Economic and policy issues in the production of algae-based biofuels: a review

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Despite the initial environmental and supply benefits associated with conventional biofuels leading to substantial policy support, research has indicated that these benefits might have been overly optimistic. Negative externalities associated with food and resource allocation have also resulted in an increasing scepticism about the long-term potential of transitioning to biofuels. This review presents the economic benefits and costs surrounding conventional biofuels and suggests the need for further development of a third-generation feedstock based on algae. The article provides guidance on the potential for a policy framework for supporting microalgae as a source of biofuels given the numerous associated positive externalities.

Keywords: biofuels, externalities, opportunity costs, microalgae, macroalgae, policy

1. Introduction

The security of supply for fossil fuels is an issue of concern globally, particularly for transport use. The majority of private and commercial vehicles are fitted with combustion engines that run on liquid fuels. Hence, transitioning to alternative means of transport such as electric vehicles raises the financial and technological costs, especially for consumers. Therefore, electric vehicles may not represent cost-effective substitutes for much of private and commercial transportation.

In contrast, liquid fuels derived from organic plant biomass, commonly known as biofuels[1] [2], are closer substitutes. Biofuels have similar combustion properties and can more easily substitute petrol and diesel with minimal modification to engines. There are generally two types of biofuels: biopetrol or ethanol made from carbohydrates (sugars); and biodiesel made from lipids (fats). Aside from being derived from a renewable source, these biofuels are also believed to reduce net carbon emissions and other socio-economic benefits [3-6].

Biofuels have been able to infiltrate some markets, particularly with the aid of policy support. These include corn-based ethanol (biopetrol) and soybean-based biodiesel in the United States of America [7], sugarcane-based ethanol in Brazil [6, 8], and rapeseed-based biodiesel in Europe [6, 9]. However, the literature has increasingly identified issues pertaining to these conventional biofuels derived from terrestrial feedstocks. These issues include (1) lower net energy returns, (2) over-estimated claims around carbon emissions reductions, (3) increased dependence on fossil fuels, and most importantly, (4) competition with food demand through crop and resource allocation. This article will provide a brief review of these issues.

Therefore, an alternative feedstock is sought that would alleviate these issues whilst achieving aims of a long-term substitute for petrol and diesel. Marine macroalgae, such as seaweed, and microalgae, a microscopic biomass, have been identified as one such potential feedstock [10, 11]. Despite cultivation and conversion technologies still being in their infancy resulting in some criticism about current financial viability, the literature has generally been positive about microalgae's potential.

The purpose of this paper is to highlight the economic and policy issues surrounding first and second-generation biofuels, and subsequently, outline the benefits and limitations of algae as a feedstock in comparison. The findings from this review suggest the potential for policy support of algae as a biofuel feedstock, particularly microalgae, based on longer term economic benefits.

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[1] There is also a class of biofuels that employ either waste cooking oil or tallow as feedstock for lipid-based biodiesel [1]. However, this paper focuses on cultivated biomass as feedstock given the related comparisons with microalgae.

2. Classification of biofuels

By convention, biofuels are classified based on the type of feedstock. Conventional biofuels refer to those that are derived from terrestrial-based feedstock. They are further subdivided into first and second-generation biofuels (Table 1). First-generation biofuels employ food-based feedstock, with the most common being ethanol from corn or sugarcane molasses and wheat starch [12], and biodiesel from soybean, rapeseed/canola oil, and palm oil [1], the latter becoming increasingly employed in India, China, and Southeast Asia [13, 14] as well as current high utilisation in Europe. Second-generation biofuels employ the use of non-edible lignocellulosic[2] crops as feedstock in energy production [15, 16]. These primarily include non-edible plant biomass like sugarcane crop residues (bagasse) [17], firewood, perennial grass, and forest and plantation residues for biopetrol [1], and jatropha[3] for biodiesel [18].

Table 1: Classification of conventional biofuels.

Biofuel class	Feedstock characteristics	Examples of biomass (biofuel)
First-generation	Food-based crops	Corn, sugar molasses (ethanol) Soybean, rapeseed (biodiesel)
Second-generation	Non-food crops	Forest residues, sugarcane bagasse (ethanol) Jatropha (biodiesel)

3. Issues with conventional biofuels

Many conventional biofuels are encumbered with higher production costs and therefore, uncompetitive retail prices [4, 7]. However, policy support through blending mandates[4] and tax credit policies have allowed some types to enter the consumer fuel market, with sugarcane ethanol in Brazil being a prime example [20].

3.1. Energy return

The energy return from conventional biofuels has been found to be much less optimistic than perceived when comparing the Energy Return on Investment (EROI) function. The EROI measures the usable energy produced from the resulting biofuel divided by the energy used in production. Studies have identified the EROI for both first and second-generation biofuels, which have often had energy intensive production requirements, being much lower than that for petrol and diesel. Corn ethanol, a major biofuel in USA, was particularly low in the EROI scales [21]. Second-generation variants require marginally less energy [22] and represented the more promising option for ethanol from both an EROI view [23, 24] as well as an energy return per area of cropland [25]; the latter due to emphasis on fast-growing perennial crops that can produce up to ten times more energy than other bioenergy outputs [26]. However,

[2] Lignocellulosic biomass is plant biomass consisting of cellulose, hemicellulose, and lignin that can be processed to produce chemical compounds for biofuels.
[3] Jatropha is a non-edible flowering plant whose seeds contain oil that can be converted into biodiesel.
[4] Blending mandates refer to legal requirements for a ratio of biofuels to regular fossil fuels (petrol or diesel) sold [19].

most second-generation feedstocks were found to have comparably low EROIs relative to fossil fuels (Table 2).

Table 2: Energy return on energy invested (EROI) for fossil fuels and common biofuel feedstock.

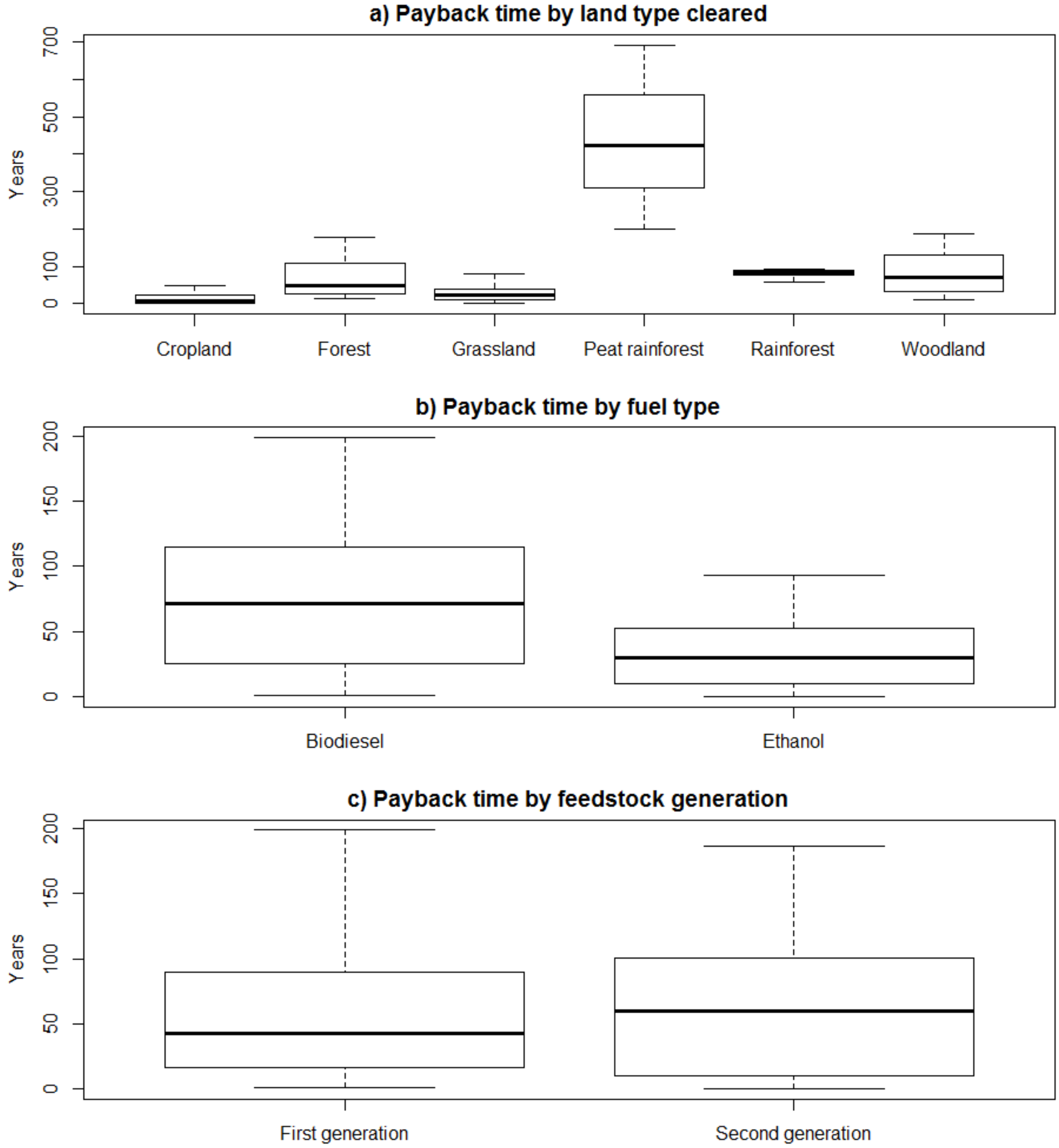
Fuel type/feedstock	EROI[a]	Source
Fossil fuels (gasoline and diesel)	9 - 10	[27, 28]
First generation ethanol		
• *Corn*	0.8 – 1.7	[29]
• *Corn*	1.1	[30]
• *Corn*	1.5	[24, 31]
• *Wheat*	1.6 – 5.8	[29]
• *Sugarcane*	3.7	[30]
• *Sugarcane*	3.1 – 9.3	[29]
• *Sugarcane*	4.4	[32]
Second-generation ethanol		
• *Cellulosic ethanol*	11	[24]
First generation biodiesel		
• *Palm Oil*	2.4 – 2.6	[29]
• *Soybean*	3.7	[7, 33]
• *Soybean*	1.0 – 3.2	[29]
• *Rapeseed*	3.7	[34]
Second generation biodiesel		
• *Jatropha*	1.4 - 4.7	[29]

a) EROI = (Usable energy acquired)/(Energy expended)

3.2. Net carbon benefits

A number of studies have suggested lower greenhouse gas (GHG) emissions by up to 90% relative to fossil fuels [1, 7, 24, 35]. However, often these studies have not accounted for the effect of land-use changes resulting from increased biofuel crop cultivation. The loss of standing carbon sinks from the conversion of land for biofuel feedstock cultivation, especially from deforestation [36-38], can outweigh GHG reductions from production and consumption [9, 39]. It is estimated that more carbon can be emitted from land clearing (17 to 420 times), which results in a substantial "payback" period for net emissions reductions to be achieved (Figure 1). Biodiesels in particular, such as those derived from palm oil in Southeast Asia [40, 41] and Jatropha in Mozambique [42], have been found to have the highest relative carbon debt repayment time from conversion of rainforests and woodlands respectively. Induced land changes from converting existing cropland have also been a source of indirect GHG costs [36, 41]. Figure 1 also suggests that the type of land cleared and emissions on combustion are more indicative of the net carbon benefit/cost than the type of feedstock that is cultivated for conventional biofuels.

Figure 1: Distribution of estimated carbon "payback" based on (a) type of land cleared, (b) type of biofuel produced, and (c) feedstock generation.



Adapted from: Gasparatos et al.**[9]**

3.3. Energy independence

An advantage of biofuels is the ability to provide some level of energy independence. This includes reduced dependence on imports and increased fuel security. This has been achieved through national-level policies in Brazil and at smaller community-levels in parts of Africa [13, 43, 44], the latter exemplifying further benefits of self-sustaining fuel sources in rural, land-locked regions [9]. The ease of access to the fuel is an advantage for developing communities in terms of employment, productivity, commerce, and local-level trade [44]. The associated employment opportunities can occur both at lower-skill levels, such as in agriculture, to higher-skilled levels such as research and development (e.g. engine innovations in Brazil) [9].

However, subsidy policies for biofuels coupled with blending mandates to support biofuel production and increase demand have been shown to potentially result in increased fossil fuel demand through a "green paradox" [45, 46][5]. Work by de Gorter and Just [19, 48] also found that the ethanol tax credit policies enacted in the USA were counter-productive when implemented together with fuel mandates, which resulted in potential increased dependence on fossil fuel imports.

3.4. Impacts to food prices and agricultural resources

Increased conventional biofuel demand may result in opportunity cost issues for agricultural crop and resource allocation [49]. This is due to the competition for these inputs with food production. Quantitative assessments have found biofuels have a greater impact on food prices than energy prices [25], particularly with first-generation feedstocks [50, 51]. Studies have found up to 40% of corn/maize price increases to be the result of ethanol mandates in USA [52-54] and projections for increasing first-generation biofuel demand will result in an increase to crop and livestock price of between 5 to 15% [55]. This reduces the affordability and supply of food, and adds pressure to increasing world hunger. However, contradictory studies suggest that increases in food prices may be the result of other factors. The slow uptake of biofuels would not sufficiently increase the competition of agricultural resources to directly affect food prices [8, 56-59]. Increasing oil prices [60], unpredictable weather patterns, demand from increasing populations, and most influentially, investment speculation [61, 62] have been suggested to be more consequential to rising food prices.

Impacts to land and water resources have been identified as a potential issue for increased biofuel demand [63]. An increasing global population and limited arable land suggest the unsustainable nature of conventional biofuels [64, 65], which would result in a 44% increase in arable land demand by 2020 [39] but this would only meet a marginal proportion of fuel demand [5, 66]. Also the induced pressure for farmers to convert food crops has already been noted to affect food prices in USA [67]. This demand for arable land has also been detrimental in the mass deforestations that have occurred in Southeast Asia for palm oil [1, 14, 37] and Brazil for sugarcane and soybeans [36, 68], which results in losses of both carbon stores and ecosystem biodiversity [38, 69, 70]. Second-generation feedstocks have also been found to raise issues with regards to land for food and fodder, particularly in poorer rural communities [6, 71].

Trade-off issues with regards to water allocation have also been identified due to the water intensive nature of biofuel feedstock cultivation. Estimates for water requirements have been

[5] This paradox can be largely overcome by simultaneously imposing a tax on fossil fuel based energy production. While a combined tax/subsidy program can provide welfare gains, a subsidy-only program is likely to result in welfare losses [47].

found to be undervalued to the point of being higher than natural replenishment rates from aquifers both in USA [72] and Brazil [30, 71].

4. Algae-based biofuels

The development of third-generation, algae-based biofuels has been highlighted to address many of the above issues [73] in particular, the impacts associated with food production from both crop and resource allocation [74]. Considerable attention over the last decade has focused on the potential for algae as a biofuel feedstock. The sugars in marine macroalgae, such as seaweed, have been found to be suitable for bioethanol production [75]. Additionally, biodiesel from macroalgae has also been suggested as being feasible [76]. However, the higher growth and lipid accumulation capacities of microalgae illustrates its greater potential for biodiesel production [77]. With bioethanol only containing 64% of the energy content of biodiesel [64], the potential for the latter to become a feasible and sustainable alternative to fossil fuels is greater; warranting greater research interest and focus for the remainder of this review. The high production efficiencies of microalgae biofuels have been suggested to provide greater fuel security for current and future fuel demands [77, 78], warranting policy investment in USA [79].

Microalgae, is intensively cultivated[6] in controlled artificial environments, either open raceway ponds or closed tubes called photobioreactors (PBRs), and in nutrient and CO_2-rich growth mediums [10]. The cultivated algae biomass is then processed in a similar way as other lipid-based feedstock to produce biodiesel. The carbohydrates in the cells can also be fermented to produce ethanol.

There are specific aspects to microalgae biodiesel production that can determine the feasibility and long-term viability of microalgae from a production standpoint; through the cultivation [81, 82], harvesting [83, 84], lipid extraction [85], and conversion to biodiesel. Studies by Brentner et al. [86] and Stephenson et al. [81] provide an indication of the different pathways at each stage of the process which can determine the biomass/biodiesel output as well as the final cost per unit. The specifics of these processes will only be addressed as it pertains to key issues, implications, and externalities[7].

4.1. Financial feasibility

As with most first and second-generation biofuels (which are largely dependent on subsidies to be commercially viable and competitive), microalgae biofuels are not currently competitive with fossil fuels [88]. However, they may be viable as potential aviation fuels

[6] Microalgae can be cultivated in extensive systems that are less technologically advanced but more land intensive [80]. Extensive cultivation has not been as efficient in productivity and is less favourable in recent microalgae literature, and thus, focus is given to intensive cultivation systems in this paper.
[7] There are a number of alternative reviews for the production processes of microalgae biodiesel from an engineering perspective [2, 87], including those that describe potential improvements in the strain and processing of the microalgae to improve its viability [77].

given their compact energy properties [89] and have been of interest at research and pilot scales for airline companies [90]. Furthermore, there are potential improvements to the cultivation [88] and processing [91], with the latter focusing on reducing capital costs through lower-cost machinery specifically designed for processing microalgae [88, 92]. Substantial reductions in costs can also be achieved if CO_2, nutrients, and water can be obtained at lower costs [92] or recycled within production [80]. Appropriate supplies of CO_2, nutrients, and water in particular are believed to be a limiting factor in the feasible production of microalgae in USA [93], and elsewhere.

Microalgae have the potential to generate other commercially valuable by-products. Lipids only make up around 30% of the harvested biomass, with the remainder of the biomass being potentially useful as animal feed [94] or other energy-related products such as ethanol [84], bio-gas [95], or even hydrogen [96] that can be used for fuel. Future commercial viability of microalgae as a biofuel may also depend on appropriate commercial use of these by-products [92, 94].

Table 3: Recent studies of microalgae lipid-based fuels with co-products and/or external benefits.

Primary output	Alternative/co-product	External benefit(s)[b]	Source
Biodiesel	Methane	CS	[97, 98]
		WT	[99]
	Non-specific co-product value		[80]
	Glycerol	CS	[91]
	Ethanol	WT	[84]
		CS	[81]
	Biogas		[86]
		CS, WT	[100]
Algae oil/ oil-based fuel	Ethanol	CS, WT	[101]
	Biogas	CS, WT	[102]
	Biogas, Stockfeed	WT	[85]

b) CS = carbon sequestration of flue gas, WT = wastewater treatment

4.2. Energy requirements

Relative to terrestrial feedstock, microalgae has a substantial energy requirement from the various machinery and capital inputs of the accelerated cultivation cycles [103]. This results in low relative net energy returns, which make it uncompetitive and even unsustainable [84, 99]. This substantial energy demand can potentially result in a net energy loss for microalgae biodiesel, or at best a marginal gain, given the current technologies [77].

Comparing open-pond and PBRs, the former is most often found to have a more efficient energy ratio. An exception was Sander and Murthy [84] who found higher value estimates for open-ponds. Open-ponds were also found to have less energy intensive cultivation, with more significant energy costs being incurred from harvesting and drying stages, adding as much as 10 times to the energy ratio [92, 99, 104].

In contrast, the more controlled environments associated with PBRs had resulted in significantly higher energy costs for cultivation, and a lower energy ratio. The majority of energy costs were attributed to construction and culture circulation [81, 82]. Slade and Bauen [92] add that assuming the majority of the energy in the production is derived from fossil fuels, the net carbon emissions from biomass production is positive, more significantly for PBRs. This has led to questions on the viability of PBRs in relation to its high energy input requirements given current technologies [105].

However, as the industry is relatively new, there is potential for improvements in the algae strain and production technology that can ensure a higher probability of positive net energy balance, though it is not yet certain.

4.3. Net carbon benefits of microalgae

Microalgae, like terrestrial agriculture, converts carbon dioxide into biomass via photosynthesis [10]. While this process has been shown to occur more efficiently in microalgae than with other terrestrial feedstocks in terms of area farmed [106, 107], conversion is still relatively expensive. Ono and Cuello [108] estimated the net unit cost of carbon sequestration using microalgae production with a solar collector at US$100 per ton carbon dioxide. They stressed the importance of producing commercially viable outputs to lower net costs.

Commercial microalgae production is also expected to have positive net carbon emissions, unlike its terrestrial counterparts, due to the controlled production environment and related machinery that require fossil-derived electricity [98, 103]. Additionally, the use of fossil fuels in the downstream processing of the biomass can also possibly counteract the GHG sequestration benefits achieved in the upstream cultivation, as with conventional biofuels [109, 110].

The recycling of flue gas from power plants in the cultivation process has also been suggested to yield a net reduction in carbon emissions. The flue gas can be sparged[8] into the growth medium of the microalgae as the input of carbon dioxide, adding benefits of more efficient carbon bio-fixation [2, 111] without affecting the biomass growth [112]. Some experimental and application studies on the efficiency of a microalgae species to employ a high-concentration flue gas (sometimes simulated) supply demonstrated the feasibility and efficiency of this application beyond terrestrial agriculture [107, 113-115]. Despite this sequestration benefit, the net CO_2 benefit from microalgae is dependent on the emissions from subsequent use of the biomass as a fuel. Assuming the CO_2 assimilated is emitted on

[8] Sparging is a technical term for bubbling gas into a liquid.

combustion, the net emissions schedule will depend on the energy intensity of the biomass processing that may use fossil fuels [2].

4.4. Nitrogen benefits

Microalgae cultivation requires inorganic nutrients within the growth medium, primarily nitrogen [2, 10]. This presents an opportunity for the use of microalgae in removing high concentrations of nitrate compounds in runoff of wastewater, a major cause of eutrophication [116]. In addition to its high nitrogen sequestration efficiency [117], microalgae cultivation also represents a cost-effective and low chemical-based method for wastewater treatment, assuming it was presented with adequate growth conditions. Batten et al. [85] were able to show that with wastewater treatment as a primary goal, microalgae biodiesel was able to be produced at less than US$1 a litre, assuming a waste carbon dioxide source, and water and nutrients were recycled in the algae ponds. However, a wastewater-based cultivation medium may restrict the potential of biofuel production, as there is an inverse relationship between nitrogen saturation in the growth conditions and production of lipids (the essential element for biodiesel production) [99, 118].

4.5. Benefits for food and resource competition

Assuming trends for increased policy support for transport biofuels, microalgae as a feedstock can alleviate some pressure that first and second-generation biofuels have on food security. Although there is the potential for some microalgae strains as supplements in human diets [2], it currently does not form a widespread dietary choice. Hence, as with second-generation feedstocks, microalgae biomass would not have a direct opportunity cost for food supply [71][9]. Microalgae cultivation also reduces competition for water given that it is preferably cultivated in wastewater [117], although as previously mentioned, the high nutrient saturation can be consequential to the feasibility of its production for relevant outputs [99, 118].

Additionally, with emphasis on shifting feedstock cultivation away from agricultural land [39], both macro and microalgae can reduce the opportunity costs associated with scarce land resources devoted to energy crops. Microalgae cultivation does not have a similar demand for arable land (marginal or otherwise) as compared to terrestrial biomass [119] given that it can be cultivated in artificial environments [10]. Macroalgae can be cultivated in ponds and other aquatic environments. Overall, algae cultivation for biofuels can potentially have minimal effect on food security and a transition to this feedstock may potentially reduce pressure on conventional feedstock-related impacts on food and agricultural resources as discussed previously.

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[9] In contrast, most macroalgae production is currently used for food, suggesting that diversion to biofuels may impact food supplies.

Furthermore, the reduced demand for arable land negates the need for widespread conversion of forests and woodlands. This reduces potential impacts on carbon sink and biodiversity loss [120, 121], which have plagued conventional feedstocks [2].

4.6. Socio-economic benefits

The development of microalgae biofuel industries also presents a number of socio-economic benefits that may contribute to a socially sustainable outcome. Social sustainability involves, amongst other aspects, the potential for a more equitable distribution of economic benefits across society, including regional and urban communities [122], and improvements in the quality of life. The most obvious of these benefits is the establishment of an energy industry that can sustain longer-term fuel demands, as well as generate employment, and economic growth in rural communities. This is in contrast to existing fossil-based industries that are dependent on a finite resources and conventional biofuels that are restricted by resource limitations [123]. As a long-term sustainable industry, microalgae biofuel production can also provide outlets for growth of related jobs across skill-levels, similar to those associated with conventional biofuels [9].

Microalgae-based industries also present opportunity for economic growth in non-metropolitan and regional areas. Public and private investment of bioenergy projects are often centred on employment and income opportunities for businesses and local communities, particularly in regional areas [124]. It has been suggested that there are significant opportunities for sustained growth of agricultural industries and incomes through conventional biofuels [121]. However, in many instances it would be difficult to justify policy support for conventional biofuel production given its impacts to broader society in terms of higher food prices and resource constraints. In contrast, the cultivation of microalgae, integrated with existing complementary industries, might present a superior alternative. In addition to supplementing incomes of seasonal industries, the synergy from bio-fixation of waste effluents and production of usable co-products (e.g. feed, fertiliser) [94] may prove economically beneficial to local communities.

5. Discussion

There is a need for further development in biomass-based fuels given the current dependence on liquid fuels for transportation. To date, most attention has been given to terrestrial-based feedstock and related production systems. The external benefits of such systems initially looked promising, receiving policy support to reflect the perceived non-market benefits (e.g. in USA and Brazil) [9]. However, the literature has indicated that these benefits may be overstated. In particular, there is growing evidence that land clearing for crop production, especially in tropical regions, may result in a net increase in GHG through the loss of substantial carbon sinks.

As summarised in Table 4, the overall social and economic benefits from conventional biofuels are also uncertain due to the impacts on food prices and supply, and the induced loss in ecosystem services through land clearing/conversion. The welfare effects of these changes are complicated. The potential for additional employment and income generated through crop-based biofuel production and improved fuel access may offset the higher food prices, especially in poorer regions. Similarly, higher food prices can result in improved incomes to farmers, many of which are also often in low-income groups. However, given that the benefits of the feedstock cultivation may not be shared efficiently across the society, the distribution of gains between net producers and consumers of agricultural commodities is an empirical question that must be answered in order to understand the overall impacts on human welfare [125].

Algae, particularly microalgae, offer a new potential for biofuels that does not appear to have the same level of associated negative externalities. As with most biomass-based biofuels, microalgae biodiesel is currently unable to compete with fossil fuels in terms of price, although this is potentially due to the relative infancy of the production and processing technology [77]. Aside from the potential for technological improvements, there is also potential for the biomass to be allocated to other output products and possibly improve the financial feasibility. However, there has currently not been any analysis into an output allocation of feasible biofuel production for a conclusion to be made on the viability of microalgae cultivation for biofuels.

An additional drawback of microalgae cultivation and processing is that they are capital and resource intensive. Aside from the construction and maintenance of the artificial environments, there are substantial requirements for energy, water, and related nutrients for the facility to be able to produce sufficient biomass [103]. Although there are opportunities to recycle waste resources as production inputs [126], the high energy requirements suggests the dependence on fossil fuel energy, at least in the short to medium-term, to sustain the various downstream processes [110].

Despite these issues, the positive externalities of microalgae biofuels illustrate potential welfare benefits for society. In addition to the environmental benefits, algae-based technologies overcome issues with resource competition, which can affect both food prices and biodiversity. Furthermore, these technologies can contribute to social sustainability through employment and income generation, particularly for regional communities that are typically dependent on seasonal industries.

The development of first and second-generation biofuels has largely benefited from various policy interventions. These include directly supportive measures; such as tax concessions, reduced fuel excises [19], and subsidies for production and infrastructure [65]; or indirect measures; like biofuel blending mandates and trade measures protecting domestic biofuel industries from lower-cost foreign suppliers [127]. Such measures were estimated to have cost US$11 billion in 2006 and the forecast for 2017 is US$25 billion [127].

The implementation of relevant policy mechanisms to reflect the economically efficient price can improve feasibility of production and its viability as a longer-term and sustainable alternative to fossil fuels [128]. The relative rapid growth in terrestrial feedstock (e.g. in Brazil) demonstrates that producers and consumers respond to incentives provided under such policies. While these policies are also applicable to microalgae production, the higher start-up costs and risks provides an additional disincentive to invest in the industry compared to the lower-cost agricultural-based production. Finding a policy mix that provides appropriate incentives for third-generation biofuels, whilst transitioning away from conventional approaches and managing the associated risks is likely to be as big a challenge; with the technological developments required to justify these incentives and the feasibility of the fuel. However, given the potential of microalgae as a biofuel feedstock, accepting these challenges would seem to be based on long-term confidence rather than idealistic assumptions.

6. Conclusion

This paper presented a review of the economic issues surrounding plant-based biofuels from first, second, and third generation feedstock. This study highlights key limitations of first and second-generation biofuels, particularly in the food versus fuel debate. Microalgae were found to alleviate much of the shortcomings that plague its predecessors, but high production and energy costs represent major limitations. Policy intervention was highlighted to have a major influence over the development and use of conventional biofuels. As such, this paper suggests that economically efficient policy support in the development of microalgae biofuels is potentially warranted based on long-term need for a liquid fuel substitute that does not raise environmental and socio-economic costs on society.

Acknowledgements

The authors would like to thank the two anonymous reviewers for their useful comments.

Table 4: Key economic benefits and limitations for first, second, and third generation biofuels for policy consideration[c].

Biofuel type	Benefits	Limitations
First generation	Policy support has shown spillover benefits to other sectors of the economy (3.3)	Low EROIs (3.1)
	Cheaper production costs allow poorer communities to have access to renewable source of transport fuel (3.3)	Potential high emissions and loss of biodiversity from land conversion (3.2)
	Benefits to lower-income farming communities particularly in developing countries (3.3)	Competition for crop allocation for food (3.4)
		Competition for agricultural resources (3.4)
Second generation	Higher EROIs than first-generation (3.1)	Can raise pressure to convert existing forestland/cropland (3.4)
	Less pressure on crop/agricultural resource demand compared to first generation (3.4)	Competition for agricultural resources (3.4)
		Insufficient supply if dependent on residual/waste biomass (3.4)
Third generation	Utilises waste effluents in cultivation; carbon sequestration (4.4), wastewater treatment benefits (4.5)	Infant technology, high costs and estimated prices (4.2)
	Can be cultivated on marginal/non-arable land (4.6)	Energy intensive nature of harvesting and processing (4.3)
	Potential for high value co-products (4.2)	Dependence on fossil fuels in production stages raises environmental costs (4.3)
	Reduces impacts to biodiversity (4.5)	
	Potential development of long-term industry, employment, and economic growth (4.6)	
	Social sustainability for regional communities (4.6)	

c) Numbers in brackets correspond to section of the review

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