OPINION

The microalgal bio-industry has undergone major transformations over the past decade, but are we finally on the right path?

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OPINION

Over the past decade, the pursuit for sustainable fuels and the increased concern of global warming have led to the proliferation of microalgal R&D in universities and research organisations all around the world. Microalgae or 'the green fuel' as it came to be known has been identified to be a highly promising biofuel feedstock due to their high areal productivity, high biofuel-convertible lipid content (for a number of species) and non-requirement for agricultural resources. In addition to fuel precursors, different microalgal species constitute a myriad of high-value nutraceutical products that have health-promoting and antioxidant effects in humans, such as chlorophylls, various carotenoids (β-carotene, lutein, violaxanthin, astaxanthin, zeaxanthin), ω3 fatty acids (EPA and DHA), sulfated polysaccharides, various phenolic compounds and essential amino acids; providing microalgae with attractive biorefinery application beyond just biofuel production.

Despite these early promises, however, the commercialization of microalgal biofuels never quite took off and many of the companies that had attempted to produce microalgal biofuels in a commercial scale, such as Solazyme, Sapphire Energy and Algenol, have either abandoned their efforts by now or shifted their company directions to nutraceutical and bioactive products. The industry never fully overcame some of the primary hurdles associated with microalgal biofuel: high capital and operating cost of large-scale cultivation, high energy cost of biomass processing and the insurmountable task of competing with crude oil and the giants of the petroleum industry.

As someone who has been involved in the field for almost a decade, I truly believe that the commercialisation failure of microalgal biofuels was a classic case of over-expectation and under-delivery. Between 2005 and 2010, there was so much hype surrounding microalgal biofuels. Investments were made on false expectations that microalgal biofuel will be commercially viable within the near future (3-4 years). In truth, the technologies associated with microalgal biotechnology at the time were probably 15-20 years away from any sort of commercialisation.

Despite early experiences from DOE's Aquatic Species Program in the 1970s, few studies were available on large-scale microalgal cultivation and biomass processing in the early 2000s. At the time, microalgal lipid content was often significantly overestimated, commonly quoted to be as high as 70 wt% of dried biomass. Only very few species are even able to achieve this lipid productivity and out of those that could, they often have to be cultivated under nutrient deprivations that substantially sacrifice biomass productivity to reach this lipid level. The figure also did not take into account the fact that a significant proportion of microalgal lipids consist of non-transesterifiable components that cannot be directly converted to biofuels. There was no energetically viable technological option for cell rupture and lipid extraction. Given all the challenges in biomass processing as well as other cost and contamination issues associated with large-scale cultivation, it was no surprise that the fledgling field could not timely deliver the cheap and carbon-neutral biofuels so badly expected from it. The sciences were not wrong; microalgae is still a highly promising biofuel feedstock for all of its merits.

The sciences were not wrong; microalgae is still a highly promising biofuel feedstock for all of its merits. The technologies to capitalise on these sciences, however, still needed time to develop. We were simply expecting too much too soon.

To survive, the field needed to evolve and it did just that! Throughout the past five years, the field has changed from being purely biofuel centric to one that aims to fully exploit the diversities of microalgal biochemical composition for the production of high-value products and biofuels. In fact, these days, the research community seems more hell-bent than ever on prospecting microalgae for nutraceutical and cosmetological purposes, with studies aiming for biofuel production being demoted to secondary priority. Microalgal companies, such as Cellana, Algenol Biotech, Qualitas Health, Martek Biosciences and TerraVia (previously Solazyme), have also realigned their objectives to focus solely on high-value nutraceutical products.

This paradigm shift was a welcomed and much-needed change. Nutraceutical products are higher priced and lower volume in nature. A shift in their direction altered key requirements for biomass processing and improved the immediate commercialisation prospect of microalgal industry. Not only did the shift afford a larger profit/cost margin, it also freed the industry from the overwhelming task of producing biofuel that was cheaper than crude oil, the price of which is subject to supply-chain politicisation on international levels and is currently at a ten-year low.

The shift towards nutraceutical products also liberated the field from the burden of achieving a net positive (or at least neutral) energy balance. To obtain any product from microalgal cells, the following six steps of biomass processing are generally needed: dewatering, cell rupture, product extraction via solvent contacting, solvent phase separation, thermal solvent recovery and product refinement (or transesterification in the case of biodiesel production). Many of these steps, however, employ energy-intensive technologies (such as centrifugation for dewatering and high-pressure homogenisation for cell rupture) that consume the resultant biofuel energy and chip away the benefits of producing biofuels in the first place. A production system aimed for nutraceutical production is no longer bound by energy balance requirements and can continue using technologies with high-energy portfolio as long as their economic cost can be justified.

Biomass processing for nutraceutical and cosmetic production needs to comply with strict safety requirements. It is imperative that the process uses extraction solvents and other reagents that are of low-toxicity and considered safe for human consumptions. Highly toxic solvents, such as chloroform, are strictly precluded; while those that are of slightly lower toxicity, such as hexane and methanol, can still be used but will have to be almost completely removed in the solvent recovery step (final concentration in the product <300 ppm). Even the handful of solvents that are considered safe for human consumption, such as acetone and ethanol, will still need to adhere to US FDA concentration limits (final concentration in the product <5000 ppm).

Such stringent safety requirements have led many researchers to re-examine the use of green extraction solvents, such as supercritical fluid, subcritical fluid and oil from other vegetative sources. These green solvents had

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previously been ruled out for biofuel production because of their high infrastructure costs and intensive operational/recovery energy demands. The requirements for safety will affect not only the extraction step but also the choice we made for the other processing steps. For example, mechanical cell rupture using high-pressure homogenisation or bead milling will be preferred than chemically induced rupture using acid hydrolysis to avoid the introduction of harmful chemicals to the system.

Efforts should be made to address the lack of scalable refinement technologies currently in existence for the final purification step. Solvents used to extract a product of interest will never have 100% selectivity. The product stream resulting from solvent extraction will therefore often contain other co-extracted biomass components that are of significant economic values and should be collected as separate streams if possible. For example, hexane extraction of biofuel-precursor triglycerides also inevitably leads to the co-extraction of a small amount of ω3 polar lipids and chlorophylls. Currently available fractionation technologies, such as column chromatography or multiple steps of chemical reactions/saponifications, are limited to lab-scale demonstration and unlikely to have large-scale application.

Over the past decade, the microalgal bio-industry has undergone major transformations. The recent shift towards the production of high-value nutraceuticals has given the bio-industry a second lease in life. Despite having different safety and energy requirements, biomass processing for nutraceutical products shares similar frameworks and fundamental principles to that carried out for biofuel application. Therefore, much of the experience collected over the past decade for biofuel processing, such as the design of efficient dewatering and cell rupture technologies, should be readily transferrable to bioproducts application, paving the pathway for large-scale demonstration. Even though the prospect for microalgal commercialisation appears imminent, the field cannot afford to grow complacent. Much work is still needed to develop a robust biomass-processing pathway that can be catered for the recovery of different metabolites and simultaneously adhere to stringent safety requirements associated with products for human consumption. Stronger academia-industry collaboration is also needed in order to ensure that research carried out in universities around the world is relevant to the current challenges faced by the industry.