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MICROALGAE AND SUSTAINABLE WASTEWATER TREATMENT: A REVIEW

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ABSTRACT
Microalgae play important roles in the realisation of energy-efficient carbon-neutral wastewater treatment. This is achievable through coupling carbon capture with wastewater treatment and consequent biomass production. Unlike activated sludge, microalgal biomass is more of a resource than a waste. This paper presents a review on the use of microalgae in sustainable wastewater treatment including organic matter, nitrogen, phosphorus and heavy metals removal. The paper also focussed on microalgal cultivation systems and the potentials of using microalgal photosynthesis in satisfying bacterial oxygen requirements in hybrid algae-bacteria systems. The use of light-emitting diodes in microalgal photosynthesis and their prospects as promising light sources in hybrid algal wastewater treatment systems was also presented.
Keywords: Bacteria; carbon capture; hybrid wastewater treatment systems; light-emitting diodes; microalgae

INTRODUCTION

Wastewaters from homes and industries require certain level of treatment prior to discharge into natural water courses. Domestic wastewater has traditionally been treated using waste stabilisation ponds (WSP), activated sludge (AS), trickling filters, etc. Traditionally, wastewater treatment involves the use of energy with consequent emission of carbon dioxide (CO_2) into the atmosphere. For example, AS process requires considerable amount of energy usually generated through the combustion of fossil fuels. However, stringent regulations on reducing carbon emissions (Department of Energy and Climate Change, 2009; Environment Agency, 2009), coupled with escalating energy prices, now call for the need to develop energy-efficient carbon-neutral wastewater treatment technologies.

Treatment processes that couple carbon capture and wastewater treatment with low or no carbon emission (Mohammed, 2013) can be considered as the most sustainable options. Microalgae use light, CO_2, nutrients and water to produce biomass through photosynthesis (Hsueh *et al.*, 2009). Commercial cultivation of microalgae usually involves the use of freshwater resources and considerable amount of nutrients. Synthetic fertilisers are also used as source of nutrients in such systems and this adds to the overall cost of the process. Interestingly, such nutrients are naturally available in domestic wastewater (Yun *et al.*, 1997), and potentially can be obtained at low-cost from this source. This can considerably reduce the cost of microalgal cultivation process with consequent benefit of water pollution control and conservation of freshwater resources.

Unlike sludge from AS which has traditionally been considered as a waste, microalgal biomass has a number of possible commercial applications. This includes use of the biomass, or its extracts, where appropriate, in biodiesel and biogas production (Meng *et al.*, 2009; Chisty, 2007), human and animal nutrition (Spolaore *et al.*, 2006), healthcare products (Yamaguchi, 1997), cosmetics and personal care products (Stolz and Obermayer, 2005), etc. As such, microalgal biomass is more of a resource than a waste. Hence, the end use of microalgal biomass eliminates the need for sludge disposal, and maximises the benefits of using microalgae to treat domestic wastewater.

The idea of using microalgae to treat domestic wastewater is not new as early publications identified this over 50 years ago (Oswald *et al.*, 1957). Studies have also been undertaken on the cultivation of microalgae with CO_2 supplementation, both within and outside the realms of wastewater treatment (e.g. Park and Craggs, 2011; 2010; Cheng *et al.*, 2006; Takeuchi *et al.*, 1992).

However, research has rarely been undertaken to evaluate the effects of coupling carbon capture with domestic wastewater treatment with a view to developing a *carbon-efficient* technology that can potentially minimise the use of fossil fuel as a source of energy in wastewater treatment, and consequently offset CO_2 emission.

Treatment of wastewater in microalgal systems is achieved through algal-bacterial (cyclic) symbiosis (Acién *et al*. 2016; Mehrabadi *et al*., 2015). This is a relationship dependent on the exchange of metabolic by-products between the two organisms. Algae produce oxygen through photosynthesis which is used by bacteria to biodegrade organic matter, with concomitant production of CO_2 (Humenik and Hanna-Jr, 1971). The CO_2 produced is in turn used by algae in photosynthesis (Van Den Hende *et al*., 2010; Oswald *et al*., 1957). However, algae also consume oxygen during respiration, especially at night, with concomitant production of CO_2 (Ludwig *et al*., 1951). Therefore, there is a need to explore such a symbiotic relationship to develop hybrid wastewater treatment systems that can potentially offset the limitations of individual systems. In such systems, sufficient carbon, as organic matter and CO_2, and optimum illumination are required to sustain the above symbiotic relationship and allow the wastewater to be treated effectively.

Microalgae and Wastewater Treatment

Microalgae play important roles in wastewater treatment in WSP through, among other things, provision of oxygen needed for bacterial biochemical oxygen demand (BOD) and ammonia removal (Weatherell *et al*., 2003). WSPs have been used worldwide in both temperate and tropical climates for domestic wastewater treatment, especially for small communities (Mara and Johnson, 2007; Oliveira *et al*., 1996). The major pollutants usually removed from wastewater using WSP include BOD, nitrogen (N), phosphorus (P), suspended solids and pathogens. Many studies were undertaken to remove these pollutants from wastewater using WSP systems (e.g. Del Nery *et al*., 2013; Park *et al*., 2011; Park and Craggs, 2010; Camargo-Valero *et al*., 2009a; Abis and Mara, 2003; Oswald, 1995; Oswald, 1990; Pearson *et al*., 1987; Oswald *et al*., 1957; etc.). Although WSPs have been used to treat domestic wastewater worldwide, their performance depends on climatic conditions, which are variable between geographical locations; and process parameters such as dissolved oxygen (DO) and pH which affect chemical equilibrium of wastewater pollutants (e.g. ammonium ions and free ammonia; Paterson and Curtis, 2005). Temperature plays important role in wastewater treatment in WSP. This is due to its thermodynamic effect on solubility of pollutants and microbial activities in aquatic systems (Paterson and Curtis, 2005). Due to the dynamic and passive nature of WSPs, temperature is practically uncontrollable in these systems.

Removal of pollutants in algal-based WSP is aided by algae-bacterial symbiotic relationship (Van Den Hende *et al*., 2010; Medina and Neis, 2007; Humenik and Hanna-Jr, 1971; Oswald *et al*., 1953; Ludwig *et al*., 1951). Therefore, a thriving algal-bacterial symbiosis is essential for efficient performance of algal-based WSP and other hybrid algal wastewater treatment systems. The evaluation of performance and process design of WSP are usually based on effluent quality requirements set locally and/or internationally by regulatory agencies (Mara, 1996).

A survey on the performance of WSP system, mainly treating domestic wastewater, with average organic loading rate (OLR) of about 25 $kg.BOD.ha^{-1}.d^{-1}$, was conducted in France (Racault *et al*., 1995). Statistical analyses on the survey data in the study revealed soluble chemical oxygen demand (SCOD) and BOD removal efficiencies of more than 85 and 95%, respectively, in the majority of the ponds. In addition, TSS, total N and total P removal efficiencies of more than 70, 60 and 50%, respectively, were also reported. Recault *et al*. (1995) pointed out that only the nutrient removal efficiencies were considerably influenced by seasonal variation. They concluded that, besides other factors, long detention times and strong seasonal variations, influencing the treatment process in WSP, could lead to dispersed data that may be difficult to interpret, and hence may limit the application of statistical modelling and accurate prediction of effluent quality in these systems.

Apparently, wide variations exist in the performance of WSP worldwide as evident from the pollutant removal efficiencies of the above studies. Overall, it is understood that the performance of these systems is higher in tropical climates than in temperate ones, under 'optimum' conditions. Nevertheless, the influence of process parameters, pond geometry, and hydraulics are also important in evaluating the performance and treatment efficiencies of WSP systems (Abis and Mara, 2005; Pearson *et al*., 1995).

COD Removal
COD and/or BOD are used to determine the relative strength of wastewater with respect to biodegradability of its organic matter content. BOD measurement is an empirical test used to determine the amount of oxygen required by bacteria to biodegrade the organic matter contained in polluted waters whereas COD measurement determines the amount of chemical oxidant required to react with the organic waste in a given amount of wastewater through combustion with the oxidant, which is subsequently expressed as equivalent oxygen demand of the polluted water (APHA, 2005). In simple terms, BOD is the measure of biodegradable organic carbon whereas COD is the measure of total organic carbon contained in a given sample of polluted water.
The consortia of microalgae and aerobic bacteria have been used to remove COD from domestic wastewater. However, the use of COD as a wastewater quality parameter has received lesser attention than BOD despite the advantages of the former over the latter. Table 1 summarises the COD removal efficiencies of some studies on WSP and other algal wastewater treatment systems.

Table 1 COD removal efficiencies of some algal wastewater treatment systems

Treatment system	COD removal efficiency (%)	Reference
Photobioreactor	73	Mohammed *et al.* (2014b)
Facultative pond	55-70	Mara *et al.* (1998)
Facultative pond	64-73	Mara *et al.* (1996)
Maturation ponds	71-85	de-Oliveira *et al.* (1996)
Photobioreactor	90	Humenik and Hanna-Jr (1971)
Maturation ponds	7-25	von-Sperling and Mascarenhas (2005)
Facultative ponds*	7-17	Soler *et al.* (1995)
Facultative ponds*	19-37	Soler *et al.* (1995)
Facultative ponds	55	Mendes *et al.* (1995)
HRAP	92	Shelef (1982)
Facultative ponds	61-67	Schetrite and Racault (1995)
Facultative pond	93	Kumar and Goyal (2010)

* Ponds located at two different sites

Nitrogen removal
Nitrogen can be removed in algal wastewater treatment systems through various ways. The main mechanisms for N removal explored by many researchers include biological uptake of ammonium and nitrate by algae (Camargo-Valero *et al.*, 2009a; Martinez *et al.*, 2000), sedimentation of algal biomass containing organic N (Camargo-Valero *et al.*, 2009a; Zimmo *et al.*, 2004), ammonia stripping to the atmosphere (Camargo-Valero and Mara, 2007; Zimmo *et al.*, 2004; Pano and Middlebrooks, 1982), denitrification of oxidised forms of nitrogen to N_2 gas (Zimmo *et al.*, 2004), and various combinations thereof (Camargo-Valero *et al.*, 2009b; Camargo-Valero and Mara, 2007).
However, conflicting arguments exist in the literature on which mechanisms are mainly responsible for N removal in WSP systems (Camargo-Valero and Mara, 2010; Lai and Lam, 1997; Reed, 1985; Pano and Middlebrooks, 1982). Nevertheless, there are instances where researchers tend to agree on one or more pathways as the dominant mechanisms for N removal in WSP, depending on the prevailing conditions in such systems. Interestingly, most of the published works on algal wastewater treatment systems agree that N removal is influenced by pH, temperature and retention time, but this has neither resolved the conflicts nor established the dominant mechanism for N removal in algal wastewater treatment systems (Reed, 1985).
Owing to the fact that the wastewater in WSP is exposed to complex ecosystem, environmental conditions and biochemical activities greatly influence the transformation mechanisms for N removal in these systems (Reed, 1985). Reed (1985) pointed out that N can go through several transformation pathways involving oxidation-reduction cycles as a result of long HRT in facultative ponds. He argued that nitrification could only occur as an intermediate step of nitrogen transformation in facultative ponds and that denitrification cannot be practically demonstrated as a permanent mechanism for N removal in WSP.

Phosphorus removal
Besides N, P is the other nutrient element responsible for eutrophication of natural watercourses. Although WSPs have been used for wastewater treatment, they are characterised by low P removal efficiency (Powell *et al.*, 2009; Mbwele, 2006); which may not be unconnected with low P uptake and its content in microalgal biomass (Powell, 2009), and less attention paid to the process design of WSP (Camargo-Valero, 2008).

In addition, low concentration of algal biomass usually found in WSP may also be responsible for low P removal in these systems (Powell *et al.*, 2011; Powell *et al.*, 2009).

Although the P content of microalgal biomass is low, about 1% on cell dry weight basis, P has been recognised as an important growth-limiting nutrient in algal metabolism which may be due to its property in easily binding to some ions (e.g. carbonates) to form precipitates and consequently reducing its bioavailability to algae (Grobbelaar, 2004). However, over supply of P has been reported to provide no solution to P limitation as it may even lead to stress with consequent low algal growth (Grobbelaar, 2004). Microalgae use P in the synthesis of intracellular compounds such as deoxyribonucleic acid (DNA), ribonucleic acid (RNA), protein (Grobbelaar, 2004; Miyachi *et al.*, 1964) as well as energy-rich compounds such as adenosine diphosphate (ADP) and adenosine triphosphate (ATP) which are essential in intracellular energy transfer processes (Borchardt and Azad, 1968).

Phosphorus is mainly present in wastewater as soluble inorganic orthophosphates, complex inorganic phosphate compounds such as sodium pyrophosphates, polyphosphates such as polymers of phosphoric acid or as organic P compounds found in organic matter and cellular materials such as phosphoproteins, complex sugars or nucleic acids (Nurdogan and Oswald, 1995; Nesbitt, 1969). Polyphosphates and organic P compounds are biodegraded to inorganic phosphates by bacteria forming, for example, more than 70% of the total P in facultative and high rate algal ponds (HRAP; Nurdogan and Oswald, 1995). Procedure for measuring P in wastewater is available in Standard Methods. However, Nesbitt (1969) argued that such procedure does not discriminate between these forms of P and that the basic test for phosphate only measures orthophosphates. He pointed out that the separation of soluble and insoluble forms of phosphorus can be achieved through filtration and that the latter can be converted to the former for the purpose of analysis through boiling with inorganic acids, especially sulphuric and nitric acids or their mixture thereof. Nevertheless, methods for measuring different forms of phosphorus using chemical extraction techniques are now available although they are cumbersome (Powell, 2009) and need further improvement.

Microalgae take up P in the form of soluble inorganic orthophosphate (Grobbelaar, 2004) for cell growth. P has been reported to be removed from wastewater in WSP mainly through biological assimilation by algae and bacteria and absorption onto sediments (Powell *et al.*, 2011; Mbwele, 2006). It is interesting to note that algal uptake and sedimentation are common mechanisms for removing both N and P in WSP, but algal uptake of P is usually much lower than N uptake as the content of the latter in algal biomass is about ten times higher than content of the former (Nurdogan and Oswald, 1995). Chemical addition leading to phosphate precipitation is another mechanism for removing P in WSP which may be 'natural', due to the presence of carbonates, iron or aluminium ions, in solution etc.; or artificial, through addition of these ions into the wastewater (Surampalli *et al.*, 1995). Nevertheless, precipitation of P with these ions occurs at high pH values (Nurdogan and Oswald, 1995).

Phosphate uptake in microalgae has been demonstrated to be of three types: metabolic uptake for cell growth, starvation uptake by P-starved cells and luxury (i.e. storage) uptake (Azad and Borchardt, 1970). Algal phosphate assimilation has been reported to depend on the chemical energy provided by photosynthesis in the presence of light or by energy-rich P-containing compounds during respiration in the dark (Becker, 1994). In addition, it also depends on other factors such as phosphate concentration in the substrate and algal biomass, pH, temperature and the concentration of trace metals such as sodium, magnesium, potassium as well as concentration of heavy metals in the cultivation medium (Powell *et al.*, 2011; Martinez *et al.*, 1999; Becker, 1994; Borchardt and Azad, 1968). Moreover, P removal usually occurs simultaneously with N removal in WSP.

Bogan (1961) used mixed microalgal culture, dominated by *Chlorella* and *Scenedesmus*, to remove P from a mixture of lake water, treated and untreated domestic sewage both in the laboratory and at pilot-scale. He focussed on algal uptake as a mechanism for P removal from the wastewater with a view to develop a high-rate P removal procedure. He reported that up to 90% of the added phosphate was removed from the cultivation medium within the first 2 h. Due to the detection of pH values of up to 10 in the culture medium and the tendency of phosphate to bind with calcium ions at high pH, Bogan (1961) suspected that coagulation of algae with calcium sulphate also played a considerable role in P removal. He found out that calcium ion concentration and pH were the main factors influencing the solubility of orthophosphate in the wastewater.

Heavy metals removal

Water pollution by heavy metals is a problem that requires attention in wastewater treatment. Microalgae require heavy metals as trace nutrients since the metals form part of active sites of essential enzymes (Wilde and Benemann, 1993).

As such, microalgae can be used to remove heavy metals from wastewater although this bioremediation technique has its associated benefits as well as problems. Some of the advantages of heavy metals removal with microalgae include low-cost, rapid kinetics of metal uptake, selectivity in removing specific metals, applicability on wastewater mixed with different heavy metals, minimal need for addition of other chemicals, possibility for recovering adsorbed metals from the spent algal biomass, etc., (Wilde and Benemann, 1993).

However, some of the problems of this bioremediation technique may include toxicity of the metal ions to microalgae which may inhibit growth with consequent adverse effect on the overall wastewater treatment process, handling of the metal-rich biomass, cost of chemical used for metal recovery or biomass disposal, and possible adverse effect of some heavy metals (such as lead) to automobile engines when the biomass is used to produce biodiesel as well as conflicting interest between this technique and biofuel production. In addition, the cost of pH control (Wilde and Benemann, 1993) in large full-scale systems such as WSP may make this technique unattractive.

Microalgae have been used to remove variety of heavy metals from wastewater. Nevertheless, the amount of removal varies between algal species and physicochemical conditions, especially pH and temperature of the growth medium, and the concentration and relative toxicity of the metal ions to microalgae (Wilde and Benemann, 1993). The main mechanisms for the removal of heavy metals from wastewater using algae include active uptake into the cells and adsorption onto living and dead cells surfaces (Golab and Smith, 1992).

Several studies have been undertaken to remove heavy metals from wastewater using pure and mixed culture of microalgae. For example, removal of lead and zinc from domestic wastewater by mixed microalgal culture (Kumar and Goyal, 2010), removal of cadmium, chromium and copper ions from synthetic wastewater by *Scenedesmus incrassatulus* (Pena-Castro *et al.*, 2004), removal of cadmium and copper from heavy metal polluted synthetic wastewater by *C. vulgaris* (Miskelly and Scragg, 1996), removal of lead ions from industrial wastewater by *C. vulgaris* and *Chlamydomonas sp.* (Golab and Smith, 1992), and selective removal of cadmium from industrial wastewater by *C. pyrenoidosa*, (Hart and Scaife, 1977), etc.

Kumar and Goyal (2010) reported removal efficiencies of up to 66 and 70% for lead and zinc, respectively, by Chlorella-dominated mixed culture of microalgae in WSP treating domestic wastewater during winter, in India. However, they also reported perceived zinc toxicity on the microalgae as a result of decline in its cell density. Correspondingly, these authors also observed increase in pH and DO resulting from the heavy metal removal. These microalgae were reported to tolerate lead concentration of up to 20 $mg.L^{-1}$, with maximum zinc and lead uptake of about 34 and 42 $mg.g^{-1}$ of microalgal biomass, respectively. The absence of lead toxicity was apparently evident from the increase in the algal productivity at this high lead concentration.

Microalgal Cultivation Systems

Microalgae are cultivated in different systems including open ponds, closed photobioreactors and hybrid systems. Open ponds and photobioreactors are the most commonly used methods of algal cultivation (Packer, 2009). These cultivation systems, their advantages and disadvantages, and design and operation principles are discussed in the following sections.

Open ponds

Open ponds (i.e. WSP and open raceways or HRAPs) are the most commonly used open algal systems for domestic wastewater treatment in small communities (Mara, 2003). The importance of well-designed ponds had been postulated to increase in this century due to their several advantages (Oswald, 1995). Ponds have been considered as bioreactors that are formed through excavation and compaction of earth surface, designed to hold and treat wastewater for a certain period of time (Oswald, 1995). According to Oswald (1995), if ponds are properly designed and well-maintained, they can produce consortia of algae and bacteria that can biodegrade organic wastes contained in wastewater and consequently produce energy-rich algal biomass. They can produce effluents of high quality that can be reused in both restricted and unrestricted crop irrigation (Mara, 2008). WSP are designed for hydraulic and process performance using empirical and rational equations available in the literature (Finney and Middlebrooks, 1980).

Open ponds have advantages over other microalgal wastewater treatment systems due to their low construction, operation and maintenance costs, negligible or absence of electrical energy requirement, high performance and ease of operation (Mara, 2008; 2003).

However, the major disadvantages of these systems are huge land requirement, especially where land is scarce and expensive; difficulty in controlling environmental conditions, such as temperature, due to their passive nature; and susceptibility to contamination by unwanted algal species, grazers, and other organisms, and water loss due to evaporation, especially in tropical and semi-arid regions (Mara, 2008; 2003).

WSP typically comprise of series of anaerobic, facultative and one or more maturation ponds (Mara, 2008; 2003). Anaerobic ponds are sometimes omitted, especially in small treatment system, if the strength of the wastewater is low (Mara, 1987). Since microalgae usually grow in facultative and maturation ponds but not in anaerobic ponds (Mara, 2003), this review only focuses on facultative and maturation ponds. Detailed discussion on anaerobic ponds is available in the literature (e.g. Mara, 2008; 2003).

Facultative ponds are usually 1 to 2 m deep (Mara, 2006; 2003). They are considered as primary when they receive their influent organic load directly from raw wastewater source or secondary when they receive a pretreated wastewater; for example, the effluent of anaerobic pond or wastewater from primary settling tank (Mara, 2006). Wastewater treatment is achieved in these ponds through algal-bacterial symbiosis as described previously (see Section 1.1). Based on the biochemical processes that take place in facultative ponds, three zones have been identified: anaerobic, facultative and aerobic (von-Sperling and Chernicharo, 2005).

Anaerobic zone, which lacks oxygen, could be formed as a result of biodegradation of settled organic matter to methane, CO_2, hydrogen sulphide, etc., at the pond bottom; oxygen-rich aerobic zone is formed at the upper water column dominated by fine particulate and dissolved organic matter; and facultative zone, characterised by intermittent availability and absence of oxygen, is formed in the water column between the aerobic and anaerobic zones (von-Sperling and Chernicharo, 2005). Due to the slow rate of waste stabilisation in facultative ponds, HRT longer than 20 days is usually required in order to achieve considerable level of BOD removal (von-Sperling and Chernicharo, 2005).

Facultative ponds are designed for BOD/COD removal based on permissible areal (surface) organic loading with typical OL from 100 to 400 kg BOD $ha^{-1}.d^{-1}$ (Mara, 2003; Finney and Middlebrooks, 1980). Treatment efficiencies of facultative ponds in terms of filtered and unfiltered BOD/COD and TSS removals could be greater than 95, 70 and 90%, respectively, which are comparable to those obtained by other wastewater treatment systems (Mara, 2006). Besides oxygen production from algal photosynthesis, these ponds receive additional oxygen from the atmosphere through the surface due to wind action (Mara, 2003). However, it is also reported that the oxygen produced by algal photosynthesis is more useful in waste stabilisation than that supplied by wind aeration (Shilton and Harrison, 2003).

Maturation ponds usually receive their effluent from facultative ponds. They could be shallower than or as deep as facultative ponds with their depth ranging from 1 to 1.5 m (Mara, 2006; 2003). They are designed for pathogens and ammonia nitrogen removals although some level of BOD removal can be achieved simultaneously (Mara, 2006). Predictive models for estimating ammonia nitrogen removal are available in the literature. However, controversies exist regarding the predictive ability of some of the equations used in designing these ponds for ammonia nitrogen removal and the accuracy of the results therefrom (Camargo-Valero and Mara, 2010). Maturation ponds effluents can be upgraded, for example, by further treatment with rock filters if enhanced ammonia nitrogen removal is required (Mara and Johnson, 2007). The main disadvantage of maturation ponds is large land area requirement though this is often overlooked where land is readily available at low-cost (Mara, 2006).

Similarly, maturation ponds are also suitable for algal growth but are mainly used for pathogen removal (Mara, 2006). The pathogen removal in maturation ponds results from increase in temperature due to high solar radiation, elevated pH due to accumulation of hydroxide ions from aqueous dissociation of carbonate-bicarbonate ions (Mara, 2006), and photo-oxidation resulting from the combined effect of high irradiance and high DO concentration (Curtis *et al.*, 1992).

Raceway ponds (also synonymously called open raceways) are another type of open systems in which microalgae are commonly cultivated. They are used to produce biomass of *S. platensis* and *Dunaliella salina* commercially in the USA and Israel, for example (Tredici, 2004). Raceway ponds consist of shallow ditch dug into the ground with a paddle wheel attached to aid mixing of microalgae with the cultivation medium (Tredici, 2004). They may have one or multiple units or cells.

Open raceways share some characteristics and advantages with facultative ponds but some of their disadvantages include long light path due to large volume per pond area leading to low algal biomass concentration which consequently increases harvesting cost; light shading; lack of control of environmental conditions; difficulty in achieving low flow velocity as turbulence is required for stirring the paddle wheel, loss of water through evaporation and difficulty in screening algal species for specific application (Tredici, 2004; Sheehan *et al.*, 1998). According to Sheehan *et al.* (1998), the major problem in screening algal species grown in open ponds is the inability of the isolated strains to dominate in such systems as they are easily out-competed by contaminant native algal species in the vicinity. To offset this bottleneck, these authors recommended the integration of laboratory and outdoor systems in microalgal research and development (R&D).

Furthermore, open raceways are designed for maximum algal biomass productivity considering pond depth, water circulation velocity, retention time, frequency of culture dilution, temperature, and pH as key design parameters (Sheehan *et al.*, 1998). As a result of improvement in pond design, biomass productivity of up to 37 $g.m^{-2}.d^{-1}$, at culture dilution frequency of 3 days, was reported in a pilot-scale raceway, amounting to photon-to-biomass conversion efficiency of about 10% (Sheehan *et al.*, 1998). Microalgal biomass productivity ranging from 15-25 $g.m^{-2}.d^{-1}$ dry algal biomass for cultivation period as long as 90 d, and 30-40 $g.m^{-2}.d^{-1}$ for shorter cultivation period are commonly obtainable in outdoor algal systems (Goldman, 1979).

Closed systems

These microalgal cultivation systems are mainly closed PBRs with their different types. PBRs are illuminated reactor devices in which microalgae and other photosynthetic organisms can be grown in aqueous medium (Tredici, 2004). They may be wholly closed or slightly open at the top. Although some PBRs may have some openings, they can nevertheless be considered as closed systems as they are covered unlike WSP whose surface is traditionally wide open and exposed to the atmosphere. PBRs are usually made of transparent materials such as Pyrex or Plexiglas to allow passage of light. The advantages of PBRs over open ponds include control of contamination and cultivation conditions such as temperature and pH (though easier at bench-scale), high biomass productivity, flexibility in choice of growing either axenic or mixed cultures, and possibility of manipulation for optimum light utilisation (Ugwu *et al.*, 2008; Tredici, 2004).

Design classification of PBRs, on one hand, is based on length of light path (e.g. flat or tubular), orientation (e.g. horizontal or vertical) shape and complexity (e.g. manifold or serpentine; Tredici, 2004), and position of illumination (e.g. internally or externally-illuminated; Mohammed *et al.*, 2014a; 2013; Ogbonna *et al.*, 1999). On the other hand, operational classification of PBR could be based on mixing (e.g. stirred-tank type; Mohammed *et al.*, 2014b), mode of gas supply and mass transfer (e.g. airlift, bubble column, single-phase, two-phase), etc. (Ugwu *et al.*, 2008; Tredici, 2004). PBRs are designed to achieve high productivity of microalgal biomass and high efficiency of conversion of light energy to biomass based on surface-to-volume ratio, material transparency and orientation for optimum light supply and utilisation; gas supply, mixing and degassing for optimum gas-liquid mass transfer; ease of maintenance; temperature control and possibility for scale-up and ease of operation; bearing in mind their capital and operating costs (Tredici, 2004).

Although R&D of PBRs and their application in microalgal cultivation have received much attention in recent years, their commercial application cannot be compared to that of open ponds (Tredici, 2004). This could, perhaps, be due to their capital and operating cost and problem of light limitation with respect to scale-up. Therefore, more research attention needs to be paid on the optimisation of light supply and utilisation in order to overcome this limitation. In addition, PBRs have been rarely used for wastewater treatment; hence there is need to integrate microalgal production with wastewater treatment in these systems.

Hybrid systems

The integration of open ponds with photobioreactors and modification in design and mode of operation can produce hybrid systems that can have the advantages of both, with consequent improvement on the limitations of the individual systems. Such systems may include integrated pond-photobioreactor; photobioreactors incorporating solar and artificial light using optical fibres to supply light from solar collectors sited outdoor; closed photobioreactors that are placed outdoor (Ogbonna *et al.*, 1999), and microalgae-activated sludge bioreactors illuminated with monochromatic light sources of specific quantum energy, for wastewater treatment (Mohammed *et al.*, 2014b).

These latter systems could, among other things, possess dual benefit of satisfying aerobic bacterial oxygen requirement through microalgal photosynthesis leading to energy saving resulting from minimal or zero artificial aeration and considerable level of COD removal through bacterial oxidation of organic matter in the wastewater.

Ogbonna *et al.* (1999) developed a simple and sterilisable internally-illuminated PBR with integrated artificial-solar light collection and distribution system. The system supplies collected light into a reactor via optical fibres. Mixing is achieved in the reactor by mechanical stirrer similar to that of conventional stirred tank reactors. The integrated light system in the reactor automatically supplies artificial light when the intensity of solar radiation falls below a pre-set minimum required value. Using this reactor with 5% CO_2 (v/v), these authors reported average biomass productivity of *C. sorokiniana* of 0.300 $g.L^{-1}.d^{-1}$ with corresponding CO_2 fixation rate of 0.846 $g.L^{-1}.d^{-1}$. These findings demonstrate the feasibility of achieving considerable biomass productivity through the use of hybrid PBR systems.

Light-Emitting Diodes

Light-emitting diodes (LED) are semiconductor devices (Gillessen and Schairer, 1987) which convert electrical energy into electromagnetic radiation with the wavelength of part or all the radiation falling within the visible light spectrum (Bergh and Dean, 1976; Bergh and Dean, 1972).

Prospects of LEDs over other Artificial Light Sources in Hybrid Systems

LEDs are gaining increasing popularity in microalgal research. They have the tendency to replace other light sources such as incandescent and fluorescent lamps due to advantages of the former over the latter (Mehta *et al.*, 2008). Such advantages include low power consumption, low input voltage, low heat output, luminous efficacy (a measure of the amount of light provided by a light source in lumens for an input amount of power in watts; (Matthews *et al.*, 2009)), lower start-up time, easy control, different colour bands and longer life span (Mehta *et al.*, 2008). Light-emitting diodes have lifespan of up to 100,000 h or more. Interestingly, used LEDs can be recycled easily as they are composed of fairly benign substances compared to incandescent lamps that contain mercury which poses higher pollution risk to the environment (Mehta *et al.*, 2008). In addition, Mehta *et al.* (2008) reported LED electroluminescence efficiency of about 90% with luminous flux as high as 120 $lumen.W^{1}$.

More importantly, LEDs have very low carbon footprint with associated opportunity for carbon credits as well as high potential towards enhancing environmental sustainability (Mehta *et al.*, 2008). They have lower carbon footprint than fluorescent and incandescent lamps. Moreover, the problems of light limitation associated with the scale-up of PBR can be overcome through focussed research on the use of LED to replace conventional fluorescent and incandescent lamps. Due to their small size, many LEDs can be mounted on a narrow strip of Vero board and inserted into PBR in a water-tight material (to prevent short-circuiting when in contact with water) in order to fully utilise their light output.

Interestingly, LEDs can also be used in hybrid microalgal cultivation systems. For example, they can be used to illuminate a pilot-scale pond located outdoor, housed in an enclosure (analogous to greenhouse) made of water-proof transparent material. The transparent material can serve dual purpose: preventing the pond from rain and facilitating intermittent utilisation of solar radiation during the day. The LED light can be solely used at night or as supplement to solar radiation on cloudy days. Alternatively, LEDs can be used to illuminate hybrid algae-activated sludge reactor. Panels of matrix board with mounted LEDs can be incorporated into such a hybrid reactor to treat domestic wastewater with a view to minimising operational cost in terms of elimination of artificial aeration required by aerobic bacteria through algal photosynthetic oxygenation.

CONCLUSION

Conventional microalgal wastewater treatment systems were reviewed highlighting their strength and limitations and emphasizing the need for developing hybrid systems which combine the benefits of individual systems. The feasibility of coupling carbon capture with domestic wastewater treatment with possible savings in bacterial oxygen requirements using the consortia of bacteria and microalgae has been highlighted. This can potentially help in developing sustainable carbon-neutral hybrid wastewater treatment technologies. However, there is need for substantial improvement in research and development towards realising these sustainable treatment options, in order to make microalgal wastewater treatment systems compete favourably with the conventional. Developing energy-efficient carbon-neutral microalgal wastewater treatment technologies requires the optimisation of illumination and inorganic carbon requirements, which may entail the use of specialist light sources such as monochromatic LEDs to maximise the use of illumination and concentrated forms of CO_2 to promote carbon capture.

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REFERENCES

Abis, K. L. and Mara, D. D. (2003): 'Research on waste stabilisation ponds in the United Kingdom - initial results from pilot-scale facultative ponds', Water Science and Technology, 48(2), 1-7.

Abis, K. L. and Mara, D. D. (2005): 'Primary facultative ponds in the UK: the effect of operational parameters on the performance and algal populations', Water Science and Technology, 51(12), 61-67.

Acién, F.G, Gómez-Serrano, C., Morales-Amaral, M.M, Fernández-Sevilla, J. M. and E. Molina-Grima, E. (2016): Wastewater Treatment Using Microalgae: How Realistic a Contribution Might It Be to Significant Urban Wastewater Treatment? Applied Microbiology and Biotechnology 100(21): 9013–9022

APHA. (2005): Standard methods for the examination of water and wastewater, 21st ed, APHA, Washington DC, USA.

Azad, H. S. and Borchardt, J. A. (1970): 'Variations in phosphorus uptake by algae', Environmental Science and Technology, 4(9), 732-743.

Becker, E. W. (1994): Microalgae biotechnology and microbiology, Cambridge, UK, Cambridge University Press.

Bergh, A. A. and Dean, P. J. (1972): 'Light-emitting diodes', Proceedings of the IEEE, 60(2), 156-223.

Bergh, A. A. and Dean, P. J. (1976): Light-emitting diodes, Oxford University Press, Oxford.

Bogan, R. H. (1961): 'Removal of sewage nutrients by algae', Public Health Reports, 76(4), 301-308.

Borchardt, J. A. and Azad, H. S. (1968): 'Biological extraction of nutrients', Water Pollution Control Federation, 40(10), 1739-1754.

Camargo-Valero, M. A. (2008) Nitrogen Transformation Pathways and Removal Mechanisms in Domestic Wastewater Treatment by Maturation Ponds. PhD thesis. The University of Leeds, United Kingdom.

Camargo-Valero, M. A. and Mara, D. D. (2007): 'Nitrogen removal via ammonia volatilization in maturation ponds', Water Science, 55(11), 87-92.

Camargo-Valero, M. A. and Mara, D. D. (2010): 'Ammonia volatilisation in waste stabilisation ponds: a cascade of misinterpretations?', Water Science and Technology, 61(3), 555-561.

Camargo-Valero, M. A., Mara, D. D. and Newton, R. J. (2009a) 'Nitrogen removal in maturation WSP ponds via biological uptake and sedimentation of dead biomass', 8th IWA Specialist Group Conference on Waste Stabilisation Ponds. Belo Horizonte, Brazil, 26-29 April, 2009. 1-9.

Camargo-Valero, M. A., Read, L. F., Mara, D. D., Newton, R. J., Curtis, T. P. and Davenport, R. J. (2009b) 'Nitrification-denitrification in WSP: a mechanism for permanent nitrogen removal in maturation ponds', 8th IWA Specialist Group Conference on Waste Stabilisation Ponds. Belo Horizonte/MG, Brazil, 26-29 April 2009. 1-9.

Cheng, L., Zhang, L., Chen, H. and Gao, C. (2006): 'Carbon dioxide removal from air by microalgae cultured in a membrane-photobioreactor', Sep and Purif Tech, 50(3), 324-329.

Chisty, Y. (2007): 'Biodiesel from microalgae', Biotechnology Advances, 25(3), 295-306.

Curtis, T. P., Mara, D. D. and Silva, S. A. (1992): 'Influence of pH, oxygen, and humic substances on ability of sunlight to damage fecal coliforms in waste stabilisation pond water', Applied and Environmental Microbiology, 58(4), 1335-1342.

de-Oliveira, R., Silva, S. A., Araujo, A. L. C., Soares, J., Mara, D. D. and Pearson, H. W. (1996): 'The performance of a pilot-scale series of ten ponds treating municipal sewage in Nertheast Brazil', Water Science and Technology, 33(7), 57-61.

Del Nery, V., Damianovic, M. H. Z., Pozzi, E., de Nardi, I. R., Caldas, V. E. A. and Pires, E. C. (2013): 'Long-term performance and operational strategies of a poultry slaughterhouse waste stabilization pond system in a tropical climate', Resources, Conservation and Recycling, 71(0), 7-14.

Department of Energy and Climate Change (2009) UK Low Carbon Transition Plan: National Strategy for Climate and Energy [Online]. Available at: http://www.decc.gov.uk/en/content/cms/publications/lc_trans_plan/lc_trans_plan.aspx (Accessed on 02-02-2010) (Accessed: 02-02-2010).

Environment Agency (2009) Limiting Climate Change - Water Industry Carbon Reduction [Online]. Available at: http://www.environment-agency.gov.uk/static/documents/Research/(16)_Carbon_water_mitigation_FINAL.pdf (Accessed: 29-01-2010).

Finney, B. A. and Middlebrooks, E. J. (1980): 'Facultative waste stabilisation pond design', Water Pollution Control Federation, 52(1), 134-147.

Gillessen, K. and Schairer, W. (1987): Light-emitting diodes, Prentice-Hall, United Kingdom.

Golab, Z. and Smith, R. W. (1992): 'Accumulation of lead in two freshwater algae', Minerals Engineering, 5(9), 1003-1010.

Goldman, J. C. (1979): 'Outdoor algal mass culture-II. photosynthetic yield limitations', Water Research, 13(1), 1-9.

Grobbelaar, J. U. (2004) 'Algal nutrition', in Richmond, A.(ed), Handbook of microalgal culture: biotechnology and applied phycology. Blackwell Science, Oxford, 97-115.

Hart, B. A. and Scaife, B. D. (1977): 'Toxicity and bioaccumulation of Cadmium in Chlorella pyrenoidosa', Environmental Research, 14(3), 401-413.

Hsueh, H. T., Li, W. J., Chen, H. H. and Chu, H. (2009): 'Carbon bio-fixation by photosynthesis of Thermosynechoccus sp. CL-1 and Nannochloropsis oculata', J Photochem and Photobiol B: Biol, 95(1), 33-39.

Humenik, F. J. and Hanna-Jr, G. P. (1971): 'Algal-bacterial symbiosis for removal and conservation of wastewater nutrients', Wat Poll Cont Fed, 43(4), 580-594.

Kumar, R. and Goyal, D. (2010): 'Wastewater treatment and metal removal (Pb2+, Zn2+) by microalgal based stabilisation pond system', Indian Journal of Microbiology, 50(Suppl 1), S34-S40.

Lai, P. C. C. and Lam, P. K. S. (1997): 'Major pathways of nitrogen removal in waste water stabilisation ponds', Water, Air, and Soil Pollution, 94(1), 125-136.

Ludwig, H. F., Oswald, W. J., Gotaas, H. B. and Lynch, V. (1951): 'Algae symbiosis in oxidation ponds I: growth characteristics of Euglena gracilis cultured in sewage', Sew and Industr Wastes, 23(11), 1337-1355.

Mara, D. (2003) 'Low-cost treatment systems', in Horan, D. M. a. N.(ed), The handbook of water and wastewater microbiology. London: Elsevier, 441-448.

Mara, D. D. (1987): 'Waste stabilisation ponds: problems and controversies', Water Quality International, 1 20-22.

Mara, D. D. (1996): 'Waste stabilisation ponds: effluent quality requirements and implications for process design', Water Science and Technology, 33(7), 23-31.

Mara, D. D. (ed.) (2006) Natural wastewater treatment. CIWEM, England.

Mara, D. D. (2008) 'Waste stabilisation ponds: a highly appropriate wastewater treatment technology for mediterranean countries ', in Baz, I. A., Otterpohl, I. and Wendland, C.(eds) Efficient management of wastewater: its treatment and reuse in water scarse countries. Heidelberg: Springer, 113-123.

Mara, D. D., Cogman, C. A., Simkins, P. and Schembri, M. C. A. (1998): 'Performance of the Burwarton Estate waste stabilisation ponds', Water and Environment Journal of the Chatered Institution of Water and Environmental Management, 12(4), 260-264.

Mara, D. D. and Johnson, M. L. (2007): 'Waste stabilisation ponds and rock filters: solutions for small communities', Water Science & Technology, 55(7), 103-107.

Martinez, M. E., Jimenez, J. M. and Yousfi, F. E. (1999): 'Influence of phosphorus concentration and temperature on growth and phosphorus uptake by the microalga Snedesmus obliquus', Bioresource Technology, 67(3), 233-240.

Martinez, M. E., Sanchez, S., Jimenez, J. M., Yousfi, F. E. and Munoz, L. (2000): 'Nitrogen and phosphorus removal from urban wastewater by the microalgae Scendesmus obliquus', Bioresource Technology, 73(3), 263-272.

Matthews, D. H., Matthews, H. S., Jaramillo, P. and Weber, C. L. (2009) 'Energy consumption in the production of high-brightness light-emitting diodes', IEEE Int Symp on Sust Syst and Tech. Tempe, AZ, USA:IEEE.

Mbwele, L. A. (2006) Microbial phosphorus removal in waste stabilisation ponds. Licentiate thesis. Royal Institute of Technology, Stockholm, Sweden.

Medina, M. and Neis, U. (2007): 'Symbiotic algal bacterial wastewater treatment: effect of food to microorganism ratio and hydraulic retention time on the process performance', Water Science and Technology, 55(11), 165-171.

Mehrabadi, A., Craggs, R. and Farid, M.M. (2015): Wastewater Treatment High Rate Algal Ponds (WWT HRAP) for Low-Cost Biofuel Production, *Bioresource Technology*, 184: 202–214.

Mehta, R., Deshpande, D., Kulkarni, K., Sharma, S. and Divan, D. (2008) 'LEDs - A competitive solution for general lighting applications', IEEE Energy 2030 Conf. Atlanta, Georgia, IEEE,

Mendes, B. S., do-Nascimento, M. J., Pereira, M. I., Bailey, G., Lapa, N., Morais, J. and Oliveira, J. S. (1995): 'Efficiency of removal in stabilisation ponds I: influence of climate', Water Science and Technology, 31(12), 219-229.

Meng, X., Yang, J., Xu, X., Zhang, L., Nie, Q. and Xian, M. (2009): 'Biodiesel production from oleaginous microorganisms', Ren Ener, 34(1), 1-5.

Miskelly, A. and Scragg, A. H. (1996): 'Removal of heavy metals by microalgae', International Biodeterioration & Biodegradation, 37(3-4), 243.

Miyachi, S., Kanai, R., Mihara, S., Miyachi, S. and Aoki, H. (1964): 'Metabolic roles of inorganic polyphosphates in chlorella cells', Biochimica et Biophysica Acta, 93(3), 625-634.

Mohammed, K. (2013) Microalgal Photobioreactors for Carbon-Efficient Wastewater Treatment. PhD thesis. Newcastle University.

Mohammed, K., Ahammad, S. Z., Sallis, P. J. and Mota, C. R. (2013) 'Energy-efficient photobioreactors for simultaneous carbon capture and municipal wastewater treatment', 10th IWA Int Conf on Ponds Tech: Advances and Innovations in Wastewater Pond Tech. Cartagena, Colombia, 19th - 23rd August, 2013.

Mohammed, K., Ahammad, S. Z., Sallis, P. J. and Mota, C. R. (2014a): 'Effects of inorganic carbon addition and red light-emitting diode irradiance on microalgal bioreactors treating municipal wastewater', under review.

Mohammed, K., Ahammad, S. Z., Sallis, P. J. and Mota, C. R. (2014b): 'Energy-efficient stirred-tank photobioreactors for simultaneous carbon capture and municipal wastewater treatment', Wat Sci and Tech, 69(10), 2106-2112.

Nesbitt, J. B. (1969): 'Phosphorus removal - the state of the art', Water Pollution Control Federation, 41(5), 701-713.

Nurdogan, Y. and Oswald, W. J. (1995): 'Enhanced nutrient removal in high-rate ponds', Water Science and Technology, 31(12), 33-43.

Ogbonna, J. C., Soejima, T. and Tanaka, H. (1999): 'An integrated solar and artificial light system for internal illumination of photobioreactors', Journal of Biotechnology, 70(1-3), 289-297.

Oliveira, R. d., Silva, S. A., Araujo, A. L. C., Soares, J., Mara, D. D. and Pearson, H. W. (1996): 'The performance of a pilot-scale series of ten ponds treating municipal sewage in Northeast Brazil', Water Science & Technology, 33(7), 57-61.

Oswald, W. J. (1990) 'Advanced integrated wastewater pond systems', Supplying Water and Saving the Environment for Six Billion People. San Francisco, November 5-8, 1990.American Society of Civil Engineers.

Oswald, W. J. (1995): 'Ponds in the 21st Century', Water Science and Technology, 31(12), 1-8.

Oswald, W. J., Gotaas, H. B., Golueke, C. G. and Kellen, W. R. (1957): 'Algae in waste treatment', Sewg and Industr Wastes, 29(4), 437-457.

Oswald, W. J., Gotaas, H. B., Ludwig, H. F. and Lynch, V. (1953): 'Algae symbiosis in oxidation ponds II: growth characteristics of Chlorella pyrenoidosa cultured in sewage', Sewage and industrial wastes, 25(1), 26-37.

Pano, A. and Middlebrooks, E. J. (1982): 'Ammonia nitrogen removal in facultative wastewater stabilisation ponds', Water Pollution Control Federation, 54(4), 344-351.

Park, J. B. K. and Craggs, R. J. (2010): 'Wastewater treatment and algal production in high rate algal ponds with carbon dioxide addition', Water Science and Technology, 61(3), 633-639.

Park, J. B. K. and Craggs, R. J. (2011): 'Nutrient removal in wastewater treatment high rate algal ponds with carbon dioxide addition', Water Science and Technology, 63(8), 1758-1764.

Park, J. B. K., Craggs, R. J. and Shilton, A. N. (2011): 'Wastewater treatment high rate algal ponds for biofuel production', Bioresource Technology, 102(1), 35-42.

Paterson, C. and Curtis, T. (2005) 'Physical and chemical environments', in Shilton, A.(ed), Pond Treatment Technology. London: IWA Publishing, 49-65.

Pearson, H. W., Mara, D. D. and Arridge, H. A. (1995): 'The influence of pond geometry and configuration on facultative maturation waste stabilisation pond performance and effcicency', Water Science and Technology, 31(12), 129-139.

Pearson, H. W., Mara, D. D. and Bartone, C. R. (1987): 'Guidelines for the minimum evaluation of the performance of full-scale waste stabilisation ponds systems', Water Research, 21(9), 1067-1075.

Pena-Castro, J. M., Martinez-Jeronimo, F., Esparza-Garcia, F. and Canizares-Villanueva, R. O. (2004): 'Heavy metals removal by the microalga Scenedesmus incrassatulus in continuous cultutres', Bioresource Technology, 94(2), 219-222.

Powell, N. (2009) Biological Phosphorus Removal by Microalgae in Waste Stabilisation Ponds. PhD thesis. Massey University, New Zealand.

Powell, N., Shilton, A., Chisti, Y. and Pratt, S. (2009): 'Towards a luxury uptake process via microalgae - Defining the polyphosphate dynamics', Water Research, 43(17), 4207-4213.

Powell, N., Shilton, A., Pratt, S. and Chisti, Y. (2011): 'Luxury uptake of phosphorus by microalgae in full-scale waste stabilisation ponds', Water Science and Technology, 63(4), 704-709.

Racault, Y., Boutin, C. and Seguin, A. (1995): 'Waste stabilisation ponds in France: a report on fifteen years experience', Water Science and Technology, 31(12), 91-101.

Reed, S. C. (1985): 'Nitrogen removal in wastewater stabilisation ponds', Water Pollution Control Federation, 57(1), 39-45.

Schetrite, S. and Racault, Y. (1995): 'Purification by a natural waste stabilisation pond: influence of weather and ageing on treatment quality and sediment thichness', Water Science and Technology, 31(12), 191-200.

Sheehan, J., Dunahay, T., Benemann, J. and Roessler, P. (1998) A look back at the US Department of Energy's Aquatic Species Program - Biodiesel from Algae. National Renewable Energy Laboratory, Golden, Colarado.

Shelef, G. (1982): 'High-rate algae ponds for wastewater treatment and protein production', Water Science and Technology, 14(1-2), 439-452.

Shilton, A. and Harrison, J. (2003): Guidelines for the hydraulic design of waste stabilisation ponds, New Zealand, Massey University, Palmerston North.

Soler, A., Torrella, F., Saez, J., Martinez, I., Nicolas, J., MLlorens and Torres, J. (1995): 'Performance of two municipal sewage stabilisation pond systems with high and low loading in south-east Spain', Water Science and Technology, 31(12), 81-90.

Spolaore, P., Joannis-Cassan, C., Duran, E. and Isambert, A. (2006): 'Commercial applications of microalgae', Journal of Bioscience and Bioengineering, 101(2), 87-96.

Stolz, P. and Obermayer, B. (2005) 'Manufacturing microalgae for skin care', Cosmetics & Toiletries, 120, 3, p.99-106.

Surampalli, R. Y., Banerji, S. K., Pycha, C. J. and Lopez, E. R. (1995): 'Phosphorus removal in ponds', Water Science and Technology, 31(12), 331-339.

Takeuchi, T., Utsunomiya, K., Kaboyashi, K., Owada, M. and Karube, I. (1992): 'Carbon dioxide fixation by a unicellular green alga Oocystis sp.', Journal of Biotechnology, 25(3), 261-267.

Tredici, M. R. (2004) 'Mass production of microalgae: photobioreactors', in Richmond, A.(ed), Handbook of microalgal culture:

biotechnology and applied phycology. Blackwell Science, Oxford, 178-214.
Ugwu, C. U., Aoyagi, H. and Uchiyama, H. (2008): 'Photobioreactors for mass cultivation of algae', Bioresource Technology, 99(10), 4021-4028.
Van Den Hende, S., Vervaeren, H. and Boon, N. (2010): 'Industrial symbiosis: C, N and P scavenging from sewage and flue gas with algal bacterial flocs', Journal of Biotechnology, 150(Supplement), 278.
von-Sperling, M. and Chernicharo, C. A. d. L. (2005): Biological wastewater treatment in warm climate regions, International Water Association, London.
von-Sperling, M. and Mascarenhas, L. C. A. M. (2005): 'Performance of very shallow ponds treating effluents from UASB reactors', Water Science and Technology, 51(12), 83-90.
Weatherell, C. A., Elliott, D. J., Fallowfield, H. J. and Curtis, T. P. (2003): 'Variable photosynthetic characteristics in waste stabilisation ponds', Water Science and Technology, 48(2), 219-226.
Wilde, E. W. and Benemann, J. R. (1993): 'Bioremoval of heavy metals by the use of microalgae', Biotechnology Advances, 11(4), 781-812.
Yamaguchi, K. (1997): 'Recent advances in microalgal bioscience in Japan, with special reference to utilization of biomass and metabolites: A review', Journal of Applied Phycology, 8(6), 487-502.
Yun, Y.-S., Lee, S. B., Park, J. M., Lee, C.-I. and Yang, J.-W. (1997): 'Carbon dioxide fixation by algal cultivation using wastewater nutrients', Chemical Technology and Biotechnology, 69(4), 451-455.
Zimmo, O. R., Steen, N. P. v. d. and Gijzen, H. J. (2004): 'Nitrogen mass balance across pilot-scale algae and duckweed-based wastewater stabilisation ponds', Water Research, 38(4), 913-920.