Chapter 1
Past, Present and Future of Microalgae Cultivation Developments

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Abstract Microalgae cultivation is a promising methodology for solving some of the future problems of biomass production (i.e. renewable food, feed and bioenergy production). There is no doubt that in conjunction with conventional growth systems, novel technologies must be developed in order to produce the large-scale sustainable microalgae products. Here, we review some of the most promising existing microalgae biomass growth technologies and summarise some of the novel methodologies for sustainable microalgae production.

1.1 Introduction

There has recently been extensive research focus on biology, physiology, engineering and their integration for microalgae cultivation to produce sustainable products such as biofuel, food, feed and high-value products. Algae belong to many different and unrelated taxonomic groups that all contain chlorophyll *a* and are able to utilise solar energy and fix CO_2 to produce organic compounds (Borowitzka 2012). More than a dozen algal species have been mentioned in the literature as potential candidates for large-scale cultivation. However, conclusive information obtained through commercial trials is not yet available to assess suitability of most of these species. The ideal microalga must be able to grow very well even under high biomass concentration and varying environmental conditions. It must be able to produce high concentration of product of interest (i.e. high-value products, lipids and hydrocarbons). However, it is unknown how many species of algae exist, with

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Table 1.1 Main microalgae species tested for medium- to large-scale biomass production

Chlorophyceae	*Neochloris oleoabundans; Scenedesmus dimorphus; Botryococcus braunii; Dunaliella tertiolecta; Nannochloris* sp.; *Chlorella protothecoides; Ankistrodesmus braunii*
Euglenophyceae	*Euglena gracilis*
Prasinophyceae	*Tetraselmis* spp. (i.e. *T. chuii and T. suecica*)
Haptophyceae	*Chrysotila carterae*; *Isochrysis galbana*
Eustigmatophyceae	*Nannochloropsis* spp. (e.g. *N. salina*, *N. oculata*, *N. gaditana*)
Bacillariophyceae (diatoms)	*Cyclotella cryptica*; *Chaetacerous* sp.; *Skeletonema* sp.
Cyanobacteria (blue-green algae)	*Arthrospira* (*Spirulina*) *platensis*

estimates ranging between several hundred thousand and several million different species—with new types identified all of the time (Guiry 2012). Only a small portion of microalgal species (several thousand) can be kept alive in culture, and only a handful of them have been successfully grown commercially. Table 1.1 summarises the main microalgae species tested for medium- to large-scale production (especially for feed, high-value products and biofuel).

However, to date, only a few of these species were successfully grown in large scale. Commercial large-scale production of microalgae for bioproducts began in early 1960s and 1970s with *Chlorella* and *Spirulina* and followed in the 1980s with production of β-carotene from *Dunaliella salina* (Borowitzka 2013a). All three species were successfully grown in mixed or unmixed open ponds (Craggs et al. 2013). The ability to grow at highly selective environments is the main reason for the successful growth of these species (*Spirulina* = high pH and high HCO_3^-, *D. salina* = high salinity and *Chlorella* = high nutrients) (Craggs et al. 2013). Moheimani and Borowitzka (2006) also showed that *Chrysotila carterae* reliable long-term culture in raceway pond is successful due to the ability of this alga to grow at very high pH. Other species that do not have this selective advantage may need to be grown in closed photobioreactors. The selection of growth technologies or production systems for microalgae will need to be based to a large extent on the microalga of choice and cultivation system.

1.2 Microalgae Cultivation and Production Process

A conventional microalgae production system consists of (a) growth and cultivation of microalgae, (b) biomass harvesting and dewatering and (c) extraction/conversion of the biomass to the product of interest (Fig. 1.1). It is to be noted that for this process to be energetically, environmentally, and economically sustainable, it is critical to recycle medium (water and fertilisers) in harvest and extraction stages of production (Fig. 1.1).

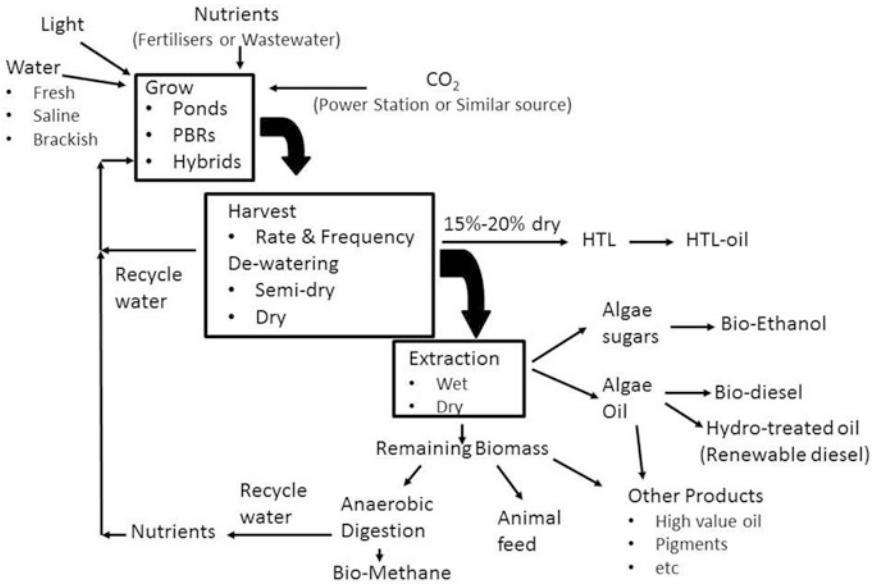

Fig. 1.1 Microalgae production flow sheet (modified and redrawn from Fon Sing et al. 2013)

1.2.1 Growth Technologies

There are two main types of microalgae cultivation systems: open ponds and closed photobioreactors (Moheimani 2012; Moheimani et al. 2011).

1.2.1.1 Closed Photobioreactors

Closed algal cultures (photobioreactors) are not exposed to the atmosphere and are covered with a transparent material or contained within transparent tubing. Photobioreactors have the distinct advantage of preventing evaporation (Dodd 1986; Moheimani et al. 2011). Culturing microalgae in these kinds of systems have the added benefit of reducing the contamination risks, limiting the CO_2 losses, creating reproducible cultivation conditions, and flexibility in technical design (Jeffery and Wright 1999). Closed and semi-closed photobioreactors are mainly used for producing high-value algal products (Becker 1994). In closed photobioreactors, the main challenge is being less economical than open ponds (Borowitzka 1996; Moheimani and McHenry 2013; Moheimani et al. 2013c; Pulz and Scheibenbogen 1998). A number of researchers have endeavoured to overcome a number of the limitations in closed including:

- reducing the light path (Borowitzka 1996; Janssen et al. 2002; Miron et al. 1999)
- solving shear (turbulence) complexity (Barbosa et al. 2003; Borowitzka 1996; Miron et al. 2003)
- reducing oxygen concentration (Acién Fernández et al. 2001; Kim and Lee 2001; Rubio et al. 1999; Weissman et al. 1988), and
- temperature control system (Becker 1994; Borowitzka 1996; Carlozzi and Sacchi 2001; Morita et al. 2001; Rubio et al. 1999; Zhang et al. 1999).

Currently, the main disadvantages of closed systems are the high cost of construction, operation both for energy (pumping and cooling) and maintenance [such as cleaning and sterilization (Borowitzka 1996)], and scaling up difficulties (Grima et al. 2000; Janssen et al. 2002; Miron et al. 1999). However, if these difficulties can be overcome, these controlled closed systems may allow commercial mass production of an increased number of microalgal species at a wider number of locations.

1.2.1.2 Open Ponds

Open ponds are the most usual setting for large-scale outdoor microalgae cultivation (Fon Sing et al. 2013; Jeffery and Wright 1999). The major commercial production of algae is today based on open channels (raceway) which are less expensive, and easier to build and operate compared with closed photobioreactors (Borowitzka 2013b; Tredici and Materassi 1992). In addition, the growth of microalgae meets is less challenging in open than closed cultivation systems; however, just a few species of microalgae (e.g. *Chlorella*, *D. salina*, *Spirulina.* sp., *Chlorella* sp. and *P. carterae*) have been successfully grown in open ponds (Moheimani and Borowitzka 2006; Tredici and Materassi 1992). Large-scale outdoor commercial microalgal culture has been methodically developed over the last sixty years (Borowitzka and Moheimani 2013a). Profitable production of microalgae, at present, are limited to a comparatively few small-scale (<10 ha) plants producing high-value health foods, most located in south-east Asia, Australia and the USA (Benemann 1992; Borowitzka and Borowitzka 1990; Richmond 1992). Two major types of large-scale open cultivation systems have been developed and have been used on a commercial basis. These are (a) unstirred ponds and (b) stirred ponds (circular and raceway) (Borowitzka 1993a, b; Borowitzka and Moheimani 2013b). The most common commercial microalgal culture system in use today is the paddlewheel-driven raceway pond (Richmond et al. 1993). The advantages and disadvantages of growing microalgae in open ponds and closed photobioreactors are summarised in Table 1.2. Relatively low cost of construction and operation are the main reasons for culturing algae in open ponds (Tredici and Materassi 1992). However, the high contamination risks and low productivity, induced mainly by poor mixing regime and light penetration, are the main disadvantages of open systems.

Table 1.2 Open versus closed photobioreactors

	Open ponds	Closed photobioreactors
Light efficiency	Fairly good	Excellent
Temperature control	None	Some
Gas transfer	Poor	Better
Oxygen produced	High	Higher
Hydrodynamic stress on algae	Low	High, very high
Surface/volume ratio	Moderate	High
Species control	Challenging	Achievable
Sterility	None	Achievable for short periods
Volumetric productivity	Low	High
Cost to scale up	Low	High

1.2.2 Harvesting and Dewatering

Energy-efficient and cost-effective microalgae dewatering, nutrient recycling and effluent water quality control are some of the major challenges facing industrial-scale microalgae production for commodity feeds and fuels (Benemann 2013; Borowitzka and Moheimani 2013b; Wyman and Goodman 1993a). Irrespective of the cultivation system, the biomass concentration of the algae culture is generally low (a few mg L^{-1} in open ponds to a few g L^{-1} in intensive closed photobioreactors). Dewatering is therefore critical for producing any materials from microalgae. The objective of harvesting and dewatering is to raise the concentration of the microalgal biomass by more than two orders of magnitude to over 10 % solids, sufficiently concentrated for subsequent processing or drying. It is widely believed that this is best achieved using a combination of technologies in a two-stage process (Benemann et al. 1982; Shelef et al. 1984; Vandamme et al. 2013), such as flocculation followed by centrifugation. This necessitates that large volumes of water need to be processed to harvest the biomass. This concentration process is typically energy intensive and results in high harvesting, thickening and dewatering costs (Mohn 1988). Available harvesting and dewatering process selection often interacts with both up- and downstream process steps in microalgae production, such as strain selection and medium composition, biomass fractionation (e.g. in a biorefinery) and water or nutrient recycling (de Boer et al. 2012; Wijffels et al. 2010).

1.2.3 Extraction/Conversion

Post-dewatering, the microalgae biomass can be used directly as a source of animal feed or human food. The cultural and economic development of society has resulted in changes in human lifestyles with developed countries' diets highly caloric, rich in

saturated fats and sugars, with lower consumption of complex carbohydrates and dietary fibre. This has brought about a greater interest in new foods that can contribute to improve nutritional health and well-being (Plaza et al. 2008). Microalgae are certainly candidates for producing high protein (*Spirulina*), high carbohydrate (*Chlorella*) and high essential oil similar to fish oil (Diatoms). Furthermore, microalgae biomass can be converted to renewable fuels. The three different pathways that can be used to extract and convert microalgae wet biomass (20 % solid) into bioenergy are summarised in Fig. 1.2. To date, hydrothermal liquefaction seems to be the most energetically positive method for biofuel production from microalgae (de Boer et al. 2012). However, extensive research and development is still required to determine the most energetically favourable and economically feasible process for extracting and converting the algal biomass for renewable bioenergy.

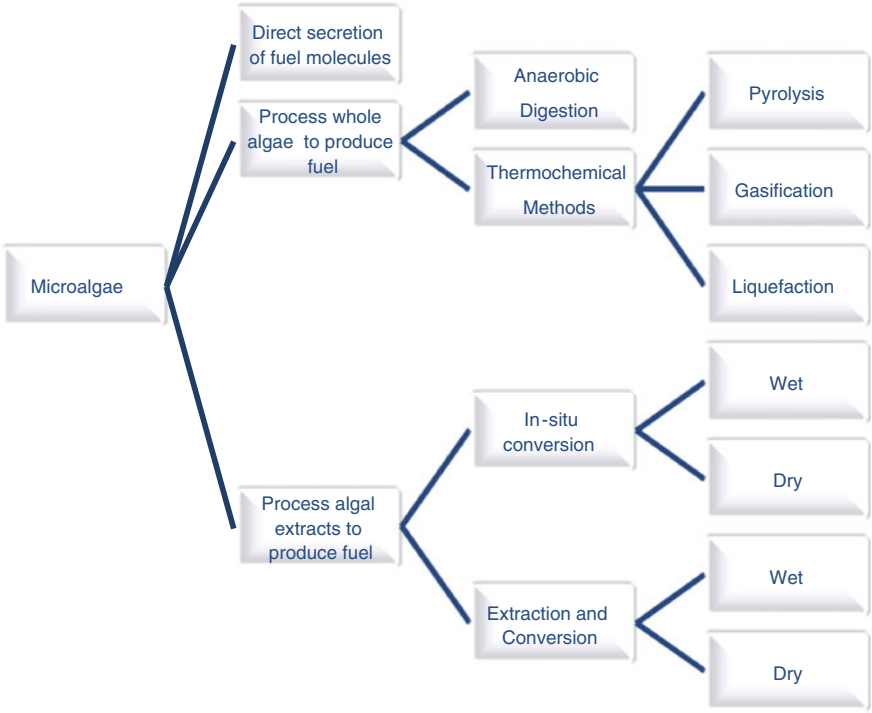

Fig. 1.2 Classification of conversion pathways for microalgae to fuel (de Boer et al. 2012)

1.3 Novel Methodologies

1.3.1 Conversion of Solar Energy to Biomass and Electricity

Photosynthesis is the driving mechanism behind microalgae biomass production but only requires a small fraction of the incident solar energy, primarily in the blue and red portions of the solar spectrum. In conventional cultivation of microalgae, the remainder of the incident solar energy simply heats the algae ponds, causing the water in them to evaporate and increase salinity which is a significant problem in biomass production. With microalgae cultivation often occurring in hot, semi-arid locations, this incidental heating is essentially a waste of the solar energy. Instead, it would be advantageous to be able to capture this unused portion of the solar spectrum and convert it to electricity for use at the cultivation site (Moheimani and Parlevliet 2013).

Figure 1.3 illustrates how the solar spectrum can be divided between the growth of microalgae and the production of electricity by a photovoltaic device (solar cell). Irradiance falling on the Earth's surface is well defined in the standard ASTM G-173-03 (ASTM 2008). This is the AM1.5 solar spectrum as shown in Fig. 1.3. Of this spectrum, only a fraction is used by photosynthesis by a microalgae culture. Some 48.7 % of the incident solar energy is considered to be photosynthetically active radiation (PAR) in the region between 400 and 700 nm (Zhu et al. 2008). However, it is clear from the absorption spectra of Nannochloropsis that some parts of the spectrum are absorbed more strongly than others. As such, the growth and performance of photosynthetic organisms are strongly linked to the quality and quantity of available light (Lindström 1984; Smith 1983) with only some parts of the spectrum being used in photosynthesis. In comparison, highly efficient crystalline silicon solar cells can absorb light strongly across the solar spectrum as shown by the spectral response of a PERL cell (Zhao et al. 1996) shown in Fig. 1.3. This suggests that although these consumers of solar energy (microalgae and solar cells) would appear to compete for the same resource, if the irradiance could be split between the two, the full utilisation of the solar spectrum would be possible. The shaded regions in Fig. 1.3 illustrate the portions of the solar spectrum that can be delivered to electrical generation and to microalgae cultivation without reducing the productivity of the microalgae. This would allow the production of biomass and electricity from the one facility.

The concept of the coproduction of electricity and agricultural production has been previously used in photovoltaic greenhouses. These are a building integrated photovoltaic system whereby solar modules are integrated into the structure of the building (Parida et al. 2011). Photovoltaic greenhouses use photovoltaic modules in the parts of the greenhouse whereby any reduction in overall PAR would not alter the growth of the plants, while the use of semi-transparent or opaque elements on the greenhouse can reduce the PAR and result in decreased productivity (Pérez-Alonso et al. 2012). This would be due to a reduction in the irradiance the plants required for photosynthesis. To overcome this issue, we propose the use of a

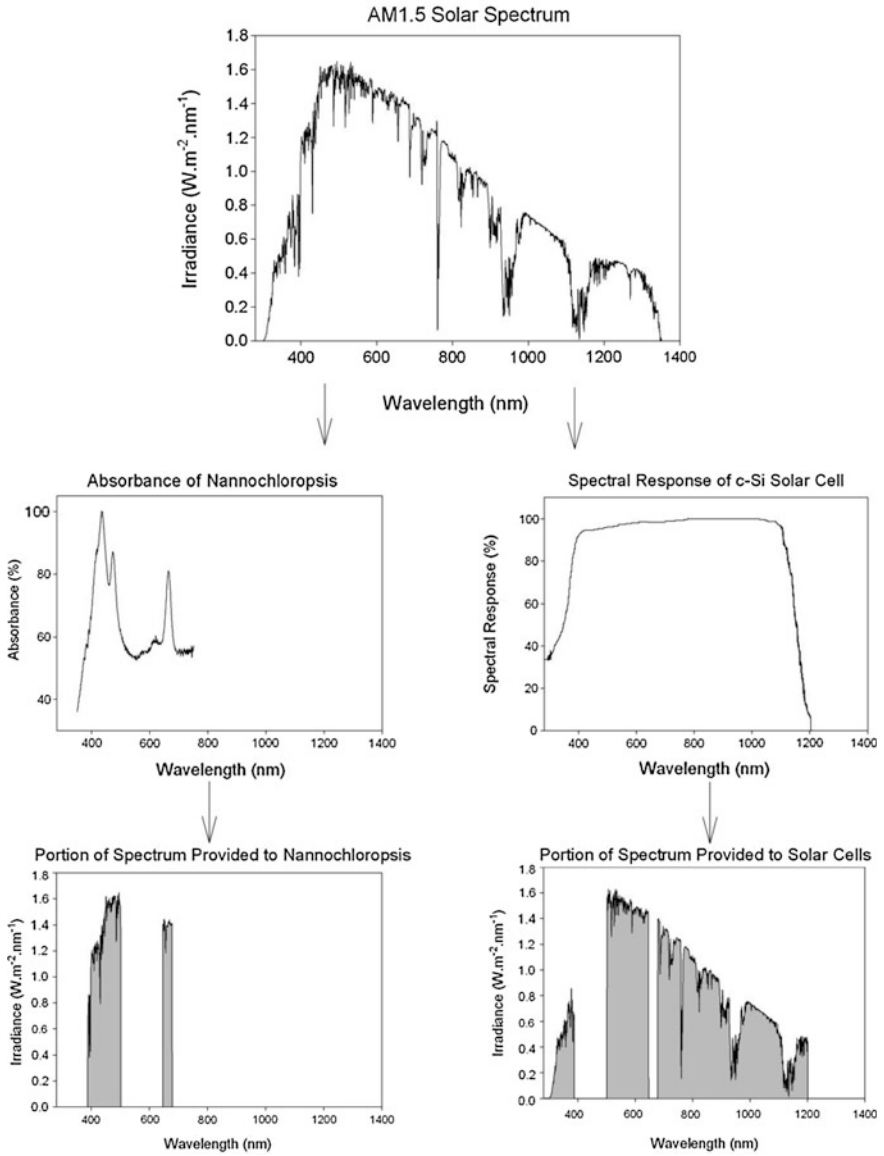

Fig. 1.3 Splitting the solar spectrum for the coproduction of biomass and electricity

semi-transparent solar module that is specifically designed to transmit the irradiance required by the microalgae and convert the remainder to electricity via a photovoltaic system. This solar module or filter can be located above the microalgae ponds (Moheimani and Parlevliet 2013).

There are a number of advantages to this system. By reducing the total irradiance incident upon the microalgae pond, the temperature of the culture would be reduced which would result in lower evaporation and a more stable salt content in the pond. As the microalgae are still receiving the portion of the spectrum required for photosynthesis, there would be no reduction in productivity. The electricity generation by the photovoltaic aspects of the system can be used on site to power motors and electronic systems to reduce the running costs of a facility. Alternatively, the electricity can be used to power additional lighting to increase the period of illumination on the microalgae or to increase the irradiance in specific parts of the solar spectrum. Using additional lighting powered by the otherwise wasted portions of the solar spectrum can increase the productivity of the microalgae. The style of system we have proposed (Moheimani and Parlevliet 2013) can improve the viability of microalgae growth for industrial purposes.

1.4 Non-destructive Extraction (Bio-oil and Bio-ethanol)

The economic viability of the current microalgae to fuel (or chemical) processes (summarised in Fig. 1.1) is limited by the high cost and energy burdens for growth inputs, capital and operating costs for dewatering, and the operating and capital costs of the growth system (Clarens et al. 2010; Lardon et al. 2009; Stephenson et al. 2010). Advances in growth, harvesting and extraction systems provide incremental improvement to these systems. The persistence of companies/research institutions and governments in continuing to pursue these systems indicates that many believe that such incremental improvement over time will ultimately result in an economically viable process. Others believe that a step change is required and are pursuing an entirely different biofuel production model in which the product of interest is continually secreted by the microalgae. This novel method is generally referred to as 'milking', as the product of interest is 'milked' from the algae without the need to destroy it and subsequently regrow it.

1.4.1 Hydrocarbons from Botryococcus Braunii

Hydrocarbons are able to be 'milked' (without cell death) from *Botryococcus braunii* using a solvent added to the growth medium (Moheimani et al. 2013a). Advances in this research further demonstrated that hydrocarbons could be repeatedly extracted (milked) from *B. braunii* using the solvent every 5 days for a total of 70 days with no addition of fertilisers (N and P) to the culture (Moheimani et al. 2013b). In this experiment, the cells were not dividing and therefore, nutrients were not required for the production of proteins and other cell elements. Instead, the majority of the light energy was used to convert CO_2 to hydrocarbons to replace those previously milked.

1.4.2 Ethanol from Blue-Green Algae (Cyanobacteria)

Algenol (Florida, USA) has been continually refining a process for continuous growth and harvest of ethanol excreted by modified cyanobacteria. In this process, ethanol is released by the organism in the vapour phase and then captured for extraction using a novel distillation process, eventually the spent microalgae biomass is converted to fuel using a variant of the HTL process. Algenol claims the following figures for their pilot plant (http://www.algenol.com/):

- **Yield**: 8000 gallons per acre of total liquid fuel production (80,000 L/ha) of which 85 % is ethanol and the remaining 15 % is hydrocarbons
- **Cost**: $1.27 per gallon

Two other companies pursuing milking-based projects are Joule unlimited and Proterro who are focused on chemicals/fuels and sugars as feedstock to traditional biofuel processes, respectively. In all of these approaches, the process is fundamentally different as the milking process extracts the oils, ethanols or other chemicals of interest from the growth medium without killing the microalgae. As a comparison, the traditional microalgae production systems 'kill' the 'cow' (microalgae) to extract the 'milk' (oil) rather than keeping the cow (microalgae) productive and continually harvesting the milk (oil) (Moheimani et al. 2013a). Milking addresses the shortfalls of the existing production systems in two major ways:

- **Nutrients**—Only the products of interest are removed (which typically contain very low N and P), and as a result, there is a limited requirement for fertilisers. Only water, CO_2 and sunlight are required to continually produce the compounds
- **Dewatering**—Microalgae are typically not removed from the culture to be milked to limit the need for dewatering (Moheimani et al. 2013b).

These systems are currently at various stages of early development. Despite this, the potential of these novel approaches to address the major issues with traditional methods warrants their continued investigation.

1.5 Wastewater as a Source of N and P

The main advantages of microalgae growth compared to land plants are the ability to grow on arid land using saline water (Fig. 1.1). This means that microalgae cultures will not compete with food crops over agricultural land and freshwater. However, microalgae, the same as any other photosynthetic organism, would still require fertilisers (especially nitrogen and phosphorous) to grow. If grown in sea water, macronutrients are necessary to be added to the culture to achieve high growth rate. Borowitzka and Moheimani (2013a) indicated that for producing 100,000 bbl of algal oil year^{-1}, there is a need for 14,447 and 219 tons of nitrogen

(as $NaNO_3$) and phosphorous (as NaH_2PO_4), respectively. Such a high volume of fertilisers will significantly affect the overall cost of production. Furthermore, phosphorous is a non-renewable resource, and at current rates of extraction, global commercial phosphate rock reserves may be depleted in less than 100 years (Cordell et al. 2009). That means that algae cultures, irrespective of their product, will be in direct competition with food crops over fertilisers. Obviously, one very important consideration in developing any potential large-scale algae production facility is the recycling of the medium (Fig. 1.1). Recycling medium especially post-extraction/conversion would allow the recycling of a large amount of fertilisers especially if the wet biomass is being converted to biodiesel and biomethane (Fig. 1.1). Furthermore, there is a possibility of combining microalgae cultivation with wastewater treatment. Combining microalgae cultures with wastewater treatment plants (domestic or animal waste) can provide microalgae with required nutrients and result in lower cost wastewater treatment than traditional approaches.

The potential of combining microalgae cultures and domestic wastewater treatment was first proposed in 1960s with the main interest to produce biofuel (Oswald and Golueke 1960). There are currently some facilities around the world (i.e. New Zealand, USA) using high rate algal ponds (HRAPS) for treating tertiary domestic wastewater. In general, microalgae growth in tertiary-level wastewater treatment can significantly reduce the electromechanical cost of treatment (Craggs et al. 2013). Another advantage of using microalgae in the domestic wastewater treatment process is more efficient nutrient removal and sunlight-driven disinfection (Davies-Colley et al. 2005). Animal waste (i.e. piggery waste) can also be treated using microalgae cultures. The environmental impacts of intensive pig production can be significant. A poorly managed piggery may risk wastewater pollution to local waterways, produce odour emissions and release greenhouse gases into the atmosphere (Maraseni and Maroulis 2008). Wastewater generated through high-intensity pig production is high in ammonia and phosphorous while also having high chemical and biological oxygen demands (Olguín et al. 2003). High phosphorous levels have been shown to correlate to high turbidity levels giving the effluent a dark colour (Ong et al. 2006). One wastewater treatment system that is gaining acceptance in Australian piggeries is anaerobic digestion ponds. These systems typically consist of a covered pond containing wastewater which is biologically treated by heterotrophic microorganisms in the absence of oxygen. The covered digesters allow the production and capture of biogas including methane and carbon dioxide. The benefits obtained from these ponds are the removal of solids through settling, capture of biogas for use as a biofuel and the reduction of odour emissions. The utilisation of methane as a fuel source can effectively reduce dependence on energy sources from outside the piggery. One challenge is that the anaerobic digestion effluent from piggeries is very high in ammonium (toxic to most organisms). If a process incorporating CO_2 uptake such as algae culture was to be adopted, ideally CO_2 (generated via burning CH_4 or separated from the raw biogas stream) will be captured and reused within the piggery. A recent review of wastewater management in Australian piggeries recommended that along with anaerobic digestion, microalgae culture systems should be investigated further as a

potential component of the Australian piggery wastewater management strategy (Buchanan et al. 2013).

To date, all trials on culturing microalgae on undiluted and untreated anaerobic digestion piggery effluent (ADPE) have failed to gain widespread acceptance in the industry. On the other hand, there are reports of the successful microalgal cultivation on piggery anaerobic digestate after dilution with freshwater (Park et al. 2010). Interestingly, in some cases, the digestate was diluted more than 15 times with freshwater. In the context of an Australian piggery system, such a method would never be practical due to the shortage of freshwater. Ayre (2013) isolated three microalgae capable of growing on undiluted, sand-filtered, piggery anaerobic digestate. This proof-of-concept study clearly illustrated the potential for culturing microalgae in such effluent with a high ammonium content. The produced algae biomass on piggery anaerobic digestate will sequester carbon and remove nutrients (i.e. nitrogen and phosphorous). The produced biomass could alternatively be used as pig feed, although the biomass pathogen load would need to be closely monitored (Buchanan et al. 2013). Another potential application for the biomass is the co-anaerobic digestion with the piggery waste.

1.6 Microalgae Growth in Saline to Hypersaline Water

The growth of algae, irrespective of cultivation system, requires large volumes of water. Almost all areas with high solar energy also have a high evaporation rate. Therefore, it is logical to use sea water for large-scale algae biomass production. As highlighted previously, it is also critical to recycle the culture medium to reduce the nutrient use. Sea water must also be used to replace evaporative loss. This means that the salt concentration in the pond will gradually increase over the time. For instance, in conditions with evaporations rate of 2 m $year^{-1}$, productivity of 20 g m^{-2} day^{-1} and 80 % medium recycling, the medium salinity will rise from 3.5 % NaCl to 25 % NaCl in 490 days. Salinity is usually growth-limiting at the extremes of salt tolerance in some microalgal species, and every microalga has an optimum salinity range (Borowitzka and Moheimani 2013a). The effect of salinity on microalgal growth relates to osmoregulation, which in microalgae is achieved through diverse strategies. Osmoregulatory metabolites are organic substances produced by microalgae that, when the latter are exposed to water stress conditions, respond appropriately to the changes in extracellular water activity. Microalgae main osmoregulators (function as intracellular osmotic regulators) are as follows: (a) polyhydric alcohols (i.e. glycerol, mannitol or sorbitol), (b) variety of glycosides (i.e. galactosyl glycerides, floridoside and isofloridoside) and (c) amino acids (i.e. glutamic acid and proline).

Freshwater algae grow between 0 and 1–2 % NaCl; hypotonic algae grow between 3.0 and 5–5.5 % NaCl; halotolerant algae grow between 6–7 and 14–15 % NaCl; and halophylic algae can grow above 15–16 % NaCl. The majority of microalgae can grow in freshwater and hypotonic conditions. Some microalgae

(i.e. diatom, chlorophyta and cyanobacteria) are capable of growth under halotolerant conditions. However, only a few species of microalgae are hypersaline (i.e. *D. salina*). There is no single strain of algae capable of optimal growth in the whole range of salinity from sea water to saturation. Interestingly, almost all companies interested in large-scale algae production focus on growing either freshwater or hypotonic algae which will not be sustainable (Moheimani et al. 2013c). Halotolerant algae can normally grow under optimal condition in a wider range of salinities (Fon Sing 2010).

An alternative method of cultivation is to mix microalgae while salinity is being increased. In such a method, a new species can be introduced to the culture of a mono-species while the salinity is rising. That is, a halotolerant microalga species will be introduced to the culture of hypotonic algae when salinity is above the optimum growth condition of the hypotonic algae. If the halotolerant alga can flourish while salinity is increased, the medium use can be maximised. The same technique can be applied for mixed cultures of halotolerant and halophylic microalgae. Such a mixed cultivation technique is yet to be tested at the laboratory or outdoor conditions. One very important advantage of mixed microalgae cultivation is avoiding unnecessary water and nutrient discharge. Considering the species change throughout the cultivation, less negative effect of autoinhibitors is also expected. When the salinity of the culture becomes very high, one option is to have large evaporation ponds for the hypersaline wastewater. Alternatively, this hypersaline water can also be used in salt gradient solar ponds for generating additional energy.

1.7 Hybrid Microalgae Culture and Desalination

The requirements for microalgal dewatering, nutrient recycling and control of effluent wastewater are becoming major challenges to producers (Borowitzka and Moheimani 2010; Charcosset 2009; Clarens et al. 2010; Wyman and Goodman 1993b; Xiong et al. 2008). It is crucial for industrial microalgae production to avoid becoming a net energy-intensive process generating effluent waste at risk of variable profitability (Borowitzka et al. 2010; Borowitzka and Moheimani 2010; Charcosset 2009; Clarens et al. 2010; Wyman and Goodman 1993b; Xiong et al. 2008). As freshwater and energy are essential commodities, finding low-cost and high energy-efficient means to process water and utilise both waste energy and wastewater streams is important (Gude et al. 2010; McHenry 2013). As open pond microalgae production can become expensive due to variable capital, operational, and down-stream processing costs derived from the low microalgae cell densities (Lee 2001; McHenry 2010), and if not optimised, industrial microalgae production will consume large volumes of water through evaporative loss (Chisti 2007; Clarens et al. 2010), generate effluent and become an energy-intensive process (Borowitzka and Moheimani 2010; Charcosset 2009; Clarens et al. 2010; McHenry 2013; Wyman and Goodman 1993b; Xiong et al. 2008). In parallel, conventional

industrial and mining process contaminated wastewater streams are also utilising desalination technologies to reduce environmental contamination and associated costs. With new methods of desalting and water processing, including reverse osmosis (RO), forward osmosis (FO) and membrane distillation (MD), desalination technologies are decreasing water processing costs markedly (Bennett 2011; Bourcier and Bruton 2009; Nicoll et al. 2011). This nascent area will require advances in technical performance, reliability and cost of water processing technology to become commercially viable (Banat and Jwaied 2008).

The introduction of microalgae to water processing is a major potential field of exploration in water processing and efficiency circles. As microalgae species can maintain high growth rates in poor-quality or contaminated water and salinities higher than sea water (Amin 2009; Beer et al. 2009; Hightower 2009), they are able to expand the existing tranche of development possibilities and enable new intensive production options (Cantrell et al. 2008; Gross 2007; Hankamer et al. 2007). Industrial-scale microalgae production will likely require large and intensive water processing technologies for both culturing and biomass recovery. Yet, achieving energy-efficient and cost-effective microalgae dewatering and water management are major challenges. Progressive vertical integration of energy and water-intensive technologies (including large-scale algae) may enable higher aggregated net industrial efficiencies and potentially create new major resources as by-products including minerals, animal feeds, fertilisers, freshwater, electricity, and biofuel. The integration and colocation of industrial microalgae production (e.g. photobioreactors and open ponds) with desalination and other industrial operations are a growing potential area. The theoretical basis behind higher aggregated efficiencies is essentially vertical integration of infrastructure, energy and material flows, reducing total costs, net waste and associated potential environmental contamination. In particular, the judicial use of fast advancing technical capabilities to process water at high efficiency or using waste heat and wastewater through colocating with other industrial facilities may effectively cross-subsidise microalgae energy and water use (McHenry 2013).

1.8 Conclusion

There is no doubt that finding alternative renewable sources of food and energy for future generations is needed. Algae may be a promising answer for the future of biomass production and a carbon-neutral fuel source, considering that microalgae produce significantly higher areal biomass than traditional terrestrial crops. Still, it is unreasonable to think that there is a ‘silver-bullet’ answer to microalgae large-scale biomass production. The conventional (mixed and unmixed open ponds) microalgae to biomass production systems have only been economical for high-value products. The cost of production of microalgae in closed photobioreactors is also most likely to be to very high and not sustainable. Some alternative cultivation methods such as biofilm (see Chap. 2) and mixotrophic growth (see Chaps. 3 and 4), milking

(Moheimani et al. 2013a, b) and combining solar panels with microalgae cultivation system (see Chap. 15) can bring down the cost of production. Combining microalgae cultivation with CO_2 bioremediation (see Chap. 7) and wastewater treatment (see Chaps. 5 and 6) can also add value to the whole algae biomass production. Furthermore, developing novel and economical dewatering systems will positively reduce the overall cost of production (see Chaps. 12, 13 and 14). Last but not least, modifying the algal species of interest can also reduce the cost of production (see Chaps. 8, 9, 10 and 11). Chapter 17 summarises the technoeconomics of the microalgae to biofuel production.

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