The Algae Value Chain Landscape: a competitive technical challenge

Algae biological capabilities provide diverse opportunities

Algae are a diverse group of organisms generally categorised as either macroalgae (i.e. seaweed), or microalgae, which are typically unicellular [1]. Algae are the bottom of the food chain in all aquatic ecosystems and there are an estimated 25,000 microalgae species, with only around 15 in current commercial use [2]. This primarily untapped resource [3] produces an estimated 5000 tonnes of commercial biomass each year, which is valued at almost USD1.5 billion annually [1,2]. Commercial algae systems to date produce human food, non-human food, neutraceuticals, biomass, biofertiliser, and also environmental remediation and monitoring applications [3].

Algae can also produce other valuable substances [3] in either fresh or saltwater cultures, including proteins, lipids, carbohydrates, and pigments [4]. Most commercially produced algae today is marketed as health food [2], although integrated industrial algal production offers multiple economic development opportunities [5]. Algae technology can provide the biological platform to integrate carbon sequestration, bioenergy, biomass production, and water nutrient removal technologies [6,7].

While algal biotechnology is still in its infancy [3], this emerging industry has the potential to revolutionise nutrition, agriculture, aquaculture, pharmaceutical and biofuel biotechnology [1]. However, there is much research and development investment required before algae production systems to reliably and efficiently realise such benefits. This discussion paper explores algal biological capacity, in addition to technological developments in relation to species and strain selection, production, harvesting and extraction, refining, and commercial consumption.

Diverse, valuable products from microalgae

Microalgae have received significant attention because of their potential to achieve a higher real photosynthetic efficiency than typical land crops due to negligible photosaturation (where portions of plants receive more energy than they can process) and an improved access to limiting inputs, such as fertiliser and water [4,8,9]. These unique biological attributes and high production mass potentials give algae an ability to reduce arable land production requirements for a range of commercial products [9-11].

In terms of volume, algae appear to be the only source of renewable biofuels capable of meeting the global demand for transport fuels [10], and exhibit superior environmental credentials to terrestrial biofuels production [12,13]. Algal biomass production can reduce "food vs fuel" competition in terms of area by an order of magnitude, when compared to other biofuels production methods [9-11]. (See Table 1).

Table 1: Comparison of biodiesel source production (Source: [10]).

Crop	Oil yield (L/ha)	Area required for 100,000t of oil (ha)
Corn	172	631,900
Soybean	446	243,700
Canola	1,190	91,300
Jatropha	1,892	57,400
Coconut	2,689	40,400
Oil palm	5,950	18,300
Microalgae[a]	98,000	1,100

[a] **50% oil (by weight) in biomass.**

Conventional biofuels are increasingly unlikely to be able to produce sufficient volume to offset current demand, and has significant negative impact on global food prices and security [10,14], in addition to growing environmental sustainability concerns. Microalgae production can assist the development of sustainable terrestrial agriculture by acting as an effective bioindicator. Bioindicators can be used to monitor soil and water for environmental pollutants [15,16], especially organic contaminants [16]. Microalgae have also being successfully used to reduce wastewater treatment costs of animal and human manures [3,15,17], with the "waste" production of an organic fertiliser [12,15].

Species and Strain Selection

A successful algal production technology is heavily dependent on marrying the right alga with the right conditions [2]. The US Department of Energy's Aquatic Species Program (1978-1996) [18,19] recognised that profitable algae commercialisation requires effective species selection, optimal cultivation, and metabolic manipulation [1]. Species characteristics such as lipid productivity, ease of cultivation and harvesting requirements are vital to the success of mass production facilities [20]. However, the choice of algal species is governed by the technology used, the resource available, the natural environment, and the project objectives [20]. Some algae species live in extreme environments and many contain unusual metabolites and enzymes [3]. Higher oil algal strains generally grown slower than low oil strains, which when contamination occurs results in greater populations of low oil species [8].

Algae that grow in relatively extreme environments (such as Chlorella, Spiralina and Dunaliella) remain relatively free of contamination by other competitive organisms [21-23]. Some algae species can maintain very high photosynthetic efficiencies in contaminated or saltwater concentrations higher than seawater (>35,000 ppm)[4,24,25]. Similarly, some algae can tolerate high temperatures and enable the use of hot flue exhausts as a source of carbon without the need for waste gas cooling [7]. Thus, algae species can be optimised to effectively grow in industrial areas and in areas unsuitable for agriculture [18] and even enable arid land expansion [26]. However, the maintenance of promising algae strains in culture collections is a challenging task and requires frequent algal transfers, exposing species to contamination and genetic drift risks [19].

Production

The effectiveness of renewable energy technologies is dependent on the local availability of renewable energy resources. As algae cell factories are driven by sunlight, their production is dependent on the solar resource. Significant limitations to microalgal growth other than the solar energy resource, is suitable water availability, and a sustainable source of nutrients [8,20]. Algal growth mediums must provide the inorganic elements that constitute the cell, including nitrogen (N), phosphorus (P), iron (Fe) and in some cases silicon (Si) [10]. New laboratory-based process optimisation studies regarding trace minerals, and other nutrients are showing promising results that incrementally enhance commercial system yield and cost-effectiveness [27].

As algae are generally composed of approximately 40% (±10%) carbon by dry weight [28], they are able to sequester CO_2 in a cellular biomass form [3]. Algae can fix CO_2 efficiently from the atmosphere, industrial exhaust gasses, soluble carbonate salts, and other sources [7]. Exogenous carbon sources offer a pre-fabricated chemical energy [1] and CO_2 must be fed to algae continuously during daylight hours to maintain high production rates [10]. However, algal production is not likely to appreciably reduce concentrations of greenhouse gasses from the atmosphere like forestry mitigation projects, but can successfully capture carbon in biofuels from point sources of carbon, such as power stations. Importantly, a requirement for large-scale cost-effective algae production is the need for a point source of carbon dioxide (CO_2). Even, the complete algal biodiesel production process can be carbon neutral by utilising waste biomass after oil extraction to provide the energy requirements for processing [10].

Production Technology

In terms of production methods, there are essentially two competing technologies for commercial algae production: open raceway ponds or closed photobioreactors. Closed photobioreactors contain the water inside complex transparent piping systems. While more controllable, efficient and resistant to contamination by other biological organisms, they are capital intensive [8]. The ability to control yield in photobioreactors are a significant advantage over ponds. However, open ponds are a low cost option. (See Table 2).

Table 2: A large-scale algal production system comparison. (Source: [21]).

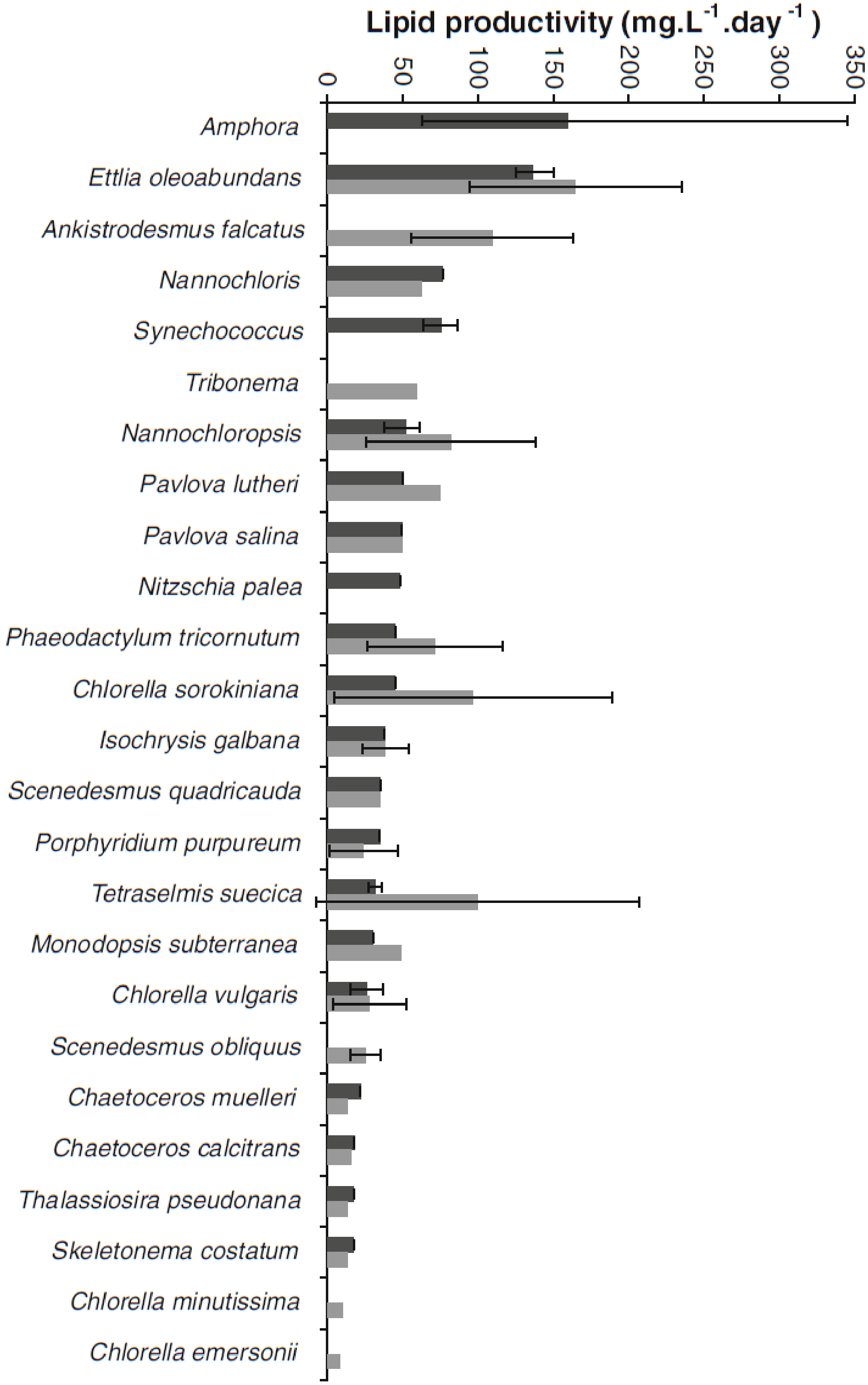
Reactor type	Mixing	Light utilisation efficiency	Temperature control	Gas transfer	Species control	Scale-up	Reference
Unstirred shallow ponds	Very poor	Poor	None	Poor	Difficult	Very Difficult	Borowitzka and Borowitzka, 1989
Tanks	Poor	Very poor	None	Poor	Difficult	Very Difficult	Fox, 1983
Circular stirred ponds	Fair	Fair-good	None	Poor	Difficult	Very Difficult	Tamiya, 1957; Stengel, 1970; Soeder, 1981
Paddle-wheel raceway ponds	Fair-good	Fair-good	None	Poor	Difficult	Very Difficult	Weissman and Goebel, 1987; Oswald, 1988
Stirred tank reactor (internal of external lighting)	Largely uniform	Fair-good	Excellent	Low-high	Easy	Difficult	Pohl et al., 1988
Air-lift reactor	Generally uniform	Good	Excellent	High	Easy	Difficult	Juttner, 1977
Bag culture	Variable	Fair-good	Good (indoors)	Low-high	Easy	Difficult	Baynes et al, 1979
Flat-plate reactor	Uniform	Excellent	Excellent	High	Easy	Difficult	Hu et al., 1996; Tredici and Zitelli, 1997
Tubular reactor (Serpentine type)	Uniform	Excellent	Excellent	Low-high	Easy	Reasonable	Richmond et al., 1993; Torzillo, 1997
Tubular reactor (Biocoil type)	Uniform	Excellent	Excellent	Low-high	Easy	Easy	Borowitzka, 1996

The productivity of pond production is reduced by poor mixing, and contamination by other algal and microorganism species that consume algae [10,11]. While less controllable, adjustments to the pond depth, cell densities, pond temperatures, dissolved oxygen concentration, and pH in pond water, increases productivity markedly despite competition from other organisms [20,29]. (See Fig. 1).

Currently a prospective area of research is using a combination of open and closed technologies in multistage growth systems to minimise algal biofuel production costs while maximising lipid (and other biofuel precursor contents) growth rates [1]. Such hybrid technological approaches allow the production of high oil strain algae populations in ideal photobioreactor conditions and their release into ponds to maximise oil production and maintain population density. A hybrid cultivation system can provide a continuous supply of high quality culture from photobioreactors into the larger open ponds, improving production security and cost [11].

The suitability of algae production for both bioenergy and biosequestration is primarily dependent on the price of competing sources of energy, including crude oil. At USD60 a barrel for crude, algal oil would be cost competitive at USD0.41 L^{-1}, whilst at USD80 a barrel algal oil would compete at US0.55 L^{-1} (all pre-tax). Post alage production, the algae harvesting and extraction process comprises roughly half of this total algal oil production cost [10].

Fig. 1: Species lipid productivity. (Average literature (dark grey), and calculated (light grey) values for biomass productivity in mg L^{-1} day^{-1}. Error bars show the min. and max. recorded lipid productivity for literature values and propagation of error for calculated values). (Source: [20]).



Harvesting, Extraction and Refining

The recovery of algal biomass from the water is generally straightforward, and can be achieved by filtration, centrifugation, chemically, and other methods. However, it is the cost reduction of recovery which is the focus of research attention [10]. Harvesting represents a major operating and capital cost component of mass production [30]. The extraction and refining of various algal products may be a significant cost, depending on the species, product, and final range of products [30]. Achieving cost- effective production is dependent on the species, the production process, and the final range of products, in addition to the development and introduction of new technology. In general, the recovery of lipids and the ratio of unsaturated fatty acids increases with higher extraction temperature and pressure, although particular products exhibit particular optimums for extraction [31]. Generating these temperatures and pressures may come at a high energy cost, which in turn increases economic costs.

Integrated biorefineries use all components of the raw material to produce useable products, which lowers the production costs of each output product [10,32]. Integrated algal biorefineries can simultaneously produce biodiesel, animal feed, biogas, and electricity [4,10]. Biorefineries are already in operation in Canada, Germany, the USA and Australia for crop biofuels, and these approaches can be used to reduce the cost of algal biofuels. Thus, algae biomass can underpin several renewable bioenergy industrial production options, including methane from anaerobic digestion, photobiologically generated hydrogen, ethanol from fermentation, or biodiesel from transesterified algal oils [4,10].

The remaining biomass can be used for other bioenergy conversion methods [26] including gasification and pyrolysis. Algal gasification can produce combustible gases, or algal pyrolysis can produce gas fuels, liquid fuels, and a solid form of concentrated biochar, all of can be used in engines or as a feedstock for biorefineries post refining [4]. The biochar may also be used to sequester carbon or perform a range of other uses to agricultural, energy, or water sectors [33]. Whilst benefits such as carbon capture, bioenergy, animal feed production from the remaining biomass, the removal of nutrients from wastewater (etc.) offers flexibility, it also adds complexity to both system designs and production chains marketing [6,7].

Commercial Distribution and Consumption

Several microalgae species are grown commercially [30] in established markets for algal products [5]. There are around 110 commercial producers of microalgae in the Asia-Pacific region, most of which are in Asia [2]. The most commercially produced algae are marketed as human health foods [2,34,35], although the range of current and future potential products is extremely large.

Microalgae products contain fats [1,4,30,35,36], sugars [4,25,30,35], proteins [2,4,30,35], vitamins [2,22,30], and minerals [22,30,35]. Microalgae biomass is a source of antioxidants [3,37], cosmetics [2,38], bioactive neutraceuticals [2,3,22,30,39,40,41], pharmaceuticals [2,3,30,34,36], biochemicals [2,3,35,36], soil conditioners [2], biomass [2,30], biofertilisers [2,12], natural dyes and colours [3,4,38], and can also be used as animal and fish feeds [22,38,42]. Examples of algal products are betacarotene, phycocyanin, astaxanthin, canthaxanthin, polysaccharides, glycerol and tocopherol [30].

Algae are a functional therapeutic food, and thus can be called nutraceuticals [3,40]. Algal sources of long chain omega-3 fatty acids are safe and bio-available for human consumption [43]. Food fortification with algae products are potentially cheaper and safer supplies of fatty acids than conventional sources [44]. Algal oils can be consumed by vegetarians as they are considered plant sources, and may eliminate some concerns about potential fish product contaminants [44]. In non-human food industries, algal supplements increase aquacultural fish feed efficiency and weight gain against control fish diets [42]. Algae products can also exhibit antiviral, antimicrobial, antifungal, cytotoxic, antihelmintic properties [3]. High value products have the greatest economic potential in the short term to offset high production costs of algal biomass [30].

The future for algal production research and development

The combination of continued market demand and technical innovation will ensure major advances and expansion of algal products and uses [36]. Further research is required to better understand molecular processes to increase production for energy, sequestration [25], new conversion technologies [26], and new products [25]. The pursuit of improved neutraceutical agents, protein therapeutics, and advanced biofuels merit further algae cross-disciplinary research and development [1]. Therefore, algae have an important strategic, ecological, and commercial role, which requires detailed biological knowledge to increase production output certainty and expand algae application, utility, and sustainability [45].

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