, Golueke CG (1960) Biological transformation of solar energy. Adv Appl Microbiol 2:223–262
Oswald W, Gotaas H, Golueke C, Kellen W, Gloyna E, Hermann E (1957) Algae in waste treatment [with discussion]. Sew Ind Wastes 29:437–457
Pahazri NF, Mohamed R, Al-Gheethi A, Kassim AHM (2016) Production and harvesting of microalgae biomass from wastewater: a critical review. Environ Technol Rev 5:39–56
Park J, Craggs R (2010) Wastewater treatment and algal production in high rate algal ponds with carbon dioxide addition. Water Sci Technol 61:633–639
Park J, Craggs R (2011) Nutrient removal in wastewater treatment high rate algal ponds with carbon dioxide addition. Water Sci Technol 63:1758–1764
Park J, Craggs R (2014) Effect of algal recycling rate on the performance of *Pediastrum boryanum* dominated wastewater treatment high rate algal pond. Water Sci Technol 70:1299–1306
Park J, Craggs R, Shilton A (2011) Wastewater treatment high rate algal ponds for biofuel production. Bioresour Technol 102:35–42
Park J, Craggs R, Shilton A (2013) Enhancing biomass energy yield from pilot-scale high rate algal ponds with recycling. Water Res 47:4422–4432
Park JB, Craggs RJ, Shilton AN (2015) Algal recycling enhances algal productivity and settleability in *Pediastrum boryanum* pure cultures. Water Res 87:97–104
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
Picot B, Bahlaoui A, Moersidik S, Baleux B, Bontoux J (1992) Comparison of the purifying efficiency of high rate algal pond with stabilization pond. Water Sci Technol 25:197–206
Pinner D, Rogers M (2015) Solar power comes of age: how harassing the sun got cheap and practical. Foreign Aff 94:111

Pittman JK, Dean AP, Osundeko O (2011) The potential of sustainable algal biofuel production using wastewater resources. Bioresour Technol 102:17–25

Pulz O (2001) Photobioreactors: production systems for phototrophic microorganisms. Appl Microbiol Biotechnol 57:287–293

Rawat I, Ranjith Kumar R, Mutanda T, Bux F (2011) Dual role of microalgae: phycoremediation of domestic wastewater and biomass production for sustainable biofuels production. Appl Energy 88:3411–3424

Rose P, Maart B, Dunn K, Rowswell R, Britz P (1996) High rate algal oxidation ponding for the treatment of tannery effluents. Water Sci Technol 33:219–227

Rose P, Boshoff G, Van Hille R, Wallace L, Dunn K, Duncan J (1998) An integrated algal sulphate reducing high rate ponding process for the treatment of acid mine drainage wastewaters. Biodegradation 9:247–257

Sahoo D, Seckbach J (2015) The algae world, vol 26, Springer, Netherlands

Shelef G, Azov Y (1987) High-rate oxidation ponds: the Israeli experience. Water Sci Technol 19:249–255

Shelef G, Azov Y, Moraine R (1982) Nutrients removal and recovery in a two-stage high-rate algal wastewater treatment system. Water Sci Technol 14:87–100

Shilton A, Mara D, Craggs R, Powell N (2008) Solar-powered aeration and disinfection, anaerobic co-digestion, biological CO_2 scrubbing and biofuel production: the energy and carbon management opportunities of waste stabilisation ponds. Water Sci Technol 58:253

Shoener B, Bradley I, Cusick R, Guest J (2014) Energy positive domestic wastewater treatment: the roles of anaerobic and phototrophic technologies. Environ Sci Process Impacts 16:1204–1222

Shukla SK, Thanikal JV, Haouech L, Patil SG, Kumar V (2017) Critical evaluation of algal biofuel production processes using wastewater. In: Algal biofuels. Springer, pp 189–225

Sutherland DL, Howard-Williams C, Turnbull MH, Broady PA, Craggs RJ (2014a) Seasonal variation in light utilisation, biomass production and nutrient removal by wastewater microalgae in a full-scale high-rate algal pond. J Appl Phycol 26:1317–1329

Sutherland DL, Turnbull MH, Craggs RJ (2014b) Increased pond depth improves algal productivity and nutrient removal in wastewater treatment high rate algal ponds. Water Res 53:271–281

Sutherland DL, Howard-Williams C, Turnbull MH, Broady PA, Craggs RJ (2015) Enhancing microalgal photosynthesis and productivity in wastewater treatment high rate algal ponds for biofuel production. Bioresour Technol 184:222–229

Toumi A, Nejmeddine A, El Hamouri B (2000) Heavy metal removal in waste stabilisation ponds and high rate ponds. Water Sci Technol 42:17–21

Van Den Hende S, Vervaeren H, Desmet S, Boon N (2011) Bioflocculation of microalgae and bacteria combined with flue gas to improve sewage treatment. New Biotechnol 29:23–31

Vandamme D, Foubert I, Muylaert K (2013) Flocculation as a low-cost method for harvesting microalgae for bulk biomass production. Trends in Biotechnol 31:233–239

WHO (2006) Guidelines for the safe use of wastewater, excreta and greywater, volume 2: wastewater use in agriculture. WHO, Geneva

Woertz I, Fulton L, Lundquist T (2009) Nutrient removal & greenhouse gas abatement with CO_2 supplemented algal high rate ponds. Proc Water Environ Fed 2009:7924–7936

Wood A, Scheepers J, Hills M (1989) Combined artificial wetland and high rate algal pond for wastewater treatment and protein production. Water Sci Technol 21:659–668

Wrede D, Taha M, Miranda AF, Kadali K, Stevenson T, Ball AS, Mouradov A (2014) Co-cultivation of fungal and microalgal cells as an efficient system for harvesting microalgal cells, lipid production and wastewater treatment. PloS ONE 9:e113497

Young P, Buchanan N, Fallowfield H (2016) Inactivation of indicator organisms in wastewater treated by a high rate algal pond system. J Appl Microbiol 121:577–586