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Feature

Microbial and algal oils: Do they have a future for biodiesel or as commodity oils?

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Summary

We review the prospects of using yeasts and microalgae as sources of cheap oils that could be used for biodiesel. We conclude that yeast oils, the cheapest of the oils producible by heterotrophic microorganisms, are too expensive to be viable alternatives to the major commodity plant oils. Algal oils are similarly unlikely to be economic; the cheapest form of cultivation is in open ponds which then requires a robust, fast-growing alga that can withstand adventitious predatory protozoa or contaminating bacteria and, at the same time, attain an oil content of at least 40% of the biomass. No such alga has yet been identified. However, we note that if the prices of the major plant oils and crude oil continue to rise in the future, as they have done over the past 12 months, then algal lipids might just become a realistic alternative within the next 10 to 15 years. Better prospects would, however, be to focus on algae as sources of polyunsaturated fatty acids.

Introduction

There has been a recent revival of interest in using microorganisms, and especially algae, as sources of oils that might be economic rivals to the major plant commodity oils as biofuels. Some expressions of interest have also suggested that this would be sufficiently cost-effective for the direct conversion of these oils into biodiesel. The proposition has an innate attractiveness as clearly microorganisms are capable of growing at many times the rate of plants; the productivity of algae in terms of biomass as well as oil is also much higher than that of higher plants. With yeasts or fungi, a typical fermentation set-up occupying, say, a 10-acre site, could yield a few thousand tonnes of oil per year. But before we get too excited with the prospects of being able to replace soybean or sunflower oils with oils from algae or yeasts, we had better consider what is involved.

First, we need to distinguish between yeasts, together with fungi, and algae. The former are heterotrophic organisms which means that they require some fixed source of carbon that serves simultaneously as a source of carbon, for the synthesis of new cells, as well as energy for the assembly of these cells. Algae, on the other hand, are usually phototrophic organisms that can use sunlight as a source of energy and CO_2 as the carbon source. Both, of course, are free. On the face of it, algae would then be the ideal choice of organism for the synthesis of biological materials: free energy, free carbon. With such advantages, one would surely be able to produce an abundance of cells (biomass) and, with the right choice of alga, then an abundance of oil within the cells. But exactly the same applies to growing plants – and plant oils, though not expensive, are not that cheap (see Table 1).

Microbial lipids = Single Cell Oils

- Oleaginous species have oil contents >20% biomass weight.
- Main producers: yeasts, fungi and algae.
- Only a small minority of species are oleaginous
- Oil accumulation requires a nutrient limitation, e.g. no nitrogen, so that excess C goes to make storage oils, not new cells.
- Carbon limitation results in low lipid levels and so must always be in excess.
- Maximum theoretical conversion of glucose to triacylglycerol is

100 g glucose gives 33 g oil.

- Highest practical conversion (with additional synthesis of cells and cell components) is 100 g glucose gives 20–22 g oil;
i.e. 5 tonnes glucose needed to make 1 tonne oil.
This applies equally to algae and yeasts.

Figure 1. Basic facts about microbial lipids.

Table 1. Prices of some plant commodity oils compared to SCOs (US$ per tonne).

Plant commodity oils (for March/April 2008)	
Soybean oil (ex USA):	1263/1247
Sunflower oil (ex Rotterdam):	1863/1838
Rapeseed (Canola) oil:	1519/1459
Corn oil (ex USA):	1842/1919
Microbial oils*	
Yeast SCO:	3000 (excluding cost of feedstock)
Algal oil:	from 5600–7000 to 21,000

* Based on calculations given in this article.

The oil accumulation process

Accumulation of oils (see Fig. 1), in the form of triacylglycerols, is not a feature of most microbial cells but is confined to a relatively small number of yeasts, fungi and algae [1]. These are the *oleaginous* species. Oil accumulation is a feature of unbalanced metabolism: when all nutrients are present in the growth medium, the synthesis of new cells, with minimal levels of lipid, will proceed. It is only when the cells run out of, or are deliberately

Table 2. Lipid contents and fatty acids of the highest oleaginous yeasts.

Yeast	Maximum lipid content* (% w/w)	Major fatty acids (% w/w)			
		16:0	18:0	18:1	18:2
Cryptococcus curvatus[a]	58–60	32	15	44	8
Lipomyces starkeyi	63–65	34	5	51	3
Rhodosporidium toruloides	66	18	3	66	–
Rhodotorula glutinis	72	37	3	47	8
Waltomyces lipofer[b]	64	37	7	48	3

[a] formerly *Candida curvata* D, then *Apiotrichum curvatum*

[b] formerly *Lipomyces lipofer*

* in all cases, >90% of the lipid is triacylglycerol.

Table 3. Lipid contents of various oleaginous, phototrophic microalgae that can be cultivated in marine or brackish waters.

Algal strain	**Oil content** (% dry wt)
Botryococcus braunii	25–75*
Isochrysis galbana	22–38
Haematococcus pluvialis	30–40
Nannochloropsis sp.	31-68
Nitzschia sp.	45
Parietochloris incisa	30-45
Pleurochyrsis carterae	33

* mainly complex branched hydrocarbons

deprived of, a key nutrient that they start to accumulate oils. (If the cells should run out of carbon then, of course, no storage of oil is possible.)

The amount of oil that cells, whether yeasts and fungi or algae, can accumulate varies with the species concerned. For examples of yeasts, see Table 2; for algae see Table 3. Thus for lipid accumulation to occur we need an excess of carbon to be present and a deprivation of a key nutrient in the growth medium. Usually, this limiting nutrient is nitrogen – normally in the form of NH_4^+.

Stoichiometry of carbon to oil conversion

Whether we are dealing with heterotrophic, oleaginous yeasts and fungi or photosynthetic oleaginous algae, the process of oil biosynthesis is the same. With algae, their carbon substrate is CO_2 but this is, in essence, fixed into a carbohydrate so that with both sets of organisms it is sensible to consider the conversion efficiency of glucose units into triacylglycerol oils (see Fig. 1).

The best conversion of glucose into oil that has been achieved in practice (which was with an oleaginous yeast growing in continuous culture) was 22.4 g oil from 100 g glucose. As the maximum theoretical stoichiometry for the conversion of glucose to triacylglycerol is 33% (w/w), and this is without production of any other cell material, then a yield of 22% is probably as high as one can go in practice. Thus, in approximate terms, **it will take five tonnes of sugar to make one tonne of oil** and this is assuming ideal growth conditions which may not always be possible particularly when considering algal cultivation – see below.

Besides being used for the synthesis of the oil, the substrate also has to generate the rest of the cell that, in turn, has to make and accommodate the oil. An optimum conversion of 100 g glucose would be to give 20 g oil plus 30 g oil-free biomass giving a total of 50 g cells. This then suggests that an oil content of 40% is probably the optimum value in order to maximize the overall biomass yield. To achieve oils contents of 60–70% (see Table 2), it is therefore not a matter of making more oil but making less oil-free biomass.

Value of the de-fatted biomass residue

After extraction of the single cell oil, the possible value of the residual biomass needs to be considered. For every tonne of oil produced there could be another tonne or more of the defatted biomass to be disposed of. Has this any value? Probably the best that could be realised would be its sale as an animal or fish feed supplement. It would not though be as valuable as, say, soybean meal as its nutritive value would probably be less; it would also contain higher levels of nucleic acids that may necessitate blending with other feed materials. It is therefore highly unlikely that the residual yeast or algal biomass would command a premium price as a animal feed material. Its safety would also have to be considered irrespective of what the extracted oil might be used for. If the biomass could not be used as a feed, then it might be usable as a source of energy either by direct combustion or conversion to methane via an anaerobic digester. The value of the biomass for these uses would therefore be relatively low.

Yeast and fungi

The accumulation of oils within yeasts and fungi has been known for many years. These oils, often referred to as *Single Cell Oils* (SCO), are triacylglycerols and can constitute up to 70% of the weight of the cells (see Table 2). The fatty acyl components of the triacylglycerols are the same as those that occur in plants. Yeasts are better candidates than fungi for production of SCO for non-food uses as they grow faster and are generally easier to cultivate on a large scale. We will therefore focus on using yeasts as our model SCO-producing organism.

As yeasts are heterotrophic, they need to be grown in stirred and aerated fermentation vessels which are usually between 100 and 250 m^3. These fermenters are expensive to build and also to run. Large fermenters need to be inoculated from smaller fermenters, starting with a simple laboratory culture. In a typical fermentation plant, there will be a series of two or three fermenters, each one larger than the previous one; each requires its own aeration and pH control system as well as having to be sterilized beforehand to ensure that the culture is not contaminated with bacteria or another yeast. Although it may be argued that if the final product – the SCO – is destined for a non-food use – *e.g.*, conversion to biodiesel – then there would be no need to worry about contamination, this could only be allowable, and then with considerable misgivings, for the final and largest fermenter. If one of the seed fermenters became contaminated with a bacterium then this would, in all probability, outgrow the oleaginous microorganism as bacteria, in general, grow 6 to 10 times faster than yeasts. Thus in the final fermenter, a mixed culture of the designated yeast with an adventitious bacterium could result in the bacterium being the predominant species in the final culture. This would cause major subsequent down-stream process problems with the bacteria blocking filters and pipelines as well as down-grading of the quality of the final oil.

Additionally, what would happen if the contaminant was a pathogenic (disease-causing) bacterium? This would be a hazard to the process workers having to handle the final biomass. Even if the bacterium was not a pathogen – but it might take days to be sure that it was not – you could not take the risk of exposing the process workers to unknown bacteria. Thus, allowing a situation to arise where contamination of the final fermenter was highly likely would be unacceptable. Once you have a contaminated system it is very difficult to eradicate the contamination and all subsequent fermentations are also likely to be contaminated. This means that the fermentation process must be a single culture system throughout all its stages even for the production of an SCO for biodiesel. Sterilization of both fermenter and the medium are then mandatory. You could not go forward with an SCO process on the basis of an open, unsterilized system.

The next problem to face is the choice of feedstock on which the oleaginous yeast is to be grown. A supply of some fermentable carbohydrate is needed; this is usually glucose or glucose syrups that can be produced by hydrolysis of starch from corn or a similar plant. Sugar cane or beet molasses, being predominantly sucrose, can also be used by some but not all oleaginous yeasts. SCO production has also been achieved using lactose derived from whey from cheese creameries. Considerations have been given to using waste agricultural materials that include both cellulose and hemicelluloses. Both these feedstocks would need prior hydrolysis which need not be expensive to convert them in usable sugars – glucose and xylose, respectively. Oleaginous yeasts are known that would use both these sugars simultaneously. Starch is also a possible feedstock but it is difficult to use directly because of its viscocity and problems in pumping it through pipes into the fermenters. But even waste agricultural products, such as straw or food-processing wastes, are not zero cost. They have to be collected, transported to the fermentation plant and stored; the costs of doing so may not be trivial. Storage of food waste materials also poses problems because of their instability with the likelihood of self-fermentation; these would then need to be heat-stabilized.

Even with these provisos, the use of agricultural waste materials has an undoubted attraction for SCO production and, indeed, for all fermentation processes. But, how many existing fermentation processes are based on using these materials? Very few, if any. If such materials are to be considered as viable options, then they have to be available throughout the year – or, at the very least, for 10 months out of every 12. Wastes from seasonable crops are produced for a short period each year making their use as a feedstock impractical.

There is one final consideration to be given to using agricultural waste materials and that is the final disposal of the spent culture broth. The product, the SCO, is within the cells. Therefore when the cells are harvested from the fermenter there is a considerable volume of waste liquor to be disposed of. If the SCO process generates, say, 60–80 g biomass/L, then over 90% of the fermenter contents need disposal. High-residue agricultural feedstocks will leave much material unconverted into cells and oils; disposal of the liquor is therefore a problem and in all probability an anaerobic digestion system would have to be added to the fermentation process itself before the waste water could be safely passed into a local river or lake.

The economics of SCO production using yeast technology are governed primarily by the cost of the fermentation process itself. The key work in this area was carried out by New Zealand workers in the 1980s [2]. Here the objective was to convert waste lactose, arising from the major cheese and butter creameries in that country, into a cocoa butter equivalent (CBE) using a yeast, *Candida curvata* (now known as *Cryptococcus curvatum*). The reason for choosing cocoa butter as the target was that, at the time of commencing the work, the price of this was about US$ 5000/tonne. However, even though the yields and conversions ratios of lactose to oil that were achieved were as high as might be expected, and the quality of the oil was entirely satisfactory as a CBE, when the work ended, the price of cocoa butter – and therefore of any CBE – had fallen by about 40%. This destroyed any potential profitability of the process. The manufacturing cost of the SCO was calculated as US$ 800-1000/tonne based on using 200,000 m^3 of whey/year. This cost did not include plant depreciation, interest on capital investment or manufacturing overheads. A calculated likely selling price of US$ 2000–2500/tonne was insufficiently profitable to warrant further development of this process.

To-day, allowing for increases in costs since the 1980s, it seems highly unlikely that any yeast (or fungal) SCO could be produced for less than £1500/tonne (~US$ 3000/tonne) excluding the costs of extracting the oil and also the cost of the feedstock. Even a feedstock with a negative value (*i.e.* it would cost real money to dispose of it within prevailing environmental restrictions) would bring down the price by no more than £100 to £200 per tonne. It therefore follows that where there are successful SCO processes [1], the ensuing oil is much more highly valued than £1500 (~US$3000) per tonne.

Algae

Algae are essentially microscopic plants that use photosynthesis and the fixation of CO_2 to grow and multiply. In addition, they need a supply of nitrogen (ammonia or nitrate will usually suffice) as well as essential elements such as P, K, S, Fe, Mg *etc*. They require aquatic environments that may vary from fresh-water to sea-water including all types of brackish waters. Some, such as *Dunaliella salina,* are capable of growing in hyper-saline environments – which can have considerable advantages as are discussed later.

In the context of this discussion paper, we will confine our comments to the role of photosynthetic algae for the possible production of lipids. Additionally, as the focus of some groups is now on the possible use of such lipids as a source of biodiesel, our comments will therefore be on the fatty acid-containing lipid components of algal cells. (There are, of course, algae that can be grown heterotrophically but, in this category, these organisms behave like yeasts or fungi and have to cultivated in large, stirred tank reactors; the economics of these processes are therefore the same as discussed above.) There are, in addition, a number of high-value lipid products, such as beta-carotene and astaxanthin, that are already in production using algae but whose value is considerably higher than fatty acids destined for conversion into biodiesel. A discussion of the economics of producing these lipids is therefore outside the scope of this review.

Table 3 provides a list of the more prominent oleaginous algae that could be considered as producing lipids in reasonable quantities. The problem, however, is that almost invariably these lipid contents have been attained when the alga concerned has been grown in a photobioreactor in a laboratory. However, as we shall learn, such photobioreactors are so expensive to run that they are not economically viable. Unfortunately, the traits for rapid growth and high lipid contents are mutually exclusive irrespective of which cultivation system is being used.

Photosynthesis is strictly an energy-interconverting process whereby solar energy is converted into biological energy (ATP) which is then used to provide the energy for CO_2 fixation and to drive other reactions in the cell. When fixed, the CO_2 is converted into carbohydrate from which all cell components are derived. The basic conversion of carbohydrate into lipid is then exactly the same as is involved in the conversion of glucose to lipid in oleaginous yeasts and fungi which was discussed earlier. This process requires more energy than does the conversion of the carbohydrate into storage polysaccharides and, therefore, there are many more algae that will accumulate polysaccharides than oil. Additionally, the process of lipid accumulation requires that the cells are deprived of nitrogen in exactly the same way as is required for oil accumulation in yeasts and fungi.

Algae have the advantage over conventional plants in that they have much faster growth rates; they do not need to start from seeds that then require time for germination and development. Algae are grown from inocula of live cells that immediately can commence growth and biomass production. However, algae need considerably more care and attention than plants. They need to be protected from predators and from competing algae. It is, therefore, important that they are grown as monocultures; this, however, places many restraints on what can be done. Various methods have been devised for their cultivation; all systems must allow the best possible access of sunlight to the cultures.

Algal growth systems

Laboratory-based photobioreactors, in which a glass vessel is surrounded by light bulbs, are clearly impractical for commercial development as the scale-up costs would be enormous. Many other systems have been developed using clear plastic tubing placed outdoors in the form of arrays (see Fig. 2). These are also very expensive to operate; they require the culture liquor to be pumped round the arrays at all times and the culture liquor has to be supplemented with CO_2. Such systems are used commercially for the production of beta-carotene using *Dunaliella salina* and astaxanthin using *Haematococcus pluvialis*. The cost of producing biomass in these tubular arrays is approx. US$40/kg. If we were to assume an oleaginous alga were to be grown similarly and that it achieved a lipid content of, say, 40% then this would give the cost of the oil at about US$100,000 per tonne. Clearly, therefore, this method has no validity for large-scale production of algal oils for biodiesel or other bulk uses.

The most economic way in which algae can be cultivated is in natural lagoons or lakes. This type of cultivation has been practiced for many years, if not centuries, in several locations around the world such as in Mexico, Australia and Lake Chad in Africa. Essentially, the algae are allowed to grow as best they can without any mechanical stirring or agitation to improve CO_2 uptake and then, after an appropriate period of time, they are harvested by the simplest available technology. Such systems have been used to produce dry biomass of *Spirulina* (a cyanobacterium) which is used mainly as a feed supplement for domestic animals; the oil content of this biomass is less than 10% and is almost entirely composed of complex membrane lipids associated with photosynthesis. This system of ‘natural’ growth is also used for the cultivation of the saline-tolerant alga, *Dunaliella salina* grown in sea lagoons in Australia. Here, the alga has a strong selective advantage over other algae and even bacteria that might contaminate the biomass and also from protozoa that would consume the algal cells. Biomass from such a process is used as a source of beta-carotene. The overall level of fatty acid-containing lipids is, however, relatively low at about 8–11% of the biomass as nothing has been done to increase the level of CO_2 entering the water which is essential to ensure lipid accumulation. Also, once the surface is covered with algal cells these will self-shade those underneath and biomass production is therefore limited by the final surface density of the cells. Yields of biomass in lagoon systems are of the order of 0.1 g/m^2 per day and it will therefore take 1 to 2 months for the cultures to reach their maximum density. Allowing for seasonal variations in the temperature, annual yields of biomass would therefore be of the order of 200–400 kg/hectare. Given the low lipid content of these cells, they could not then be a realistic source of fatty acids for biodiesel or similar applications. Furthermore, cultivation of algae as a realistic source of biomass would require an extremely large area of lagoons which is far from being available.

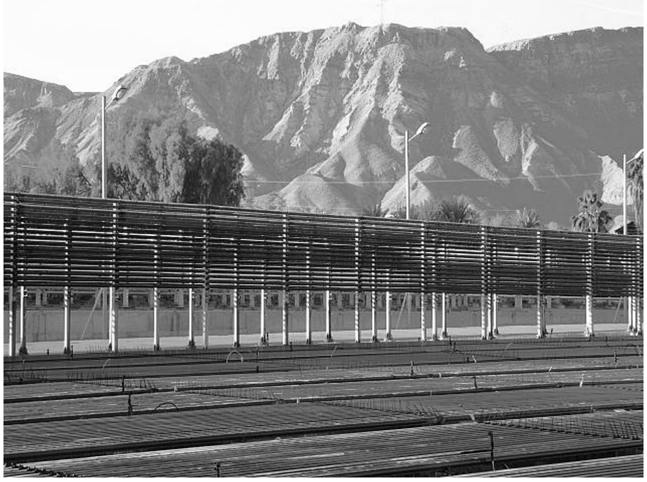

Figure 2. Cultivation of *Haematococcus pluvialis* for the production of astaxanthin using a tubular, outdoor reactor. With kind permission of Professor S. Boussiba, Ben Gurion University of the Negev, Israel; (a colour photograph of this figure is available on: http://bidr.bgu.ac.il/bidr/research/algal/Facilities.htm).

The alternative to natural lagoons or lakes is to cultivate algae in open ponds (see Fig. 3). Again, the algae are exposed to the atmosphere though the overall environment can be controlled a little better than in a lagoon. There is, however, no control over water temperature and light intensity and these variations limit cultivation to 9 months or less per year even in the best of locations. As much as 25% of the biomass being produced daily can be lost overnight due to respiration of the cells. (This is a factor that is often forgotten when extrapolating data from other cultivation systems.) Unless cultivation is at a basic pH, CO_2 utilization is much less efficient than in a photobioreactor or even in a tubular system. Because of the system is an open one, the alga have to be robust enough to withstand the chance arrival of predatory protozoa and other possible algae, and even bacteria, arising from aerial contaminations. These limitations have, up to now, restricted the use of open ponds for the cultivation of the cyanobacterium, *Spirulina*, using a high alkalinity medium (but these cells have such a low lipid content that they are not of interest in this present context) and the green alga, *Dunaliella salina*, growing in a highly saline medium. Even using these extreme environments, the risk of contamination is not entirely eliminated. A typical set up for the open pond cultivation of

Figure 3. A typical open pond driven by a simple paddle wheel for the cultivation of an alga. With kind permission of Professor S. Boussiba, Ben Gurion University of the Negev, Israel; (a colour photograph of this figure is available on: http://bidr.bgu.ac.il/bidr/research/algal/Facilities.htm).

algae is shown in Fig. 3. The cost of biomass production of *D. salina* in such as system is estimated to be about US$ 7/kg.

In addition to their use for the cultivation of *Chlorella*, *Spirulina* and *Dunaliella*, open ponds have also been used for the cultivation of *Pleurochrysis carterae*, which is perhaps one of the more promising candidates for biofuel production. A biomass productivity of 0.19 g L^{-1} d^{-1} was reached with a lipid content of 33%. This would then extrapolate to a yield of oil of about 22 tonne ha^{-1} per year [3]. At the present time, this seems an entirely reasonable estimate of the efficiency of the process. If the costs of biomass production were the same as those for *D. salina* (see previous paragraph), this gives the cost of oil at US$ 21,000/tonne.

The key factor in algal cultivation is the supply of CO_2. The CO_2 content in the atmosphere is too low to allow algae to grow at their optimum rate or to produce biomass efficiently even in agitated open ponds; low CO_2 concentrations mean that the cells are effectively and permanently carbon-limited and, under such conditions and for the reasons advanced above for the accumulation of oils in yeasts and fungi, will not engender lipid accumulation in the cells. Accordingly, open pond cultivation of algae requires direct supplement of CO_2 which is normally provided from gas bottles. An alternative source might be to use the combustion flue gases from a nearby power plant that may contain up to 10% CO_2. The presence of other gases ($N0_x$ and SO_x) in these flue gases may add to the benefits of algae being used to clean up such gases but, in the case of the NO_x gases, may limit the ability of the cells to accumulate lipid as they would prevent the cells becoming nitrogen limited, which is a prerequisite for lipid accumulation. Additionally, it has to be pointed out that locations suitable for large-scale cultivation of algae may be far removed from urban environments where appropriate power plants are normally found.

Given the high costs of cultivating algae in anything other than open ponds, it therefore follows that these are the only available means of large-scale cultivation. However, because of the energy limitations of the system, bearing in mind that these cultures are at the vagaries of the weather and variations in temperature between seasons and also, but importantly, between daytime and night time, there are few algae that are realistic propositions for lipid production. Where such species have been considered, and these include *Botryococcus* which produces a branched hydrocarbon rather than a lipid, none are suitable for outdoor cultivation as they either grow too slowly (which is the case for *Botryococcus*) or are readily susceptible to contamination or attack by adventitious protozoa and even bacteria. However, development of herbicide- or bacteriocide-resistant strains could be of help in this respect as this would allow periodic chemical treatment of the culture to curtail contamination.

Costs of producing algal oils

The costs for producing an algal oil by this method range from US$ 21,000/tonne using *P. carterae* (see above) to a conjectural price of approx. US$ 800/tonne (John Benemann, personal communication). This latter figure assumes that a productivity of 110 tonnes oil/hectare per year could be achieved. (We would stress, however, that the organism that could attain this yield has yet to be identified and, indeed, this productivity is some five times higher than the best reports on algal lipid formation to date.) The costings include a minimal capital charge of 20% per annum, but not maintenance costs, which works out at a capital charge of US$ 200/tonne. Annual operating costs are estimated at about US$ 15000 per hectare. A final cost is therefore likely to exceed US$ 1100/tonne; the selling price to include an adequate financial return on investment would therefore be >US $1400/tonne. In our view, bearing in mind that the best yield of algal oil (see above) is a fifth of these projected values then a more realistic price of algal oil would be five time higher than this; *i.e.* >US$ 7000/tonne. As, at present, soybean oil commands a price of about US$1250/tonne (see Table 1), the opportunity for developing an algal oil for biodiesel still looks unattractive. Dimitrov [4], in a critique of the GreenFuel Company claims for efficient and cheap production of algal oils, has suggested that it is unlikely that their technology could be used to produce crude oil at less than US$ 800 per barrel; as there are approx. 7 barrels in one tonne (depending on the density of the oil) then this gives a final cost of about US$5600/tonne oil. In a report from the Department of Energy, USA, it was calculated that an algal biomass with an oil content of 40% could be produced at about US$ 1750/tonne of oil [5]. This, we believe, given the current state of algal development and for the reasons advance above, is an unrealistically low value.

The consensus of opinion therefore suggests that even with the most propitious alga grown under near-ideal conditions, oil would not be produced for less than about US$ 5600–7000/tonne. The best practical attainment to date indicates a price in considerable excess of this value – $21000/tonne. None of these costings, however, appear to include the cost of oil extraction.

Conclusions

At the present stage of technical development, there would appear to be no useful algal or yeast species that could be grown sufficiently cheaply and, at the same time, produce an oil usable as a source of fatty acids for biodiesel. Oil contents of algal cells destined for such an application should be at least 40% as otherwise there would be far too much residual biomass that would need disposal. Again, as discussed above with yeasts, the cost of disposal of the algal biomass after oil extraction cannot be discounted. At best, it might be used as a cheap animal or fish feed supplement. Burning or converting the residue, via anaerobic digestion into methane would yield little net revenue. The best scenario that we can envisage is the use of non-agricultural land which would then not take land away from current plant crop production; such land would be either existing lagoons or be flooded from a nearby river or sea. Unfortunately, cultivation of algae in this way does not lead to lipid accumulation because of CO_2 limitation.

However, the use of tailor-made, rather than wild type, algal strains may reduce production costs to a level that could bring algal oil within reach of economic viability within a decade or so. We would, though, point out that algal lipids are very often high in polyunsaturated fatty acids (PUFA). It therefore seems to make little sense in trying to produce facsimile fatty acids in algae to those present in the major plant commodity oils (*i.e*., oleic, palmitic and linoleic acids) when the PUFA would have much greater potential for income generation. It would, therefore, be much more realistic to produce the highest possible value algal lipids that might rival such materials as fish oils and even the high-value microbial PUFA used in infant formulas [1], rather than produce oils that are already available in considerable abundance and cheaply from agriculture.

But, in a final cautionary note, we do see that the prices of plant commodity oils (see Table 1) have doubled, and in some cases, nearly trebled over the past 12 months due to increased demand both for food and for biodiesel production; if this trend continues then the margin between the price of algal lipids and plant oils will continue to diminish. Perhaps, therefore in 10 to 15 years' time, plant oils will be so expensive that algal lipids will then have a realistic market opportunity – but this will be at the expense of the entire world having to pay substantially more for all its basic food ingredients, and not just plant oils. Only the investors will win; the customers will wind up paying for it by increased food and fuel prices.

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