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Microalgal bioenergy, biosequestration, and water use efficiency for remote resource industries in Western Australia.

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ABSTRACT

In 2008-09, the mining sales value in Western Australia (WA) was AUD71.3 billion [1]. The resource industry continues to generate significant infrastructure investment and supply expansion developments in remote and arid regions of the state. The sector is also a major driver of liquid fuel demand growth, and currently represents approximately 40% of total transport fuel use, and around 60% (more than 2,000 ML) of diesel consumption in WA each year [1]. The gas and electricity supply interruptions from the June 3 2008 Varanus Island gas facility explosion led to temporary production cuts in several major resource operations [2], and subsequently lead to a focus on diversifying to an increasingly indigenous clean energy supply portfolio [3]. The potential of microalgae technology to address such energy and carbon (C) emissions issues, within a limited water context in the energy intensive Australian resource industry, is substantial. However, there is much research and development investment required for microalgal bioenergy, biosequestration, and water use efficiencies to be integrated into mineral resource production streams. This work explores microalgal biological capacity in the region, microalgal technological developments to date, and the synergies required for microalgae production developments to generate cost-effective and robust returns in the demanding resource industry in the remote and arid mining context.

INTRODUCTION

Mining is a major contributor to Western Australia’s (WA) robust economic growth, and the state hosts 513 commercial mineral projects with 893 operating mine sites producing over 50 different minerals [1] (See Figure 1). Due to the energy demand scale and associated costs, a large proportion of the mining transport fuels are supplied from Singapore refineries rather than the local BP refinery in Kwinana, south of Perth [3].

Therefore, Australian diesel prices are closely linked to the Singapore benchmark price. The 2009 bulk diesel prices in Australia roughly ranged from USD0.50 L^{-1} to USD0.70 L^{-1} (pre-tax), and the resource industry generally enjoys competitive long-term energy supply contracts [4]. The suitability of microalgae for mining bioenergy in Australia is thus fundamentally tied to the Singapore mineral oil price. At USD60[a] a barrel[b] for crude mineral oil, microalgal oil would be cost competitive at an estimated USD0.41 L^{-1}, whilst at USD80 a barrel, microalgal oil would compete at USD0.55 L^{-1} (all pre-tax). Therefore, a reasonable medium-term target price for price competitive microalgal oil for use in microalgal biodiesel production with mineral diesel is USD0.48 L^{-1} pre-tax.

An economic analysis undertaken by Chisti (2007) compared the operating costs of current industrial-scale photobioreactors (PBRs) and open ponds. Assuming 30% oil content by weight, the current cost of small-scale production for the PBR was estimated at USD9.83 L^{-1} and the open pond was USD12.6 L^{-1} [5]. At larger scales of 80 ha of ponds and the equivalent biomass production in a modular PBR system, the microalgal oil PBR and pond production price estimation using current technology was projected to be USD1.40 L^{-1} and USD1.81 L^{-1} (pre-tax), respectively [5]. The recovery process comprised roughly half of this total microalgal oil cost [5]. This simplified example describes the scaling issue in basic economics, however, there are a number of additional uncertainties associated with industrial-scale algal production, including resource limitations and supply chain synergies. While microalgal bioindustrial technology is still in its infancy [6], this emerging industry has the potential to revolutionise nutrition, agriculture, aquaculture, pharmaceutical and biofuel biotechnology [7]. This chapter argues that algae also have the potential to redefine the supply chain of mining systems in regional and remote areas with limited access to conventional energy and water supplies.

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[a] At the time of writing 1AUD was worth 0.85 USD.

[b] A barrel of oil is approximately 156 L.

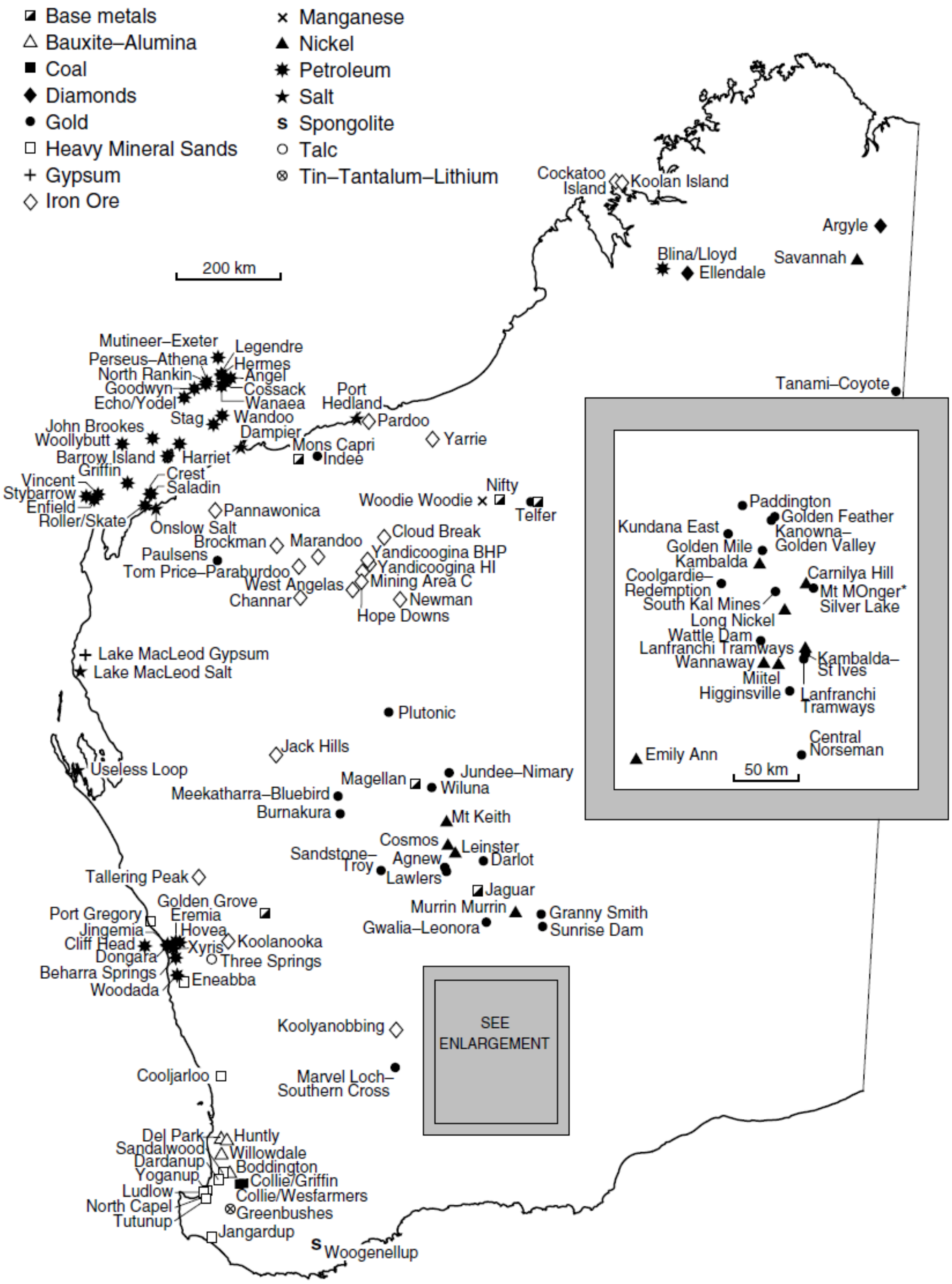

Fig. 1: Major mineral and petroleum projects in WA. Source: [1].

THE ENORMOUS POTENTIAL FOR MICROALGAL ENERGY

Current global biofuel production is dominated from terrestrial plant and animal sources. This supply is increasingly unlikely to be able to produce sufficient volume to offset current demand, and has significant negative impact on global food prices and security [3, 5]. In terms of volume, microalgae appear to be the only source of renewable biofuel capable of meeting the growing global demand for transport fuels [5]. However, aquatic microalgal biofuel production is currently more expensive than land-based production, although this may change with greater knowledge of the unique attributes and high production mass potentials of microalgae [5].

Algae are a diverse group of organisms generally categorised as either macroalgae (i.e. seaweed), or microalgae, which are typically unicellular [7]. Some microalgae rely strictly on photosynthesis, and others metabolise sugars [7]. Mixotrophic[c] cultivation of microalgae utilises their ability to consume carbon (C) substrates, and perform photosynthesis concurrently [8]. Culturing algae mixotrophically can render solar energy as a supplemental energy source, as organic substrates form the primary energy source [8] as exogenous C sources offer a pre-fabricated form of chemical energy [7]. The maximum specific growth of mixotrophic culture is higher than heterotrophic[d] culture for most microalgae [8]. For perspective, heterotrophic culture of *Chlorella* culture in a stirred fermentor tank should in theory attain 91-353 g L^{-1} day^{-1} at a cost lower than USD3 kg^{-1} [8].

Microalgae biomass can be used as a form of energy [9]. Microalgae can provide several renewable bioenergy products, including methane from anaerobic digestion, photobiologically generated hydrogen, ethanol from fermentation, or biodiesel from transesterified microalgal oils [5, 10]. Microalgae biomass can also be gasified to produce combustible gases, or pyrolysed to produce gas, liquid, or solid fuels[e], which can all be used directly, or as a feedstock for biorefineries [10]. Integrated biorefineries use all components of materials to produce useable products, which lowers the production costs of each output product [5, 12]. Biorefineries are in operation in Canada, Germany, the USA, and Australia for terrestrial crop biofuels, and these approaches can also be used to reduce the cost of microalgal conversion. Integrated microalgal biorefineries can simultaneously produce biodiesel, animal feed, biogas, and electricity [5, 10]. Such technologies show promise for translating small-scale demonstration of C neutral microalgal biodiesel production (by utilising waste biomass after oil extraction to provide the processing energy requirements) into industrial-scales [5].

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[c] Mixotrophic means combining autotrophic and heterotrophic mechanisms to obtain nutrition. Autotrophic means obtaining nutrition by either using light as an energy source (phototrophic), or oxidising inorganic compounds (lithotrophic).

[d] Heterotrophic means obtaining nutrition by digesting organic compounds.

[e] Yields of microalgal hydrogen by pyrolysis and steam gasification increase with higher temperatures, with steam gasification yielding greater yields than pyrolysis Demirbas, A., *Thermochemical conversion of mosses and algae to gaseous products.* Energy Sources, 2009. **31**: p. 746-753.

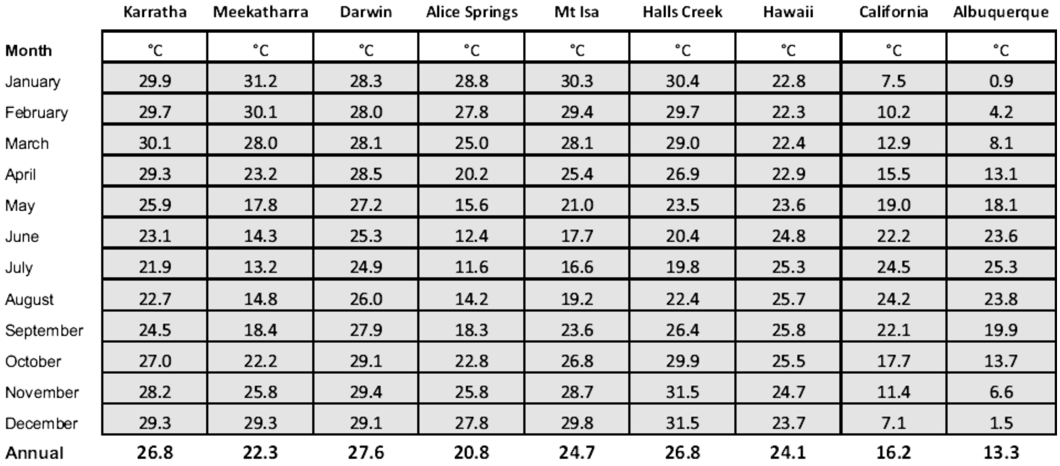
Microalgal production techniques can be used to enhance relative proportions of internal constituents, such as increased lipid production for producing polyunsaturated fatty acids and triglycerides to increase biodiesel output [7, 13]. The introduction of environmental stresses such as nutritional deficiencies result in decreased microalgal cell division and higher lipids production [14, 15]. This demonstrates that progressive optimisation of nutrients and trace minerals specific to particular cultured species can incrementally enhance yields of specific products [16]. New laboratory-based trace mineral and other nutrient optimisation research is showing very promising results to incrementally enhance commercial system yield and process cost-effectiveness [16]. Enhancing sugar and starch production increases the relative proportion of ethanol, while any increase in waste biomass can increase pyrolysis and gasification inputs [13]. However, much research is required to better understand molecular processes to optimise starch fermentation into ethanol and hydrogen, and improved conversion of starches into lipids for biodiesel [17]. There is also much research required to develop more efficient microalgae conversion of solar to chemical energy [15, 18].

THE SOLAR RESOURCE DEPENDENCY

The applicability of specific renewable energy technologies depends heavily on the local availability of renewable resources. Biofuel production is ultimately a means of collecting and storing solar energy [15] and photosynthesis plays a central role in biofuel production [13]. As microalgae cell factories are driven by photosynthesis, their production is dependent on the solar resource. In the USA, the average incident solar energy at the earths’ surface is between 12 and 22 MJ m^{-2} day^{-1}. Australia has a slightly higher incident solar energy resource range from 13 to 24 MJ m^{-2}. However around 90% of the Australian continent ranges between 18 and 24 MJ m^{-2}, and almost 50% of the continent receives between 22 and 24 MJ m^{-2}. Using the theoretically maximum photosynthetic efficiency of 11.6%, the maximum conversion of solar to chemical energy is around 1.4-2.55 MJ m^{-2} day^{-1} in the USA [15], or between 1.43-2.78 MJ m^{-2} day^{-1} in Australia. The 50% of the Australian continent with excellent solar resources, also hosts the vast majority of mining operations. In this half of the continent, the maximum solar to chemical energy conversion potential is between 2.55-2.78 MJ m^{-2} day^{-1}. The vast majority of the state of WA exhibits this potential and also hosts a very large proportion of the national mine inventory, located primarily in remote arid areas.

The US Department of Energy (DoE) funded open pond microalgal biofuel research in New Mexico, California and Hawaii. The DoE’s Aquatic Species Program (ASP) (1978-

1996) [19, 20] discovered that while arid areas provided ample sunlight, such areas can exhibit cooler temperatures at night that limit high production volumes [14]. To maintain consistent production many microalgae species must be kept generally between 20 to 30 degrees Celsius [5]. (See Table 1 for a comparison of monthly mean air temperatures between the USA and Australia). Artificially introducing temperature control is possible, but will add to production complexity and cost. Thus, in general, microalgae production sites must be chosen according to environmental conditions that prove optimum growing conditions [21]. Fundamental limitations to providing optimal growing conditions other than solar energy and temperatures is water and nutrient availability [15, 18].



	Karratha	**Meekatharra**	**Darwin**	**Alice Springs**	**Mt Isa**	**Halls Creek**	**Hawaii**	**California**	**Albuquerque**
Month	°C	°C	°C	°C	°C	°C	°C	°C	°C
January	29.9	31.2	28.3	28.8	30.3	30.4	22.8	7.5	0.9
February	29.7	30.1	28.0	27.8	29.4	29.7	22.3	10.2	4.2
March	30.1	28.0	28.1	25.0	28.1	29.0	22.4	12.9	8.1
April	29.3	23.2	28.5	20.2	25.4	26.9	22.9	15.5	13.1
May	25.9	17.8	27.2	15.6	21.0	23.5	23.6	19.0	18.1
June	23.1	14.3	25.3	12.4	17.7	20.4	24.8	22.2	23.6
July	21.9	13.2	24.9	11.6	16.6	19.8	25.3	24.5	25.3
August	22.7	14.8	26.0	14.2	19.2	22.4	25.7	24.2	23.8
September	24.5	18.4	27.9	18.3	23.6	26.4	25.8	22.1	19.9
October	27.0	22.2	29.1	22.8	26.8	29.9	25.5	17.7	13.7
November	28.2	25.8	29.4	25.8	28.7	31.5	24.7	11.4	6.6
December	29.3	29.3	29.1	27.8	29.8	31.5	23.7	7.1	1.5
Annual	**26.8**	**22.3**	**27.6**	**20.8**	**24.7**	**26.8**	**24.1**	**16.2**	**13.3**

Table 1: Australian and USA location monthly mean air temperatures.

WATER, ENVIRONMENTAL, AND CARBON CHALLENGES

Microalgae appear to exhibit superior environmental credentials to terrestrial biofuels [22]. Microalgal land use and water consumption are much smaller than comparative terrestrial crops [23], and in theory microalgal biomass production can reduce arable land competition between terrestrial crop biofuels with conventional food agricultural production by an order of magnitude [5, 14, 24]. This ability is essentially a factor of their potential to achieve a higher real photosynthetic efficiency than typical terrestrial crops, primarily due to negligible photosaturation and improved access to limiting inputs [10, 14, 15]. Microalgae species can maintain high photosynthetic efficiencies in poor quality, or contaminated water, and even in salinity levels higher than seawater (>35,000 ppm) [10, 17, 25]. Therefore, microalgae can be grown on land unsuitable for conventional agriculture [19] and expand the development possibilities in arid lands [13], or introduce new intensive production options [26].

While exhibiting excellent solar resources and high ambient temperatures, Australia is a very dry continent with little rainfall in the interior. Extensive microalgae pond production systems require large volumes of water. Evaporative losses can be very significant for microalgal ponds in dry regions, which limit their scope and scale when access to water is limited [5]. If groundwater sources are available for large-scale pond facilities in dry regions, the security of microalgal production increases, as heavy rainfall and low temperature events can often lead to the loss of microalgal pond cultures [10, 27]. An opportunity arises to utilise large volumes of excess mine water for microalgal production, and increasing freshwater and energy demand and corresponding decreases in supply quantity and quality is stimulating cross-disciplinary investment in the energy-water nexus [12, 16, 28]. Most of the water supply for mine operations is used for dust suppression and processing, while the remainder is piped to controlled discharge points downstream. An average mining operation in WA generally extracts between 2 and 5 GL of groundwater annually [29]. Most borefields are designed to ensure sustainability of water flow, however, mine borefields are intended to lower the watertable for safe mining operations and extraction must exceed groundwater flows. Water use at the mine is often only around 5% of the available dewatered volume. The generally small seasonally active rivers available in Australia require significant storage volumes to create robust water supplies, and the growing demand from co-located industries other than mining is an appropriate post-treatment synergy in particular cases.

The growing Australian dryland salinity issues and increasing scarcity of freshwater is driving the expansion of new desalination capacity to supply more urban areas, but increasing in regional centres. Many groundwaters exhibit various levels of salinity, and whilst some microalgae are adaptable to salinity levels higher than seawater [25], saline minewater can also be conditioned to supply remote desalination technologies in Australia’s regional interior, with the possibility of zero salty discharge from the mine. Hypersaline discharge from mining dewatering operations can have an impact on local physio-chemical and biological attributes [30], and trapping saline water in holding ponds and combining desalination with microalgal production may be a cheap means of reducing volumes of saline minewater pre and post discharge.

Despite such possibilities, large-scale commercial production is dependent on many factors including microalgal biology, cost of land, labour, energy, the nuances of the environment, water, and available sources of microalgae nutrition [31]. Microalgal growth mediums must provide the inorganic elements that constitute the cell, including nitrogen (N), phosphorus (P[f]), iron (Fe) and in some cases silicon (Si). Generally, commercial fertilisers are used to supply these nutrients and are relatively inexpensive [5]. In areas where mine or regional agricultural wastewater supplies or runoff is high in nutrients, some contaminants, or salt concentrations, microalgal technology can be used to produce biofuels and potentially remediate some constituents that form a production input. Microalgae species are able to use animal wastes as a substrate for animal feedstock production [32] while reducing wastewater treatment costs [26, 33], or diverting nutrients by producing an organic fertiliser from microalgal biomass [22, 33]. Regional location of microalgal facilities can return around two-thirds of the microalgal production nutrient inputs to agricultural systems from microalgal effluents after the recovery of valuable components from microalgal cells [22].

An opportunity arises to integrate C sequestration with other industrial operations using microalgal technologies [17]. Microalgae cells are approximately 40% (generally ±15%) C by dry weight, and therefore can sequester CO_2 in their cells [6]. The CO_2 can be sourced from the atmosphere, soluble carbonate salts, industrial exhaust gasses, and other sources [34]. A requirement for large-scale cost-effective microalgae production is a point source of CO_2, as the gas is required by microalgae continuously during daylight hours to maintain high production rates [5]. Microalgal biosequestration is comparable to forest biosequestration, although the process is not likely to appreciably reduce concentrations of greenhouse gasses from the atmosphere, but can increase C-use efficiency by capturing industrial operation point source emissions. An important factor in microalgal C capture from flue gasses is some microalgae species higher temperature range tolerance [34]. Some microalgae tolerate high temperatures which allow flue exhaust C capture without the need for cooling [34], although there is generally a need for heat exchangers and several other prerequisites for gas pre-processing (such as scrubbing, and pressurisation), in addition to relatively expensive emissions extraction from point source exhausts, pipeline construction, and pumping costs. While it is commonly stated that CO_2 is often abundantly available as a waste gas at zero cost, the reality is that CO_2 addition is simply another input cost to industrial-scale microalgae production.

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[f] Phosphorus nutrient inputs may become a key limiting factor in industrial-scale microalgal production in some regions with a limited P supply. This may also bring industrial-scale production in direct competition with conventional terrestrial food production.

PRODUCTION TECHNOLOGIES

Microalgae are either grown in open or closed systems [35], although most commercial microalgal production system today are open and relatively simple [31, 36]. The two primary competing technologies for commercial microalgae to date is open raceway ponds and closed PBRs [15]. The ability to control yield in PBRs are a significant advantage over ponds. However, there are practical, technical and economic reasons for the existence of two generic “open” and “closed” production methods.

Open ponds have relatively low capital requirements [5, 24], and the most commonly used open systems include natural water bodies, and constructed large shallow ponds, tanks, circular ponds, and raceway ponds [35]. Shallow ponds have medium capital and low operating costs, although exhibit low yields and variable reliability [21]. Raceway ponds are more expensive to build and operate than shallow ponds, but yields and production reliability are improved [21]. Pond productivity can be increased by modifying cell densities, temperatures, dissolved gas concentrations, and pH [18, 27]. Pond productivity decreases with poor mixing, and contamination by less productive microalgal species and organisms that consume microalgae [5, 24]. Microalgae that grow in highly selective environments (such as *Chlorella*, *Spiralina* and *Dunaliella*) remain relatively free of contamination by other microalgae and protozoa [8, 31, 35, 37], although species that do not have a selective advantage must be grown in closed systems [31]. Other limitations in open systems include poor solar utilisation, atmospheric CO_2 diffusion, large land area requirements, and evaporative losses [35]. Evaporative losses can limit their scope and scale when water is a scarce commodity [5], which often inversely proportional to excellent solar resources. While open pond microalgae production is relatively technically simple, it is not necessarily inexpensive due to variable capital, operational, and down-stream processing costs [8].

Closed PBRs contain microalgae in transparent piping systems, are relatively controllable, efficient, and resist contamination [15]. The ability to control environmental conditions offer significant advantages [5, 24], although PBRs located outdoors can still require significant environmental conditioning depending on prevailing weather conditions [35]. While generally more controllable, efficient, and resistant, PBRs have high capital and operating costs [8, 15, 31]. Therefore, volumetric biomass productivity needs to be much higher to offset such high costs [8], and PBR designs should cater for specific microalgal strains, the target product, geographical conditions, and overall economics [35]. Whilst closed systems can increase yield and quality over open-systems [37], most PBRs do not satisfy the Good Manufacturing Practice requirements for pharmaceutical products [8]. Many high value microalgal products must be grown totally free of heavy metal or micro-organism contamination [31], and contamination of microalgal systems will increase the populations of less sought species [15]. Technical difficulties in sterilising some PBR designs negatively impact high value production [8] (such as pharmaceuticals), although these PBRs can still be an effective technology to produce fuels with limited contamination levels.

Higher oil microalgal strains generally grow slower than low oil strains, which when contamination occurs results in greater populations of low oil species [15]. This is more of a productivity concern than a safety issue when producing fuel precursors. However, depending on the economics of production and downstream processing, a range of PBR technologies may still be suitable for the production of various biofuels. Tubular PBRs have very high capital and operating costs, but are very reliable and can produce very high yields [21]. Similarly, algal fermenters are also very expensive to construct and operate, but produce very high yields and are very reliable [21]. These high yields and reliabilities may offset such high costs of these PBR technologies. However, few microalgae PBRs can effectively utilise solar energy by their relatively enclosed nature [35] and require additional light collection and distribution systems, in addition to the significant issues of mass transfer limiting the practicality of PBRs for large-scale production [35]. Therefore, major research and development activity is required to optimise PBRs for particular regions and products, and to date, there is great difficulty optimising production system scale-up. The industry is well aware that extrapolations from small operations are an unreliable predictor of larger system production and economic success [21].

Reducing microalgal biofuel production costs entails maximising lipid content and other biofuel precursors, increasing growth rates, and can include the development of multistage growth systems [7]. Hybrid technological approaches have been assessed by Huntley and Redalje (2006) in systems of up to 2 ha in the USA. This approach included production of high oil strain microalgae populations in ideal PBR conditions to be released into ponds to maximise oil production and maintain population densities. They found that hybrid cultivation systems can provide a continuous supply of high quality culture from PBRs into the larger open ponds, improving production security and cost [24]. Ponds are used to generate large volumes of biomass, and are often successfully used to introduce environmental stresses (commonly nutrient deficiencies) to decrease microalgal cell division and produce higher ratios of lipids after a period [14, 15]. However, an indication of the immaturity of the microalgae industry is the lack of convergence of production technologies. This mirrors the early years of other renewable energy conversion technologies, such as wind turbines, photovoltaics, and concentrated solar thermal developments. Continued investment in mass microalgae production will accelerate such scaling and optimised technology convergence. This will likely be towards various specialised designs reflecting the range and diversity of microalgae species and output products.

PRODUCTION AND PROCESSING REQUIREMENTS

A successful microalgal production biotechnology is heavily dependent on marrying the right microalga with the right conditions [32]. The DoE's ASP recognised that profitable commercialisation requires species and strain selection, metabolic manipulation, and also optimal cultivation specific to the strain [7]. Species characteristics (such as lipid productivity, ease of cultivation and harvesting requirements) are vital to the success of mass production facilities [18]. Species strain selection is governed by the technology used, the resource available, the natural environment, and the project objectives [18]. Long-term microalgae production and culture collection maintenance is a challenging task and requires frequent transfers, exposing species to contamination and genetic drift risks [20].

C capture, bioenergy, nutrient removal from wastewaters, and animal feed production from the remaining biomass, offers flexibility, although it introduces system complexity for production, harvesting, and processing [34, 38]. The recovery of microalgal biomass from the water is generally straightforward, and can be achieved by filtration, centrifugation, chemically, or other means. However it is the cost of algal recovery and processing which is the focus of research attention [5], as harvesting represents a significant operating and capital cost component of microalgal systems [21] and is generally half of total production costs [5].

Extraction and purification of microalgal component products may also be a significant cost, depending on the species, the product, the technology availability, and final use [21]. This area is in need of much investment to provide sufficient certainty of the final product quality for algal biofuels to compete with conventional mineral fuel and biofuels. The application of sophisticated screening and other processing techniques can introduce greater certainty of quality for parallel fuel, food, and pharmaceutical production [32], but will also add to system complexity and cost. A general aim is productivity maximisation to offset high capital costs of growth systems, harvesting, and processing [31]. The reduction of very high total production supply chain costs is why integrated biorefineries are an perceived to be an attractive means to generate products from all available components of the microalgal biomass [5, 12]. In general for biodiesel production, the recovery of lipid and the ratio of unsaturated fatty acids increases with higher extraction temperature and pressure, although other products exhibit particular optimums for extraction [39]. Optimisation is required at almost every step of microalgal production to compete with existing substitutes.

ALGAL ENERGY DEVELOPMENTS

Efficiency in the entire microalgal production chain in regional and remote areas is especially important due to the relative higher cost and limited access to many inputs at the industrial-scale level. The unique attributes of microalgae, Australia's emissions intensive industry, and Australian environmental conditions has lead to the world's largest purpose-built microalgal biofuel and high-protein stock feed facility project for flue gas C capture [40]. The facility developers, MBD Energy, have agreements to construct full-scale demonstration plants at three coal-fired power stations to biosequester CO_2 emissions at source [40, 41]. Once these three full-scale demonstrations are completed, there will be a greater certainty of conversion efficiency and cost-effectiveness for coal-fired power stations. However, the ability of microalgae to capture C remains tied to the performance of the microalgae biomass production process. The work undertaken by Huntley and Redalje (2006) in the hybrid configuration obtained photosynthetic efficiencies of around 1% (over 700 GJ ha^{-1} yr^{-1}), which is typical of land crops [24]. The oil yield was roughly 60% of this output, producing over 11,000L ha^{-1} yr^{-1} [15, 24].

These efficiencies have now been surpassed by researchers in a joint project between Murdoch University in WA and the University of Adelaide that combines microalgal culture research, harvesting, extraction and biofuel production. Professor Borowitzka, the lead researcher from Murdoch University, has developed a system that produces over 25 t of microalgal oil (and sequestered 60 tCO_2-e) per hectare per year, and has operated continuously for around 2 years at the time of writing. This advance has lead to the construction of a multi-million pilot plant in Karratha focussed towards expansion into the mining regions in northern WA. The project's international partners are Parry Neutraceuticals of India, and South China Institute of Technology. This development follows on the experience of Professor Borowitzka who was a leading member of the team which developed and commercialised the *Dunaliella salina* ß-carotene production at

Hutt Lagoon in WA. At around 750 ha of ponds, it is the largest commercial algae production plant in the world [42].

In addition to food supplements and C capture, microalgal biofuel production has diversified into a new diverse research area to produce a range renewable, C neutral, and biodegradable transport fuel, and for energy alternatives post processing [15]. Research on living microalgae and biocatalysing bacteria cooperation to produce renewable electricity in a PAMFC [9] is also a new field of endeavour for microalgae. Strik *et al.* (2008) achieved a photosynthetic efficiency of 6.3% and integrated microalgae and microbial fuel cell combinations, into a photosynthetic fuel cell [9]. In this system, microalgal photosynthesis produces chemical energy and electron production by electrochemically active bacteria at a graphite bioanode of a microbial fuel cell [9]. New options such as these are exciting developments, although it is a long way from a commercially competitive industrial-scale option, and in the development of microalgal bioenergy technology, it is clear that leveraging off existing commercial systems will pay dividends in initial investments.

CURRENT COMMERCIAL ALGAE PRODUCTION AND VALUES

Microalgae are the bottom of the food chain in all aquatic ecosystems and comprise the greatest abundance of plant biomass in aquatic environments [43]. There are an estimated 25,000 microalgae species, with only around 15 in current commercial production [21, 32] for established markets for microalgal products [44]. This almost untapped resource [6] produces an estimated 5000 t of biomass each year, which is valued at almost USD1.5 billion annually [7, 32]. There are around 110 commercial producers of microalgae in the Asia-Pacific region alone, most of which are in Asia [32]. However, the second largest global microalgal production facility (after Hutt Lagoon in Western Australia), is operated by Earthrise Nutritionals in Hawaii. They produce microalgal food supplements in the USA with 44 ha of pond surface area. Macroalgal products are traditional foods in many cultures and their consumption continues to expand [39, 45]. The Chinese used microalgae 2000 years ago as a food source in times of famine [36], and these complex interplays of health, social, environmental, and economic concerns are driving algal research to this day [46].

Integrated industrial microalgal production offers multiple commercial development options [44]. Commercial microalgae production to date has produced human food, non-human food, neutraceuticals, fertiliser, ecological applications, and many other valuable substances [6, 47]. The most commercially produced microalgae are marketed as human health foods [32, 48, 49], although the range of current and future potential products is enormous. Microalgae produce vitamins [8, 21, 32], minerals [8, 21, 49], proteins [10, 21, 32, 49], fats [7, 10, 21, 47, 49], sugars [10, 17, 21, 49], antioxidants [6, 45], cosmetics [32, 36, 47], pharmaceuticals [6, 21, 32, 47, 48], soil conditioners [32], biomass [21, 32], biochemicals [6, 32, 47, 49], bioactive neutraceuticals [6, 8, 21, 32, 49-52], biofertilisers [22, 32], natural dyes and colours [6, 10, 36], in addition to animal feeds [8, 36, 53]. Some microalgae also produce useful carotenoids [21, 47], phycobilins [21], polyketides [47], mycosporine-like amino acids [47], glycerol [21], steroids [47], tocopherol [21], lectins [47], astaxanthin [21], canthaxanthin [21], functional sulphated polysaccharides [21, 47, 49], zeaxanthin, [49], halogenated compounds [47], and some toxins [47]. Many of these products can be produced in either fresh or saltwater [10]. Production diversity add flexibility, but requires robust pre-and-post-treatment, and precise system control [34, 38]. High value microalgae products have the greatest economic potential in the short term [21] and may effectively subsidise the production of microalgal bioenergy, as the remaining biomass is essentially a waste product of manufacture.

Microalgae are a promising source of new products and applications [6]. A growing number of consumers prefer natural origins of food products [39], and microalgal foods (such as long chain omega-3 fatty acids) are safe and bio-available for human consumption [54]. Food fortification with microalgae products are potentially cheaper and safer supplies of fatty acids than conventional sources [55]. Microalgal oils are also able to be consumed by vegetarians as they are considered plant sources, and can eliminate some concerns about potential fish product contaminants [55]. In terms of animal feed, microalgal supplements at particular doses increase aquacultural fish feed efficiency and weight gain against control diets [53]. Microalgal products have also successfully suppressed rumen methanogenesis without depressing overall rumen fermentation, although more research is required to determine wide-scale application [50, 51]. Some microalgae thrive in extreme environments and many extremophile microalgae contain unusual metabolites and enzymes [6]. Some microalgae products exhibit antiviral, antimicrobial, antifungal, cytotoxic, and antihelmintic properties [6], in addition to having potential as a substrate for modulating activity of multidrug resistance (MDR) transporters in marine bivalves (such as mussels) [56]. Alternative microalgal applications include nitrogen fixation in rice cultivation, and erosion process suppression from assisted surface solidification in arid regions [6]. A common commercial horticultural use of algae is also to stimulate plant germination, flowering, and as a stem and leaf growth promotent [6]. Microalgae can also be used as a sensitive bioindicators for lipophilic organic contaminants to detect the presence of pharmaceutical and personal care products in wastewater treatment plants [43].

The pursuit commercial algae production and expansion of new industries (such as advanced neutraceutical, protein therapeutic, and biofuels) merit further microalgae cross-disciplinary research and development [7]. It is likely that the combination of continued technical innovation and market demand will ensure major advances and expansion of microalgal products, uses [13, 47], and production technologies [13]. Whilst many of these products and synergies are divorced from the current mining and resource industries in the remote and arid areas, the industrial-scale supply chains inputs will require exploration of suitable locations to develop a secure and cost-effective system with robust production benefits. A key limitation to cost-effective industrial-scale microalgal production is likely to become land and water resources and relevant supply chain synergies between points of production and consumption.

CONCLUSION

Microalgal technology can integrate C capture, bioenergy, animal feed production, and wastewater nutrient removal (etc.), to add production output flexibility [34, 38] for a regionally customised production system. Harnessing the unique attributes of microalgal for industrial-scale biofuel production to achieve the important ecological, commercial, and energy security goals of early terrestrial biofuel aspirations will require a shared repository of detailed research and technical knowledge spanning many research portfolios. Cross-collaboration is an imperative to provide production certainty and expand algal applications into new areas [57]. Fundamentally, microalgae energy production systems will need to be able to compete with existing production systems commercially [36]. This includes conventional mineral oil and gas, coal, agricultural biofuels, and many other substances microalgal products may compete against. As many laboratory-scale PBRs and open systems are unsuccessfully scaled up due to difficulties in maintaining light, temperature, energy efficient mixing and mass transfers [35], these engineering concerns requiring research, development, and extension investment. Therefore, considerable work is required before commercialisation and integration of microalgae bioenergy products before algae can effectively and reliably compete with conventional energy sources required at the resource project level. In the meantime, existing high-value products may provide some options for parallel development to offset some risk and production costs for particular microalgal species [35].

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REFERENCES

1 Government of Western Australia and Department of Mines and Petroleum. 2009. Western Australian mineral and petroleum statistics digest 2008-09. Perth, Western Australia.

2 McHenry, M P. 2009. Policy options when giving negative externalities market value: Clean energy policymaking and restructuring the Western Australian energy sector. Energy Policy 37, 1423-1431.

3 Centre for International Economics. 2007. Western Australia biofuels taskforce report: Appendix 4 - the economics of biofuels for Western Australia. The Department of Industry and Resources, Canberra.

4 Australian Institute of Petroleum. 2009. Weekly diesel prices report - week ending 6 December 2009. http://www.aip.com.au/pricing/facts/Weekly_Diesel_Prices_Report.htm.

5 Chisti, Y. 2007. Biodiesel from microalgae. Biotechnology Advances 25, 294-306.

6 Pulz, O and Gross, W. 2004. Valuable products from biotechnology of microalgae. Applied Microbiology and Biotechnology 65, 635-648.

7 Rosenberg, J N, Oyler, G A, Wilkinson, L, and Betenbaugh, M J. 2008. A green light for engineered algae: redirecting metabolism to fuel a biotechnology revolution. Current Opinion in Biotechnology 19, 430-436.

8 Lee, Y-K. 2001. Microalgal mass culture systems and methods: their limitation and potential. Journal of Applied Phycology 13, 307-315.

9 Strik, D P B T B, Terlouw, H, Hamelers, H V M, and Buisman, C J N. 2008. Renewable sustainable biocatalyzed electricity production in a photosynthetic algal microbial fuel cell (PAMFC). Applied Microbiology and Biotechnology 81, 659-668.

10 Amin, S. 2009. Review on biofuel oil and gas production processes from microalgae. Energy Conversion and Management 50, 1834-1840.

11 Demirbas, A. 2009. Thermochemical conversion of mosses and algae to gaseous products. Energy Sources 31, 746-753.

12 Wyman, C E and Goodman, B J. 1993. Biotechnology for production of fuels, chemicals, and materials from biomass. Applied Biochemistry and Biotechnology 39 (40), 41-59.

13 Hankamer, B, Lehr, F, Rupprecht, J, Mussgnug, J H, Posten, C, and Kruse, O. 2007. Photosynthetic biomass and H2 production by green algae: from bioengineering to bioreactor scale-up. Physiologia Plantarum 131, 10-21.

14 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, USA.

15 Vasudevan, P T and Briggs, M. 2008. Biodiesel production - current state of the art and challenges. Journal of Industrial Microbiology and Biotechnology 35, 421-430.

16 Xiong, W, Li, X, Xiang, J, and Wu, Q. 2008. High-density fermentation of microalga *Chlorella protothecoides* in bioreactor for microbio-diesel production. Applied Microbiology and Biotechnology 78, 29-36.

17 Beer, L L, Boyd, E S, Peteres, J W, and Posewitz, M C. 2009. Engineering algae for biohydrogen and biofuel production. Current Opinion in Biotechnology 20, 264-271.

18 Griffiths, M J and Harrison, S T L. 2009. Lipid productivity as a key characteristic for choosing algal species for biodiesel production. Applied Microbiology and Biotechnology 21, 493-507.

19 Gross, M. 2007. Algal biofuel hopes. Current Biology 18 (2), R46-R47.

20 Knoshaug, E P, Sestric, R, Jarvis, E, Chou, Y-C, Pienkos, P T, and Darzins, A. 2009. Current status of the Department of Energy's Aquatic Species Program lipid-focused algae collection. National Renewable Energy Laboratory, Golden, Colorado.

21 Borowitzka, M. 1992. Algal biotechnology products and processes - matching science and economics. Journal of Applied Phycology 4, 267-279.

22 Chisti, Y. 2008. Response to Reijnders: do biofuels from microalgae beat biofuels from terrestrial plants? Trends in Biotechnology 26 (7), 351-352.

23 Dinh, L T T, Guo, Y, and Mannan, M S. 2009. Sustainability evaluation of biodiesel production using multicriteria decision-making. Environmental Progress & Sustainable Energy 28 (1), 38-46.

24 Huntley, M E and Redalje, D G. 2006. CO2 mitigation and renewable oil from photosynthetic microbes: a new appraisal. Mitigation and Adaptation Strategies for Global Change 12, 573-608.

25 Hightower, M. 2009. Energy and water issues and challenges - completing the energy sustainability puzzle. Presented at REUSE 09, Brisbane, Australia. Sandia National Laboratories, New Mexico, USA

26 Cantrell, K B, Ducey, T, Ro, K S, and Hunt, P G. 2008. Livestock water-to-bioenergy generation opportunities. Bioresource Technology 99 (7941-7953).

27 Moheimani, N R and Borowitzka, M. 2006. Limits to productivity of the alga *Pleurochrysis carterae* (Haptopphyta) grown in outdoor raceway ponds. Biotechnology and Bioengineering 96 (1), 27-36.

28 Charcosset, C. 2009. A review of membrane processes and renewable energies for desalination. Desalination 245, 214-231.

29 Van Vreeswyk, A M E, Payne, A L, Leighton, KA, and Hennig, P. 2004. Technical Bulletin No 92 - An inventory and condition survey of the Pilbara region, Western Australia Department of Agriculture, Perth, Western Australia.

30 Gregory, S J, Ward, J, John, J, and 2009. Changes in the chemistry and biota of Lake Carey: a large salt lake impacted by hypersaline discharge from mining operations in Western Australia. Hydrobiologia 626, 53-66.

31 Borowitzka, M. 1999. Commercial production of microalgae: ponds, tanks, tubes and fermenters. Journal of Biotechnology 70, 313-321.

32 Raja, R, Hemaiswarya, S, Ashok Kumar, N, Sridar, S, and Rengasamy, R. 2008. A perspective on the biotechnological potential of microalgae. Critical Reviews in Microbiology 34, 77-88.

33 Avino, P, Carconi, P L, Lepore, L, and Moauro, A. 2000. Nutritional and environmental properties of algal products used in healthy diet by INAA and ICP-AES. Journal of Radioanalytical and Nuclear Chemistry 244 (1), 247-252.

34 Wang, B, Li, Y, Wu, N, and Q, Lan C. 2008. CO2 bio-mitigation using microalgae. Applied Microbiology and Biotechnology 79, 707-718.

35 Ugwu, C U, Aoyagi, H, and Uchiyama, H. 2008. Photobioreactors for mass cultivation of algae. Bioresource Technology 99, 4021-4028.

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

37 Zhu, Y-H and Jiang, J-G. 2008. Continuous cultivation of *Dunaliella salina* in photobioreactor for the production of b-carotene. European Food Research and Technology 227, 953-959.

38 Schneider, D. 2006. Grow your own? http://www.americanscientist.org/issues/pub/grow-your-own.

39 Herrero, M, Cifuentes, A, and Ibanez, E. 2006. Sub- and supercritical fluid extraction of functional ingredients form different natural sources: plants, food-by-products, algae and microalgae. a review. Food Chemistry 98, 136-148.

40 Chan, Y. 2009. Australia to launch "worlds largest" green slime facility. http://www.businessgreen.com/business-green/news/2253115/mbd-energy-launch-world-largest.

41 MBD Energy Ltd. 2009. Homepage - building commercially and environmentally sustainable solutions to carbon capture and storage. http://www.mbdenergy.com.

42 Coogan, M A, Edziyie, R E, La Point, T W, and Venables, B J. 2007. Algal bioaccumulation of triclocarban, triclosan, and methyl-triclosan in a North Texas wastewater treatment plant receiving stream. Chemosphere 67, 1911-1918.

43 Skjanes, K, Lindblad, P, and Muller, J. 2007. BioCO2 - a multidisciplinary, biological approach using solar energy to capture CO2 while producing H2 and high value products. Biomolecular Engineering 24, 405-413.

44 Kuda, T, Tsunekawa, M, Goto, H, and Araki, Y. 2005. Antioxidant properties of four edible algae harvested in the Noto Peninsula, Japan. Journal of Food Composition and Analysis 18, 625-633.

45 Jensen, A. 1993. Present and future needs for algae and algal products. Hydrobiologia 260 (261), 15-23.

46 Cardozo, K H M, Guaratini, T, Barros, M P, Falcao, V R, Tonon, A P, Lopes, N P, Campos, S, Torres, M A, Souza, A O, Colepicolo, P, and Pinto, E. 2007. Metabolites from algae with economical impact. Comparative Biochemistry and Physiology, Part C 146, 60-78.

47 Sabra, W, Zeng, A P, and Deckwer, W D. 2001. Bacterial alginate : physiology, product quality and process aspects. Applied Microbiology and Biotechnology 56, 315-325.

48 Dvir, I, Stark, A H, Chayoth, R, Madar, Z, and Arad, S M. 2009. Hypocholesterolemic effects of nutraceuticals produced from the red microalga *Porphyridium* sp in rates. Nutrients 1, 156-167.

49 Fievez, V, Boeckaert, C, Vlaeminck, B, Mestdagh, J, and Demeyer, D. 2007. In vitro examination of DHA-edible micro-algae 2. Effect on rumen methane production and apparent degradability of hay. Animal Feed Science and Technology 136, 80-95.

50 Bozic, A K, Anderson, R C, Carstens, G E, Ricke, S C, Callaway, T R, Yokoyama, M T, Wang, J K, and Nisbet, D J. 2009. Effects of the methane-inhibitors nitrate, nitroethane, lauric acid, Lauricidin and the Hawaiian marine algae *Chaetoceros* on ruminal fermentation in vitro. Bioresource Technology 100, 4017-4025.

51 Dvir, I, Chayoth, R, Sod-Moriah, U, Shany, S, Nyska, A, Stark, A H, Madar, Z, and Arad, S M. 2000. Soluble polysaccaride and biomass of red microalga *Porphyridium* sp. alter intestinal morphology and reduce serum cholesterol in rats. British Journal of Nutrition 84, 469-476.

52 Li, M H, Robinson, E H, Tucker, C S, Manning, B B, and Khoo, L. 2009. Effects of dried algae *Schizochytrium* sp., a rich source of docosahexaenoic acid, on growth, fatty acid composition, and sensory quality of channel catfish *Ictalurus punctatus*. Aquaculture 292, 232-236.

53 Eufemia, N, Girshick, S, and Epel, D. 2000. Algal products as naturally occurring modulators for the multidrug resistance (MDR) transporter (abstract). Marine Environmental Research (Abstracts) 50, 332-333.

54 Arterburn, L M, Oken, H A, Hoffman, J , Bailey-Hall, E, Chung, G, Rom, D, Hamersley, J, and McCarthy, D. 2007. Bioequivalence of docosahexaenoic acid from difference algal oils in capsules and in a DHA-fortified food. Lipids 42, 1011-1024.

55 Whelan, J and Rust, C. 2006. Innovative dietary sources of N-3 fatty acids. Annual Review of Nutrition 26, 75-103.

56 Jamers, A, Blust, R, and De Coen, W. 2009. Omics in algae: paving the way for a systems biological understanding of algal stress phenomena? Aquatic Toxicology 92, 114-121.