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The cost benefit of algal technology for combined CO_2 mitigation and nutrient abatement

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Abstract

The use of microalgae culture technology (MCT) for mitigating CO_2 emissions from flue gases and nutrient discharges from wastewater whilst generating a biofuel product is considered with reference to the cost benefit offered. The review examines the most recent MCT literature (post 2010) focused on the algal biomass or biofuel production cost.

The analysis reveals that, according to published studies, biofuel cost follows an approximate inverse relationship with algal or lipid productivity with a minimum production cost of \$1 L^{-1} attained under representative conditions. A 35-86% cost reduction is reported across all studies from the combined harnessing of CO_2 and nutrients from waste sources. This compares with 12-27% for obviating fertiliser procurement through using a wastewater nutrient source (or else recycling the liquor from the extracted algal biomass waste), and 19-39% for CO_2 fixation from a flue gas feed.

Notwithstanding the above, economic competitiveness with mineral fuels appears to be attainable only under circumstances which also feature:

a) the inclusion of cost and environmental benefits from wastewater treatment (such as the energy and/or greenhouse gas emissions benefit from nutrient and CO_2 discharge abatement), and/or
b) multiple installations over an extended geographic region where flue gas and wastewater sources are co-located.

Keywords: *Algae; cost; flue gas; wastewater*

Glossary of terms

AD	Anaerobic digester/digestion	NPV	Net present value
BNR	Biological nutrient removal	OP	Open pond
BESP	Break-even selling price	OPEX	Operating expenditure
EIA	Environmental impact assessment	PBR	Photobioreactor
ERoI	Energy return on investment	PE	Photosynthetic/ photo-conversion efficiency
CAPEX	Capital expenditure	TN	Total nitrogen concentration
GHG	Greenhouse gas	TP	Total phosphorus concentration
GHI	Global horizontal irradiation	USNREL	US National Renewable Energy Laboratory
GIS	Geographic information system	WwTW	Wastewater treatment works
MCT	Microalgae culture technology		
MW	Megawatt		

1 Introduction

Microalgae culture technology (MCT) offers a means of both sequestering flue gas CO_2 and removing nutrients from wastewater in a single process, as well as providing a recoverable resource in the form of biofuel from subsequent extraction and conversion steps (Fig. 1). The number of research publications into the application of MCT, configured as open ponds (OPs) or photobioreactors (PBRs), for these duties has been increasing exponentially at a compound annual growth rate of 6.4-6.7% per year since the mid-1960s [1]. Recent reviews of the subject have encompassed CO_2 capture from flue gas streams [1-3], nutrient removal from wastewater [1, 4-8] and resource recovery – with biofuel production from wastewater sources receiving particular attention [3, 6, 8-11]. Other reviews have considered process integration [12] and net environmental impact of MCT through greenhouse gas (GHG) emissions [13, 14]. Whilst higher-value products than biofuel are attainable from algal biomass, biofuel production appears the most realistic option since contamination of this product by wastewater constituents is less critical than would be the case for some alternative products.

The potential offered by MCT is well-documented in the above review articles, offering a low-energy means of combined flue gases and wastewater treatment without the requirement for aeration for the latter duty. Since aeration makes up more than half of the energy demand of classical biological wastewater treatment [15], the potential overall operational expenditure (OPEX) savings are significant. Combination with flue gas treatment constrains implementation to circumstances where the flue gas and wastewater sources are co-located, limiting supplementary expenditure associated transport of either one of these two sources – though transport of the gas may be less costly than that of the liquid [16]. Crucially, the cost of nutrient and CO_2 supply for the MCT is then obviated.

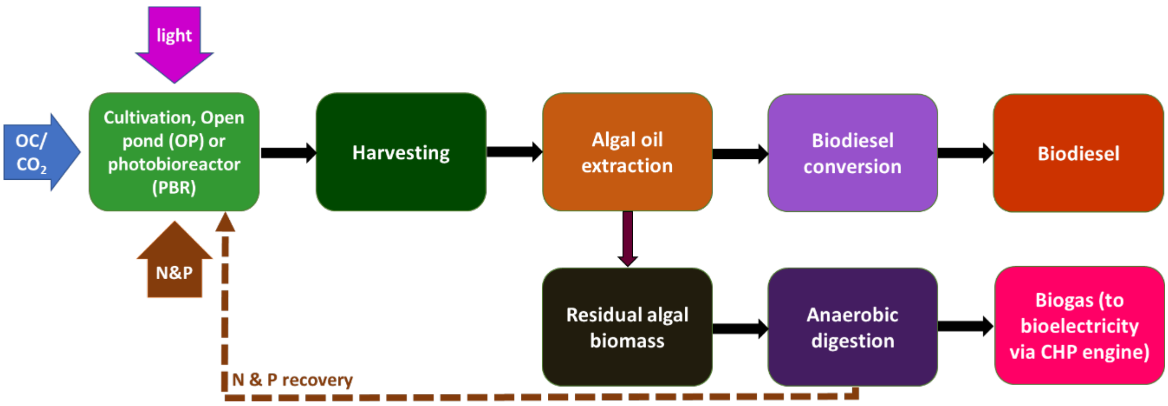

Figure 1: Biofuel from microalgae culture technology (MCT), schematic. OC Organic carbon, CHP combined heat and power (adapted from [17])

However, even under such favourable conditions, assessment have pointed to generally unfavourable economics [18], with the cost benefit being obviously highly dependent on the the fuel market value. The cost benefit is otherwise sensitive to a number of often inter-related factors which ultimately determine extent to which the significant costs associated with technology implementation are mitigated both by the value of the biofuel and the environmental benefit of reduced aqueous and gaseous pollutant discharge. Other key contributory factors ostensibly associated with the biofuel production include:

a. The plant size, and specifically the economy of scale;
b. Plant location and distribution;

c. The feedwater quality;
d. The algae and algal lipid productivity;
e. Ancillary processes, and specifically conversion to biofuel.

These factors all reflect the multi-faceted and complex nature of the subject, encompassing not only the microbiological and process engineering aspects of the technology but also the ambient conditions (which effect biomass generation, and specifically the productivity), environmental impacts and fixed costs. It is the widely accepted critical dependence of the viability of MCT on the algal product value which has led to the increasing use of economic/ econometric methods for minimising the production cost of the biofuel for cost benefit or neutrality. Since the start of 2011 there have been over 50 cost or cost-related analyses of the various MCT system facets. A significant number have considered CO_2 and/or nutrient cost offsetting, primarily through the harnessing of CO_2 from flue gases for the former and either the use of wastewater feed stream or nutrient recycling for the latter (Table 1).

Most analyses conducted have been techno-economic in nature, essentially cost benefit analyses based on available and/or assumed/derived technical information. Within this general scope there have been many different approaches to quantifying the cost benefit. The most common of these involve determination of the required cost (or the break-even selling price, BESP) of either the algal biomass or the derived biofuel for overall cost neutrality [19-24], and within this scope many parameters have been examined.

There have also been a large number of analyses of the system energy balance, based on the energy return on investment (ERoI), which have need recently reviewed [22]. More recent examples have provided an energy balance for applying OP to wastewater treatment [10], as well as a comparison of the CO_2 balance of biofuel production by an OP to that of conventional diesel production [25]. These analyses predominantly provide outputs in terms of the ERoI, and/or net CO_2 or GHG emissions, but not necessarily the BESP. The use of carbon accounting seems to be complicated by the range of energy:carbon conversion factors used, which can range from 0.26 kg CO_2 kWh^{-1} or lower for "carbon neutral" conditions [22] to 0.95 kg CO_2 kWh^{-1} for a coal-fired power station [26]. Notwithstanding this, recent studies have incorporated environmental impacts into the cost model [27-29] to offer a more robust BESP.

Of key interest are those studies assessing the cost benefit of treating wastewater, in terms of energy saving and environmental impact assessment (EIA) and so overall cost, in addition to reducing CO_2 emissions and generating biofuel; such a basis can reasonably inform the case of combined flue gas/wastewater treatment. This review aims to identify circumstances where the benefit of both the biofuel and the supply of the substrate sources for the algae at near-zero cost can most effectively mitigate against the key outgoings. The most convenient and consistent basis for this is through analysis of the impact of both the proportional decrease in and the end value of the biofuel BESP; the latter can then be directly compared with the market price of the mineral fuel. The review proceeded through capturing of all cost analyses, along with closely related EIA/ERoI studies, published from 2011 onwards and the collation of all relevant cost data therein. The impact of offsetting of the cost of the CO_2 and/or nutrient supply was determined primarily through identifying and isolating these cost contributions. Other significant contributors to cost were also identified and quantified, and the related operating parameters examined.

Table 1: Cost analyses examples, 2011 onwards: MCT with cost offsetting

Reference	*Primary system facets/variables considered, or study objectives*	*Key correlation(s)/output(s)*
***Combined CO_2 and nutrient cost offset*[1]**		
[19, 20]	All key fundamental factors contributing to cost for OP (2012a) and PBR (2012b)	Costs of installation at small and large-scale; cost benefit of zero-cost CO_2 and nutrient feed.
[30, 31]	Energy and carbon accounting; EIA	OP vs PBR; cost benefit of zero-cost CO_2 and nutrient feed.
	Water and nutrient recycling; excess nutrient demand met by supplementation	OP vs PBR at different productivities and lipid content.
[16]	Co-location of multiple flue gas and wastewater sources at national scale.	Potential production capacity and selling price of biofuel in US with reference to nutrient and CO_2 availability and infrastructure requirements.
[32]	Covered 100 ha pond	Full CAPEX and OPEX determination
[23]	OP; Algal species; light wavelength (blue, green, red, white)	Impact of (a) zero-cost nutrient and CO_2 supply, and (b) light wavelength on biofuel selling price.
[22]	Algal growth; lipid productivity; scalability; environmental impact	Summary of published lipid yields, biofuel costs. Impact of productivity on fuel cost, and biomass processing technology on GHG emissions.
[33]	Optimisation based on maximum algal yield and maximum operating margin	Impact of (a) 90% nutrient recycling and (b) zero cost CO_2 supply
[34]	Multiple flue gas and wastewater sources at regional scale.	Impact of regional decentralisation of processing facilities on cost
[24]	PBR technology (OP & PBR); Power plant technology (3 types); irradiation intensity; CO_2 fixation rate.	BESP of the generated electricity ($/MW) and CO_2 avoidance cost ($/t) against the selling price of the algal biomass ($/t)
[29]	All key fundamental factors contributing to cost (incl carbon credit) for WwTW centrate feed.	Cost sensitivity to algal concentration, biofuel yield, chemicals cost, PBR CAPEX, nutrient feed, harvesting technology, and productivity
***CO_2 cost offset*[1]**		
[21]	Review of published studies with cost harmonisation	Impact of digestion of spent biomass on process economics.
[25]	Co-production of biofuel and animal feed; algal vs. conventional biofuel production; pure nutrient feed	CO_2 generated per unit of energy produced (kg CO_2 per unit energy)
[35]	Updated USNREL analysis; pure nutrient feed.	Impact of flue gas source on biofuel cost
[28]	National scale implementation of MCT for generation of 5b US gall/y.	Biofuel selling price adjusted for locational and seasonal changes in productivity
***Nutrient cost offset*[1]**		
[36]	Energy return on investment (ERoI) for three different scenarios	ERoI based for WW treatment
[37]	Algal oil-extracted residue fed to AD	Most economic option identified in terms of lifetime NPV
[38]	PBR viability for wastewater treatment based on three algal species	Impact of scale up from 150 to 1500 L PBR. Cost per m^3 treated wastewater
[78]	Regional-scale implementation with co-located WwTW's	Trade-off between space and wastewater source availability

[1]Offsetting of CO_2 cost normally through flue gas feed; Off-setting of nutrient cost normally through wastewater feed or nutrient recycling. [2]AD anaerobic digester; EIA Environmental impact assessment; ERoI Ratio of energy produced to energy consumed; GHG greenhouse gas; OP high-rate algal pond (or open raceway); MW megawatt; NPV Net present value; PBR photobioreactor; WwTW wastewater treatment works; USNREL US National Renewable Energy Laboratory [39].

2 Key process facets and parameters

2.1 Plant size

A comparison of the impact on cost of key system facets, such as plant size, across different studies is challenged by the different bases on which key parameters are expressed. This in turn is dependent on the primary focus of the published study. As a result, plant size has been expressed in terms of the bioreactor area footprint or volume [19, 20, 27, 35, 40], the algal or algal-derived product production rate [19, 20, 23, 29, 40, 41]; the carbon dioxide fixation rate [34], or the wastewater treatment flow capacity [6, 19, 20]. Whilst these parameters are inter-related, the nature of the relationship is dictated by further assumptions, most critically concerning productivity (Section 2.4).

The footprint is directly impacted by the technology configuration. OPs demand a higher footprint than PBRs due to the shallow pond depth (generally <0.4 m); the difference can be more than an order of magnitude for the same production capacity [30]. PBRs can be configured as vertical columns, horizontal tubes, with a serpentine flow of the algal biomass through them, or flat panels. As a consequence of this, the equipment costs of PBRs are considerably higher than for OPs, which normally more than nullifies the cost benefit of the reduced land requirement.

For the more widely studied OP technology, data calculated within individual studies suggest that there is little economy of scale for the cultivation stage beyond a certain size. Brownbridge et al [42] computed a \$1.2-2.2 kg^{-1} decrease in biomass cost per Mt y^{-1} increase in capacity, or around 1% per 10,000 t y^{-1} increase in capacity, beyond a capacity of 40,000 t y^{-1}. Rickman et al [26] determined the product cost to decrease by only 0.5% on increasing the pond size by an order of magnitude from 100 ha, confirming previous observations [21] based on a four-scenario study. Such outcomes are perhaps unsurprising given that many of the OP cost contributions (e.g. land and mixing energy) are directly proportional to the total algal mass [43]. Against this, and based on an actual MCT facility, an 82% decrease in biofuel cost has been calculated on increasing the capacity from 3.8 to 200 t algal biomass per annum [19]. However, this was associated with other efficiencies in the production process through dispensing with capital equipment.

It has been observed, however, that scaling of bench-sale productivity data specifically is insufficiently rigorous, with productivity from large-scale facilities being estimated from linear extrapolation of laboratory data [22]. Inclusion of seasonal and spatial trends (Section 2.2), which significantly impact on productivity, appear to have been addressed only relatively recently in cost analyses [28].

2.2 Plant location and distribution

It is self-evident that a process which operates through photosynthesis will be more productive when the light intensity is greater. Irradiation intensity is determined ostensibly by the geographical location, and thus local climate, of the installation since algal technologies are normally powered by natural daylight: the use of artificial light is estimated to add \$25 kg^{-1} dry-weight biomass to the cost [44], rendering this approach economically inviable. For example, the average global horizontal irradiation (GHI) in kWh per m^2 pond area per day is estimated to decrease by >28%, from >6.75 to <4.25, from the Middle East to East Asia [35]. Factors of 2-3 changes in BESP have been estimated from changing location from Northern Europe to either Southern Europe or the Carribean, according to two separate Dutch studies [43, 45].

A consideration pertinent to the widespread implementation of MCT across a geographical region is the distribution of the algal reactors with reference to potential flue gas [28], wastewater [88], or combined flue gas and wastewater sources [16]. The latter study, an analyses of algal biofuel production potential in the US based on a centrate WwTW (wastewater treatment works) feedwater (Section 2.3) combined with flue gas-sourced CO_2, concluded that on a national level the nutrient supply in wastewater was limiting in the production process, a deduction supported elsewhere [46]. The Orfield et al [16] study concluded that 1700 megalitres/a of bio-oil could be produced nationally at a cost of $0.55/L within certain regions, though it has also been calculated that the nutrient content in the centrate stream limits US national algal biofuel production to <400 ML y^{-1} [46]. Orfield et al determined the total aggregate area across the southern USA potentially available for economic production of algal biofuel, based on co-located wastewater treatment works and flue gas sources identified through GIS (geographic information system) analysis, to be 83,000 ha. A similar analysis, conducted for a region of Mexico, concluded the break-even selling for the biodiesel to be $0.97 L^{-1} for MCT implementation [34].

A further constraint on the viability of regional implementation is land availability. Urban wastewater treatment works (WwTWs) tend to have limited available land for installing the MCT reactors or ponds but have large amounts of surplus wastewater, whereas in rural locations the reverse is normally the case [88]. A key contributor to the cost analysis, therefore, is the infrastructure required for transporting the wastewater to the MCT location.

2.3 Feed wastewater source and quality

The classical MCT wastewater treatment application is as a tertiary treatment process following the secondary clarification stage of a WwTW [38, 47-51]. In such applications MCT has been shown to remove up to 95% of both the N and P for continuous operation (Table 2) for hydraulic residence times of, for the majority of studies, 2-10 days. As previously noted [1], the extended residence time compared with that of the classical biological nutrient removal (BNR) process (8-10 hours) combined with the shallow depth of the pond means that the footprint of the OP can be two orders of magnitude greater than that of the conventional BNR process.

A significant difference in the BESP appears to arise if the wastewater source is more concentrated in nutrient. With this in mind, a number of recent studies have considered the use of centrate from the WwTW anaerobic digesters as the source for organic carbon and N and P [16, 29, 47, 52-56]. The use of this concentrated source of carbon and nutrients increases the efficiency of their assimilation by the microalgae, with >90% removal of the nutrient load from this stream being reported [47, 52, 55]. A further significant benefit is gained in obviating the cover required for H_2S management (a 20% reduction in the total annual cost of a 1200 m^3 bioreactor [29], with further cost reductions associated with the reduced pollutant load on the wastewater treatment works (~8%). This is then reflected in the reduced biofuel selling price, calculated as being as low as $0.55-0.59/L according to other assumptions made [16, 29].

Whilst, the benefit offered by MCT as a tertiary treatment process for nutrient removal from wastewaters is lost by employing this configuration, the benefit in terms overall environmental impact, in terms, appears to be significant. A five-fold reduction in GHG emissions and eutrophication potential combined with a ten-fold reduction in water use, based on a PBR configuration, has been calculated for implementing MCT using centrate as the feed nutrient source rather than the tertiary wastewater [46]. Moreover, the feed nutrient concentration impacts on the economic viability through the algal productivity (Section 2.4), centrate offering significant promotion of growth [53, 55].

Table 2: Recent MCT nutrient removal papers, real wastewaters, continuous systems (adapted from [1].

Wastewater (municipal)	Technology	Productivity[1] $g\ d^{-1}$	%N rem	%P rem	HRT[2] d	Reference
Secondary	Biofilm	-	30-50	50-80	2	[57]
Centrate[3]	Helical tube	920	94	89	2	[52]
Centrate[3]	Biofilm	2.9[4]	70±8	85±9	10	[53]
Secondary	Tubular air-lift	18-21	86-95	69-94	5	[47]
Secondary	OP	5-8	62-77	51-63	10	[47]
Primary	OP	15-48[5]	*47-79*[5]	20-49[5]	5.5-9	[51]
Primary	OP	-	56-67	15-28[6]	2	[48]
Primary	OP	14-17	74-75	58-79	4	[49]
Primary	OP	-	*59-79*	12-34	4-9	[50].
Primary	Parallel plate	42-60	*72*	92	0.64	[58]
Centrate[2]	Column	Up to 1000	>90	-	3.3	[55]

[1]per m^2 for OP, per m^3 for PBR; [2]hydraulic residence time; [3]concentrate from centrifuge; [4]units of $g\ m^{-2}\ d^{-1}$, i.e. with reference to biofilm area rather than reactor volume; [5]Seasonally dependent on pond organic matter: highest concentration in summer, lowest in winter,7-18°C temperature range, % removal decreases with increasing load; [6]pH-dependent; AD anaerobic digester; BMPBR biofilm membrane bioreactor; Col column; OP open pond. *Refers to ammonia rather than TN.*

2.4 Productivity

Biofuel production relies on the generation of algal lipids, which is a function of both the algal production rate and proportion of lipids in the algal cells. Productivity of both the algal biomass and lipids is affected by a number of parameters relating to both the amount and quality of the light and the extent to which it is effectively harnessed by the algae. These parameters include MCT technology configuration (PBRs being more intensive with respect to area footprint than OPs), algal species, irradiation intensity and light wavelength [23], as well as the feed source characteristics.

Reported productivity of algal lipids varies significantly between studies, from less than 7 [59, 60] to more than 120 $m^3\ ha^{-1}\ a^{-1}$ [35, 61] according to conditions employed or assumptions made (Table 3). A similarly wide range of values applies to the productivity, in $g\ m^2\ d^{-1}$, of the algal biomass, with the highest values reported for high-strength feedwaters such as municipal wastewater centrate [7]. Whilst subsequent biofuel production costs are also dependent on the conversion methods used - primarily solvent extraction, hydrothermal liquefaction and pyrolysis [46, 62-65, 69] - it has been widely observed that costs are most sensitive to algal biomass productivity [13, 21, 66-68] and/or lipid content [13, 28, 29, 68, 69]. For example, increasing the lipid content for an OP from 25% to 50% has been reported to decrease the biofuel BESP by 39% [28], increase the NPV by 6-8% [66], and the ERoI by 63% [13]. A similar increase in algal productivity, from 25 to 50 $g\ m^{-2}\ d^{-1}$, produces a 19% decrease in BESP [28] and a 10-12% increase in the NPV [66]. In these published analyses the biofuel cost sensitivity to all other factors considered, including nutrient recycling, CO_2 supply costs and amortised pond construction costs, have been shown individually to be at least 70% lower than the corresponding sensitivity to either lipid content or algal productivity [28, 66, 69].

Table 3: Published cost analyses, 2011 onwards: production cost ranges in $ per unit biomass mass or biofuel volume against installation size (area or volume, production capacity) and algal or lipid productivity

Author(s)	Rea-ctor	*Installation size* ha or m^3	Productn cap[a], t/y *ML/y*	*Productivity* $g/m^2/d$ *g/L/d* algae	$m^3/h/y$ lipid	*%* lipid	*Production costs* Biomass, $/kg	Biofuel, $/L
Combined CO_2 and nutrient cost offset								
[19], OP	OP	100	-	20	-	25	0.93 - 0.6	-
[20], PBR	PBR	*1570*	200	30(15-45)	-	-	17 - 2.4	-
[27]	OP	333	-	20-30	-	20-50	-	1.7 - 3.4
	PBR	*3-7×10^5*	-	*0.65-2.0*	-	20-50	-	3.1 - 5.8
[30]	PBR	10	-	20-40	-	-	12-13 - 5.1	-
[16]	OP	83k	*1700*	-	25	25(20-30)	-	0.78 (0.61-3.5)
[23]	OP	-	1260-2520	8.5 -17	-	19 30	2.7 - 1.0 1.0 - 0.73	7.8 - 2.9 2.9 - 2.1
[22]	-	-	-	10-13[b]	6.4-127	-	-	9 - 0.52[c]
[30]	OP	400	-	10-20	-	-	2.3 - 0.45	-
[24]	-	-	-	-	-	-	0.44 - 1.0	-
[32]	CPR	100	14308	39.2	-	40	-	5.6
[29]	PBR	2.6	3760	35-57	-	29	-	0.59
CO_2 cost offset								
[19]	OP	100	-	20	-	25	0.93 - 0.64	-
[35]	OP	40	-	30	-	50	-	0.97 - 0.56
	OP			60				0.85 - 0.58
[26]	OP	120	-	23	-	22	0.62	2.2
[69]	-	-	*0.04*	30	-	-	-	5.0 - 8.4
[28]	OP	485[d]	*19000*	14.6	-	-	-	2.6 - 3.3
[34]	Multi-location	-	-	-	-	-	-	0.97
Nutrient cost offset								
[70]	OP	500	-	24	37	40	-	3.6
	PBR			40	55			22
[40]	OP	1951	*38*	25	-	25	-	2.6
	PBR			*1.25*		25	-	5.4
[43]	OP	1-100	-	*21*	-	-	1.8	
	PBR	1-100	-	*41-64*			1.0	*3.64*
[21]	OP	2000		20	-	25	0.8	3.05
[41]	OP	-	*38*	25	-	25	-	3.9
	PBR			*1.25*				9.9
[42]	-	-	*0.1*	22-33	-	30	-	1.2-2.4
[68]	-	-	-	-	-	-	-	1.3-2.4 - 1.0-1.1

CPR covered photobioreactor; [a]capacity expressed as mass of biomass (t/y) or volume of biofuel (ML/y) generated, ML megalitre; [b]based on previously published data; [c]based on biomass processing; [d]multiple installation locations; *units of t/ha.* Cost offsetting as defined in Table 1. Ranges of biofuel costs elaborated in Fig. 3

Correlations provided for biofuel cost C_b against algal productivity P_A in g m^{-2} d^{-1} [26, 28]; show the expected inverse relationship (Fig. 2):

$$C_b = m\, P_A^{-n}$$

where *m* and *n* = 46.1 and 1.07 respectively according to Rickman et al (2013) [26] compared to 15.7 and 0.66 for the same parameters from the analysis of Davis et al (2014) [28].

Thus, for a threshold biofuel cost of \$1 L^{-1} the productivity required is 36 g m^{-2} d^{-1} according to the analysis of Rickman et al [26] compared with 65 g m^{-2} d^{-1} from that of Davis et al [28], the difference being attributable to the differing boundary conditions assumed. A correlation of biofuel cost against lipid productivity in m^3 ha^{-1} a^{-1} based on 13 published post-2010 OP-based data points, as compiled by Quinn and Davis [22], indicates a similar inverse trend in biofuel cost vs lipid productivity (Fig. 2), albeit with significant data scatter due to the range of systems considered. In this case *m* and *n* = 38.0 and -0.87, yielding a required productivity of 62 m^3 ha^{-1} a^{-1} for a biofuel cost of \$1 L^{-1}. Biofuel costs also follow the same inverse relationship with photosynthetic (or photoconversion) efficiency PE [70], as would be expected given the link between PE and lipid production.

Even for a relatively narrow range of values for algal productivity (20-30%) and lipid yield (25-35%), however, the absolute values determined for the cost of the biofuel have ranged from \$2.8 to 6.7 per litre with no apparent trend in data taken across different studies, according to a review of selected outputs [21]. These data arose from test sites in the US and featured in the 2008 National algal biofuels technology roadmap of the US Department of Energy's biomass programme, with no offset for wastewater treatment/nutrient supply or, for most studies, flue gas treatment/CO_2 supply. Cost harmonisation for four of the studies produced a much narrower range of costs of \$2.9-3.5 L^{-1} [21], somewhat higher than the value of \$2.6 L^{-1} reported in the highly cited work of Davis et al [40].

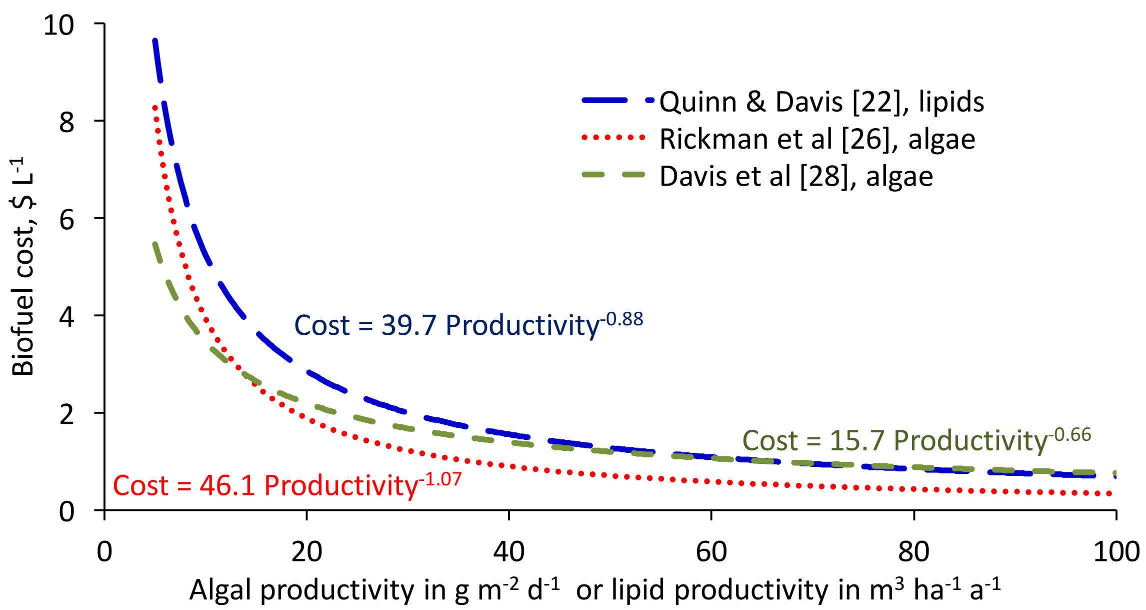

Figure 2: Biofuel cost vs lipid or algal productivity

Productivity is clearly influenced by a broad range of factors. Those germane to combined CO_2 sequestration and nutrient removal are CO_2 and nutrient load, with light intensity also being a key variable with local climate. A cursory analysis of the impact of cultivation conditions based on real wastewater feeds (Table 4) indicates biomass productivity increases of up to 74% compared with the reference conditions across a range of studies. Regression analysis of this data set suggests, with a coefficient of determination of 0.99, that algal productivity increases by around 5% per % CO_2 concentration in the feed gas and by almost 2% per mg/L phosphate (as P) in the wastewater. Economic viability is thus clearly affected by the cultivation conditions and, specifically, the nature of the CO_2 and nutrient sources.

Table 4: Reported algal biomass productivity under different process conditions

Cultivation mediumr	TP_{in}, *mg* L^{-1}	TN_{in} *mg* L^{-1}	*Light intensity,* $\mu mol\ m^{-2}\ s^{-1}$	*Inlet* CO_2, *%v/v*	P_A, *g biomass*$^{-1}$ $L^{-1}d^{-1}$	*% prom-otion*	*Refs*
MLA	6	28	200	0.03*	0.14	*R*	[79-81]
MLA	6	28	200	5	0.39	64	
MLA-Ww	8	56	180	0.03*	0.16	14	
TS	1.2	19	132	0.03*	0.04^a	*R*	[82]
TS					0.01^b	74	
nr	140	39	800	nr	1.02	*R*	[55]
C	126-158	14-18			1.03	10	
AM	7	25	300	5	0.27	*R*	[83]
AM			500		0.36	*R*	
40% C	5	149	300		0.27	0.7	
50% C	8	258	300		0.31	13	
40% C	5	149	500		0.38	5.3	
50% C	8	258	500		0.44	19	
Ww	2.5	22	610	nr	0.073	*R*	[84]
Ww	41	3		nr	0.079	8	

MLA Marine labs American Society of microbiology-derived medium; *R*: reference condition; Promotion ratio = % by which growth is promoted; TS treated sewage; C centrate; Ww municipal wastewater; AM algal medium; nr not reported; *atmospheric air.

2.5 Ancillary processes

Whilst a range of extraction technologies have been studied or reviewed [24, 46, 62-65] and their costs determined, a number of studies [34, 40, 45, 69] have indicated most of the cost of the biofuel production process to be attributable to biomass cultivation and harvesting. Conversion to biofuel from the intermediate product appears to add little to the biofuel cost, although optimisation of harvesting, oil extraction and biodiesel production has been calculated to reduce the BESP by up to 41% depending on the precise process technologies employed [69]. This includes using flue gas for algal biomass drying as well as for cultivation. The cost of the OP cultivation stage alone, on the other hand, has been calculated as contributing as much as 83% to the total cost [34], and for a PBR process more than 80% of the CAPEX is associated with the reactor itself [40]. Almost all analyses which compare the OP and PBR technologies conclude that the overall cost, either as total expenditure or net present value (NPV), of the PBR technology is greater than that of the simpler but larger-footprint OP.

The OPEX of algal harvesting specifically, based on conventional recovery processes (sedimentation, dissolved air flotation and centrifugation) and assuming an algal biomass concentration of 1 g L^{-1} containing 35% lipid, have been calculated as being \$0.44 L^{-1} gasoline equivalent [62]. The same authors calculated this figure to decrease to \$0.015 L^{-1} on employing ultrasonic separation with sonication for downstream lipid extraction.

However, other analyses [40] suggest that inclusion of capital costs increases the figure to almost \$1 L^{-1}, attributable mainly to equipment costs. This reinforces an often-stated point that a significant reduction in process equipment costs is required to reduce the cost of algal biofuel generally.

A few studies [21, 27, 71] have included an anaerobic digestion (AD) process for recovering the latent energy of the extracted algal biomass through conventional methanogenesis of the organic matter to methane. Whilst this provides a further energy benefit, the overall cost benefit appears to be marginal [21] unless the AD technology is already installed on site and has spare capacity. A consideration of integration of MCT with the power plant providing the CO_2 from the flue gas revealed that, for a standard photosynthetic efficiency of 4% the algal biomass value was 24-26% higher than the BESP irrespective of the power plant technology [24].

3 Summary of quantitative impacts

Comparison of quantitative outputs of recently-published cost analyses is challenged by both the diversity in the cost and energy balance determination methods and, crucially, the omission of fundamentally important parameters such as the lipid productivity and lipid:biofuel conversion factor. Most studies since 2011 have concluded that, based on a standard set of assumptions for productivity (15-30 g m^{-2} d^{-1}), lipid (or useful organic product) content (20-35%) and an OP design, the biofuel selling cost exceeds \$2/L. Costs can be slightly offset through the value assigned to the residual extracted algae, assumed to be between \$0.27 kg^{-1} [67] and \$1.8 kg^{-1} [61]. However, this is not sufficient to allow the biofuel to be cost-competitive with mineral-based fuel (which, at 2016 prices, is well below \$1/L). Even for the case where solar power is harnessed to meet the heating energy demand (for biomass drying), the calculated BESP of the biodiesel from one study exceeded \$2 L^{-1} [72].

The key factor of interest, however, is whether the implementation of MCT for combined CO_2 fixation from flue gases and nutrient removal from wastewater significantly mitigates against the MCT costs. In general, the mean reduction in cost provided by harnessing wastewater and flue gas for nutrient and CO_2 respectively is between 35% and 86% across the 6 recent studies where such a comparison can be explicitly made (Fig. 3). This compares with 12-27% for obviating fertiliser procurement through harnessing wastewater (or else recycling the liquor from the waste extracted algal biomass), and 19-39% for harnessing the CO_2 from a flue gas feed. In most cases the comparison is simply through determining the impact of omitting the CO_2 and nutrient feed costs on the overall cost of the biofuel [19, 30] or energy/CO_2 equivalent of the overall process [13]. It has been suggested [65], however, that the infrastructure costs associated with harnessing nutrients from a wastewater feed exceed the cost of nutrient supply from routinely purchased fertilisers.

In some cases, where the centrate (the concentrated wastewater stream from sludge processing operations) has been used as the feedwater, the additional benefit of the reduced nutrient load on the wastewater treatment works has been determined [29]. A few studies [16, 34] have incorporated logistical considerations regarding the optimal siting of facilities for multiple wastewater and flue gas sources within a specific geographical region. It appears to be only for these examples of more extensive implementation and/or the introduction of supplementary energy/cost parameters that a viable low BESP value (below \$1/L, Table 3) is attained. In the absence of such circumstances, many authors have concluded that a step improvement in technology efficiency, either at the harvesting/extraction stages or, more effectively, the cultivation stage, is required to bring the break-even biofuel selling price (BESP) down to parity with conventional fossil fuels. In the absence of such technical improvements, it has been suggested that biofuels can only be made economically viable through public policy intervention [73].

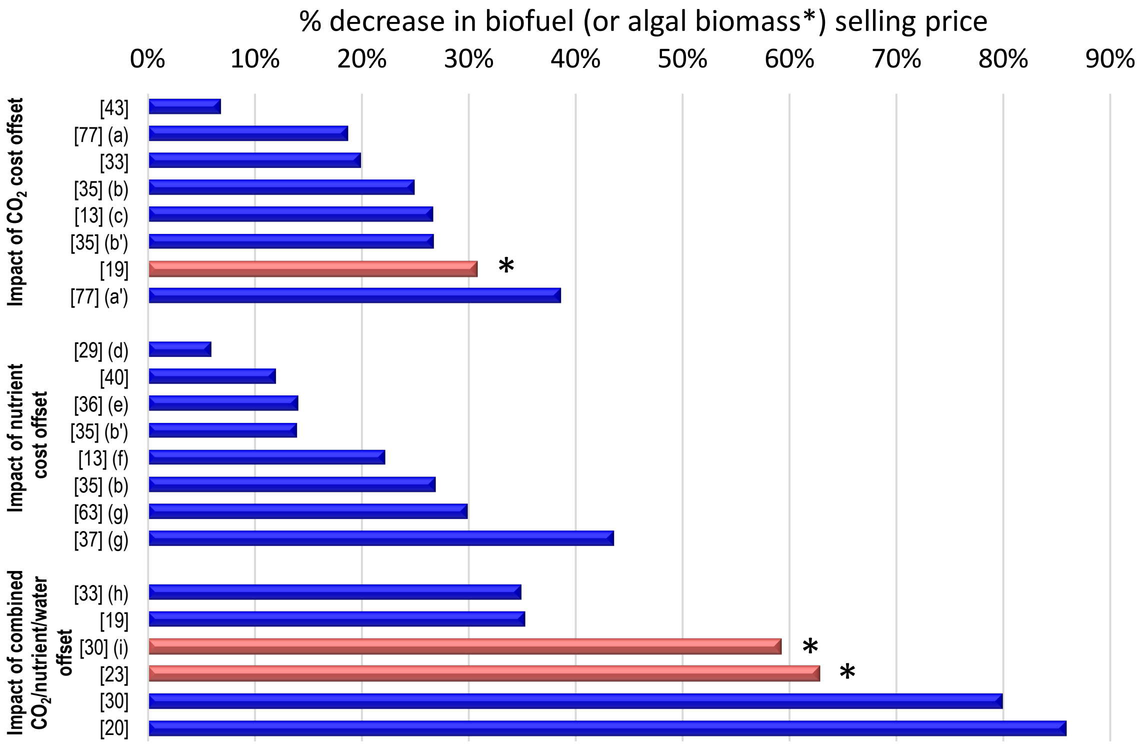

Figure 3: Average % cost reduction in algal biomass* or biofuel product according to published OP analyses
(a) High-cost biomass, (b) Higher productivity (60 g m^{-2} d^{-1}), (c) Ave of 4 data, (b') Lower productivity (30 g m^{-2} d^{-1}), (a') Lower-cost biomass, (d) P-rich ash for P fertiliser feed, (e) Ave of 8 data, 10-17%, (f) Ave of 8 data, (g) % of OPEX, (h) Recycling 90% of nutrients + zero cost CO_2, (i) PBR

Ultimately, though, algal biofuels can never exclusively provide the source of transport fuel because of global nutrient limitations. In the case of the EU, for example, the displacement of mineral fuel with biofuel would demand a doubling of the current fertiliser production rate in the region [30]. Nutrient limitation has also been identified as constraining factor in the US [16]. Overall, an additional 53 million tonnes of phosphate would be required annually to displace mineral-based petroleum by algal biofuels, an ultimately unsustainably amount given the limited of phosphorus globally [74].

However, N and P largely form part of the residuals (i.e. the extracted algal biomass) and can then potentially be recovered and reused for the MCT process. This being the case, a key consideration is whether recovery of nutrient in this manner is (a) technically feasible, and, (b) more cost effective than nutrient supply from municipal wastewaters or from standard chemical dosing. High nutrient loads, as would be encountered in the liquor from anaerobic digestion of the residual algal biomass (see Fig. 1) have been demonstrated to increase algal biomass productivity. If the MCT nutrient demand can be mostly satisfied by this stream then the cost benefit offered by the wastewater effluent treatment would be solely through obviating the BNR process, although the overall environmental benefit of using a recycled, concentrated nutrient source appears to be significant [46].

Given the questionable cost benefit of MCT in terms of a sustainable fuel source and the global nutrient limitation, the technology should perhaps be considered as an alternative extensive (i.e. high-footprint, low-energy) system for wastewater treatment, comparable to constructed wetlands. Whilst algal ponds [75] and algal biofilms [76] have been considered in conjunction with constructed wetlands for process enhancement, there has yet to be a comparative techno-economic analysis of the two technologies specifically for tertiary wastewater treatment for nutrient removal. Small-scale tertiary wastewater treatment systems with centralised facilities for lipid extraction, as considered by Hernández-Calderón et al [34], may prove to more economically viable than the process alternatives.

4 Conclusions

A review of recent literature on the economics of algal technology (MCT) for biofuel production indicates that, although offering a 35-86% reduction in the biofuel break-even selling price (BESP), the harnessing of CO_2 from flue gases and nutrients from wastewater does not provide sufficient economic competitiveness under most circumstances. However, analyses indicating near-parity of the BESP with mineral-based fuel costs encompass flue gas and wastewater feeds as well as the following features:

a. Inclusion of all cost benefits from wastewater treatment and CO_2 abatement, such as energy credit for the reduced wastewater treatment load, and/or
b. Multiple installations over an extended geographic region allowing for co-location of MCT with wastewater and flue gas sources.

Most analyses otherwise indicate the expected inverse relationship of biofuel cost with algal or lipid productivity, with the minimum calculated biofuel BESP attainable under normal conditions being around \$1 L^{-1}. Whilst productivity can be increased through using concentrated nutrient and CO_2 waste sources, the economic viable of large-scale MCT for biofuel production is nonetheless contingent on (a) a significant decreases in costs, and specifically equipment costs in the case of photobioreactors or running costs in the case of algal ponds, and/or (b) public policy intervention. Moreover, global large-scale algal biofuel production is limited by the long-term availability of phosphorus. In view of this, future focus should perhaps be on sustainable nutrient recovery.

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