Algae-to-liquid biofuel pathways — a literature review of technology, techno-economics and sustainability

Algae have long been considered as a potential novel biofeedstock for advanced biofuel production, but challenges associated mostly with cultivation and processing present barriers to realising its potential on a commercial scale. This article summarises the results of a literature review undertaken by Concawe to assess the latest data on technical progress, and to highlight both recent advances and remaining barriers.

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Introduction

Over the past two decades, algae have emerged as a promising biofeedstock, particularly when cultivated in controlled artificial environments that allow production management and avoid competition with food resources. Classified as aquatic biomass, algae are included in Annex IX, Part A of the Renewable Energy Directive (RED) as eligible feedstocks for advanced biofuel production without any restrictions on the amount that can be used.

The initial wave of enthusiasm for algae, reflected in a surge of start-ups and scientific publications, has since diminished, with most companies, including major refiners, withdrawing investment from this pathway.[1,2] Early studies suggested that algae could achieve productivities 5–45 times higher than terrestrial crops; however, these estimates proved overly optimistic and have not been realised due to persistent technical and economic challenges in cultivation and processing.[3]

The most recent comprehensive review of algae for biofuel applications was published by the IEA in 2017.[3] Nevertheless, algae continue to be cited as the primary feedstock candidate for long-term biofuel production, and are often referred to as third-generation biofuels. In this context, Concawe has undertaken a literature review to compile updated information and data on technological progress in algae-based advanced biofuel production, with the objective of highlighting both recent advancements and the remaining barriers.

Types of algae and biofuel pathways

Algae can be broadly classified into two main groups based on cellular structure: macroalgae and microalgae. Macroalgae are multicellular aquatic plants, commonly referred to as seaweed, and can be further subdivided, according to pigmentation, into green, red and brown macroalgae. This distinction is important because each subgroup differs in its biomolecular composition. Microalgae, by contrast, are unicellular organisms found in both freshwater and marine environments. They have attracted far greater research attention for biofuel production, primarily because they can be cultivated in artificial environments where growth conditions are controlled.[4]

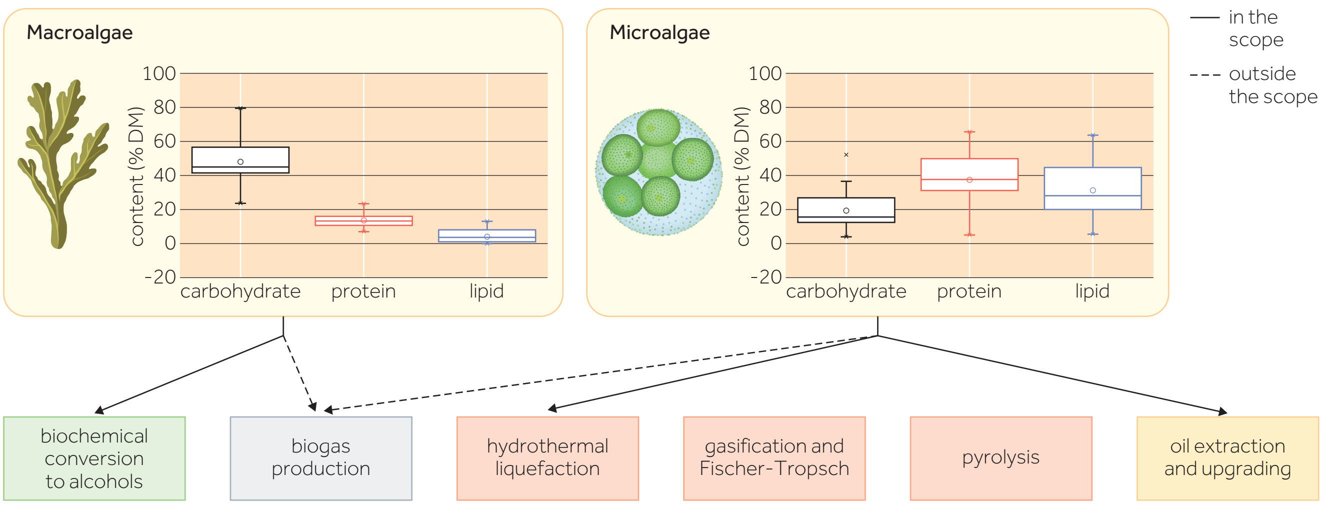
A key factor driving biofuel industry interest in microalgae is their potentially high lipid content, which can be extracted and processed in existing refinery facilities, similar to established pathways for vegetable oils and used cooking oil (UCO). As shown in Figure 1 on page 20, the lipid composition of microalgae is highly variable depending on the species and cultivation conditions. The prevalence of lipid-rich species has motivated extensive research into biofuel production pathways based on lipid extraction and upgrading.

Conversely, any application of conventional thermochemical processes, such as gasification and pyrolysis, is limited. This limitation arises because harvested microalgae typically have very high water content (> 99%), making such processes both energy and cost-intensive.[3,5] An exception is hydrothermal liquefaction (HTL), which can efficiently process wet feedstocks and has therefore received growing research interest as an alternative route for microalgae-based biofuels.[3]

Macroalgae, although also variable in composition depending on species, season and climate, are generally characterised by significantly lower lipid concentrations and higher carbohydrate levels.[3] Consequently, research into lipid extraction has been limited, while thermochemical processing of macroalgae has also been limited due to their high water content as feedstock. The most investigated conversion pathway for macroalgae has been carbohydrates utilisation through conversion to alcohols, particularly ethanol.

Both microalgae and macroalgae can be processed for biogas production, but research in this area has been comparatively limited and, given the stronger focus of this study on liquid biofuels, this pathway is considered to be outside the scope of the present review.

Figure 1: Biochemical composition of macroalgae and microalgae, and an overview of the most compatible and extensively researched pathways for biofuel production from each group (indicated by the arrows)
(box plots showing molecular composition are adapted from Gao *et al.*, 2020[6])



Industry status

According to FAO[1] data (2021), Europe accounts for only 0.8% of global algae production, with the vast majority located in Asia, where seaweed is primarily cultivated for food and pharmaceutical applications.[7] Notably, none of the algae currently produced at commercial scale are used for biofuels. For Europe, recent data collection and mapping exercises indicate that 67% of European production consists of seaweed, while the remaining 33% is microalgae;[8] the geographical distribution is illustrated in Figure 2 on page 21. In terms of end uses, the primary markets are human food, nutritional supplements and cosmetics.

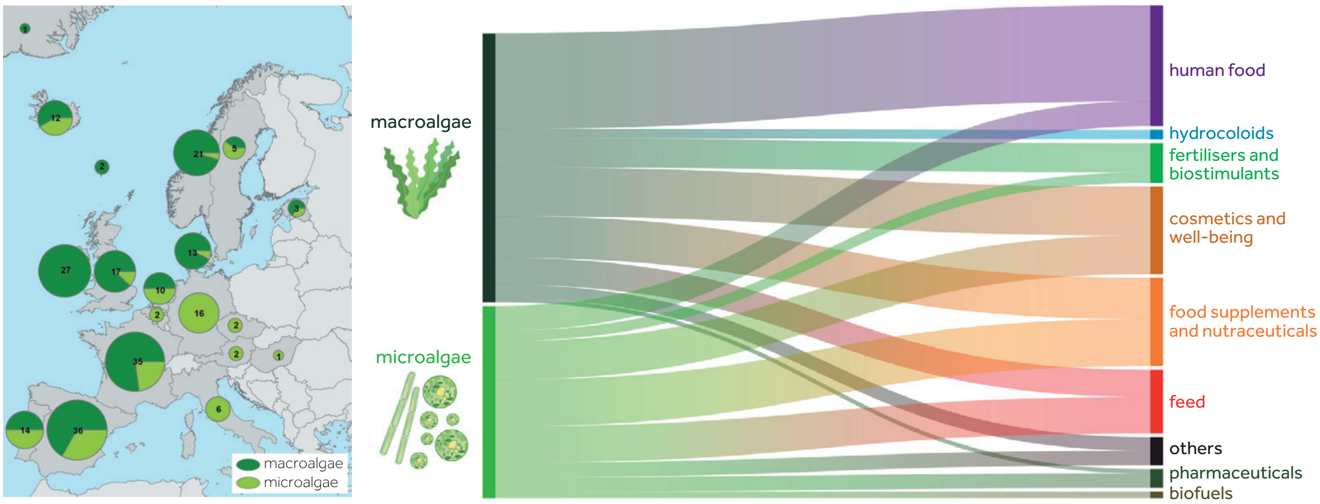
[1] Food and Agriculture Organization of the United Nations

Industrial interest in biofuel from algae production within Europe has declined sharply in recent years. While numerous EU projects were launched in the previous decade, today only two projects are active: FUELGAE and SusAlgaeFuel. Despite this downturn, the European Commission has signalled its intention to strengthen algae production across the EU through the EU Algae Initiative.[9] Although addressing biofuel challenges is explicitly mentioned among the targeted actions, the main emphasis of the initiative is expected to remain on food and feed applications.

Figure 2: Distribution of macroalgae and microalgae production facilities, and flows of algae to different applications in Europe
(adapted from Araujo *et al.*, 2021[8])

Distribution of companies producing algae

Flows of algae to various applications



Algae production systems

Algae production lies at the core of algae-to-biofuel pathways, as most of the associated technical and economic challenges are concentrated at this stage. At present, seaweed supply mainly comes from direct harvesting of wild stocks.[8] However, under the RED, algae derived from wild stocks are not considered eligible, and only algae cultivated in ponds or bioreactors qualify. This requirement has not yet been widely applied for seaweed, which therefore remains dependent on natural harvesting.

By contrast, microalgae have attracted greater interest due to their properties and potential for cultivation in controlled environments such as open ponds or photobioreactors. Key parameters influencing microalgae growth include sunlight, temperature, pH, and nutrients supply. Although microalgae generally exhibit higher productivities than terrestrial plants, large-scale artificial production faces significant spatial constraints. For example, utilising a CO_2 emissions stream of 100 kt CO_2/year to feed algae ponds would require ponds covering an area of around 1,000 hectares.

Figure 3: Examples of microalgae production systems[10,11]

Open pond system

Tubular photobioreactor

The question of which microalgae production system is most suitable and efficient has been the subject of ongoing debate. Open ponds are the most common and least costly option, but they offer limited controllability, are highly sensitive to weather fluctuations, and are vulnerable to contamination. Closed photobioreactor (PBR) systems provide much better control of growth conditions, but at the expense of substantially higher capital and energy costs.[12] While PBRs may be viable for high-value products such as pharmaceuticals, they remain cost-challenging for biofuels, where open ponds are generally preferred.

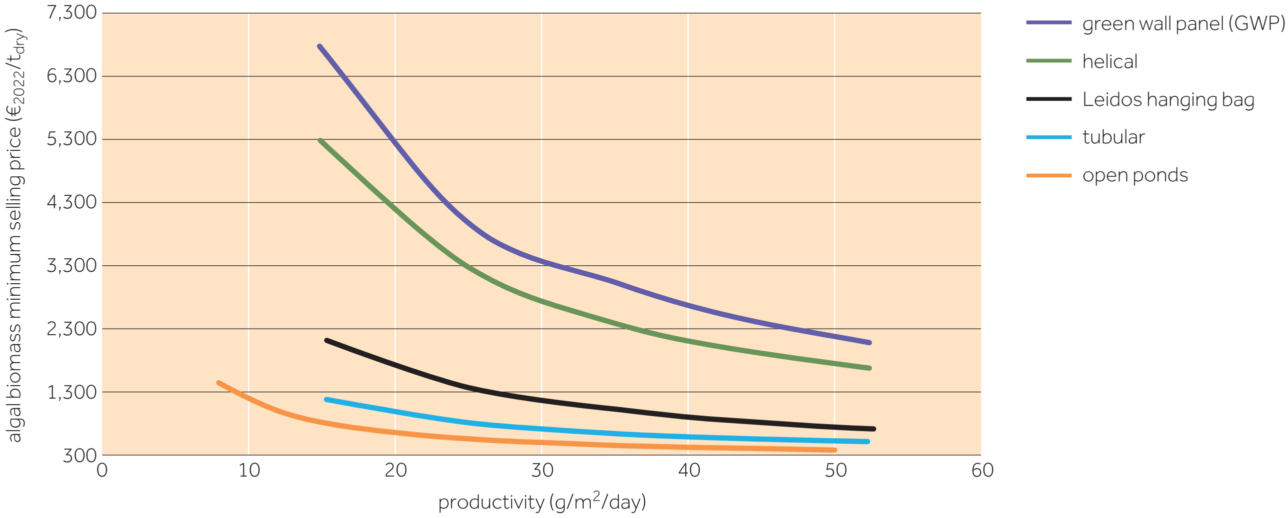
The state-of-the-art annual average biomass productivity in open ponds, based on experimental trials at AzCATI,[2] is 18.6 $g{\cdot}m^{-2}{\cdot}d^{-1}$.[13] This is considerably lower than the projections made by NREL[3] a decade ago, which anticipated reaching 25–30 $g{\cdot}m^{-2}{\cdot}d^{-1}$ by 2022.[12] Based on the latest advances, expectations have now been revised, with a productivity target of 25 $g{\cdot}m^{-2}{\cdot}d^{-1}$ by 2030.[14] A persistent challenge in these systems is the trade-off between biomass growth and lipid productivity: strains and conditions that favour high lipid accumulation often inhibit overall biomass yields, complicating scale-up under favourable cost and output conditions.

Closed systems can achieve higher production rates; however, their costs are significantly higher (see Figure 4 on page 23). They may only become comparatively efficient in regions with limited sunlight, such as Central and Northern Europe, where open pond productivities cannot exceed 15 $g{\cdot}m^{-2}{\cdot}d^{-1}$.

[2] Arizona Center for Algae Technology and Innovation, azcati.asu.edu

[3] National Renewable Energy Laboratory, www.nrel.gov

Figure 4: The biomass minimum selling price[4] for open ponds and different closed photobioreactor designs[15]
(prices were indexed to 2022 and converted from USD to EUR)



Biofuels from algae: economics

The biofuel minimum selling price (MSP)[5] was used as the indicator for reviewing the economic performance of algae-to-biofuel pathways, as it is the most frequently reported metric in the literature. The review concentrated on the pathways that have received the most attention across the techno-economic studies in the literature:

For macroalgae:

- bioethanol (BioEtOH) production

For microalgae:

- lipid extraction and processing (LE);
- hydrothermal liquefaction and processing (HTL); and
- combined algae processing (CAP) targeting the co-production of fuels and chemicals.

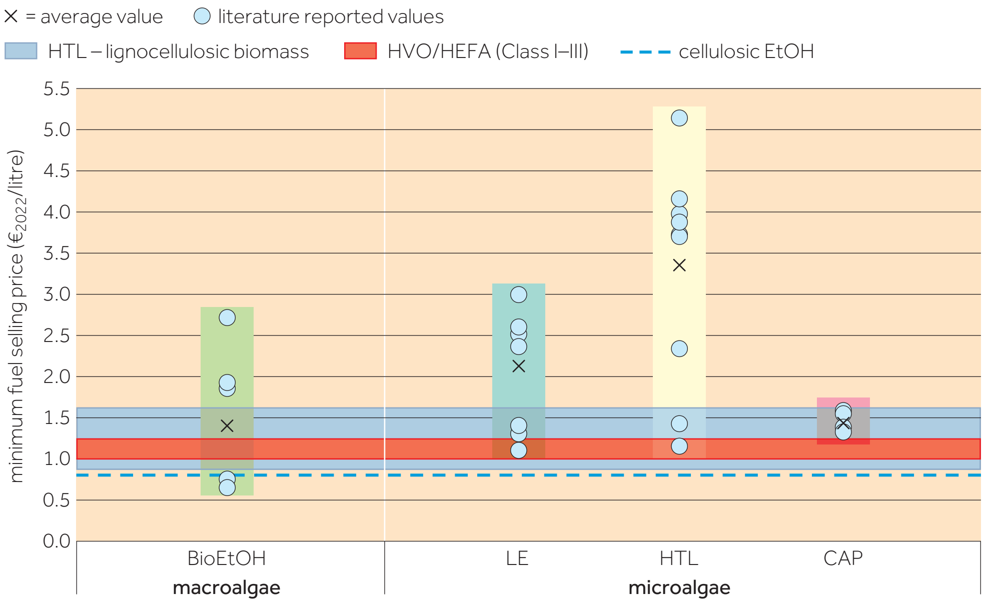
The results of this review are summarised in Figure 5 on page 24.

[4] The minimum price at which algal biomass must be sold in order to cover the total production costs, including capital investment and operating expenses, under assumed process and economic conditions.

[5] The minimum price at which biofuel must be sold in order to cover the total production costs, including capital investment and operating expenses, under assumed process and economic conditions.

Figure 5: Distribution of literature-reported values for the minimum fuel selling price across various algae-to-biofuel pathways explored

(Minimum fuel selling price of biofuel alternatives)



Notes:

Pathways included:

- BioEtOH = biochemical pathway to ethanol
- LE = lipid extraction for renewable diesel or biodiesel
- HTL = hydrothermal liquefaction to renewable diesel
- CAP = combined algae processing-multiproduct biorefinery (e.g. polyurethane co-production)

The coloured boxes represent the economic ranges reported across studies.

For macroalgae, the number of economic studies is relatively small, and the assumptions applied vary widely. This leads to significant variability in the results and makes drawing firm conclusions difficult. Reported MSP values for ethanol range from 0.66 to 2.71 EUR/litre, with a statistical average of 1.30 EUR/litre. The lower end of this range generally reflects highly optimistic assumptions, such as near-ideal conversion yields, which are not representative of the current technological status. Conversely, studies that rely on more realistic assumptions typically present less favourable results. Across all studies, a consistent conclusion is that achieving feedstock supply costs below ~80 EUR/tonne, coupled with improvements in conversion efficiency from biomass to ethanol, will be critical to achieving economic competitiveness for macroalgae-derived ethanol.

For microalgae, the results are more consistent across the literature, as they are based on the harmonisation performed by Cruce *et al.* (2021) for key parameters such as biomass productivity (set at 25 $g{\cdot}m^{-2}{\cdot}d^{-1}$ representing a future target higher than the current maximum reported productivity of 18.6 $g{\cdot}m^{-2}{\cdot}d^{-1}$).[16] Within these assumptions, lipid extraction (LE) pathways demonstrate lower costs than hydrothermal liquefaction (HTL), with the statistical average MSP calculated at 2.2 EUR/litre compared to 3.4 EUR/litre for HTL. Notably, the HTL pathway exhibits a much wider cost range, coming from the lower technology readiness level (TRL) and higher uncertainty in conversion yields relative to the more established oil extraction and upgrading routes. In both pathways, energy consumption and the capital investment for pond systems are consistently identified as the dominant cost drivers, underlining the importance of improvements in upstream cultivation systems to achieve meaningful cost reductions.

Another important conclusion concerns the potential of multi-product biorefineries designed to maximise the value of algal components. In particular, the co-production of polyurethanes, primarily studied by NREL, has been shown to significantly improve the economics of algae-to-fuel pathways.[13] However, the relatively smaller market size for such co-products poses a potential bottleneck for large-scale deployment of this concept.

When compared with alternative biofuel options, algae-derived biofuels remain a significantly more expensive route. Even under optimistic assumptions, such as achieving productivities of 25 $g{\cdot}m^{-2}{\cdot}d^{-1}$, which reflects future targets, algae-based fuels are estimated to be considerably costlier than advanced biofuels produced from lignocellulosic feedstocks (eligible in Annex IX) or HEFA/HVO[6] pathways from used oils and fats.

To improve the economics of algal biofuels, technological advancements in upstream cultivation are essential. The development of systems capable of sustaining annual average biomass productivities in the range of 25–30 $g{\cdot}m^{-2}{\cdot}d^{-1}$ represents an important step, but this alone is insufficient to offset the high production costs. These productivity gains must be coupled with increased lipid yields in algal cells (approaching 50%), since lipids constitute the feedstock for lipid extraction pathways and also enhance conversion efficiencies in HTL processes. However, achieving both high biomass growth and elevated lipid contents simultaneously remains a major bottleneck, as these two factors are generally counteractive.[3]

Biofuels from algae: sustainability

The sustainability of algae-to-biofuel pathways was assessed through a literature review of reported greenhouse gas (GHG) intensities ($gCO_2eq/MJfuel$). Results were grouped according to the GHG accounting methodology applied in each study, such as allocation or system expansion.[7] Data for macroalgae-to-ethanol are limited, whereas microalgae pathways have been more extensively examined. For the latter, the study by Cruce *et al.* was used as the reference basis, as it applied harmonisation of system boundaries across different LCA assessments, thereby providing a more consistent basis for comparison.[16]

The results nevertheless show significant divergence, reflecting the range of assumptions and GHG methodologies employed (see Figure 6 on page 26). For example, studies employing system expansion, where credits are granted for co-products such as electricity or fertiliser that displace fossil-based equivalents, report much lower GHG intensities than those applying allocation methods (no displacement credit). These differences highlight both the sensitivity of outcomes to methodological choices and the role of process configuration and targeted co-products in achieving low GHG emissions.

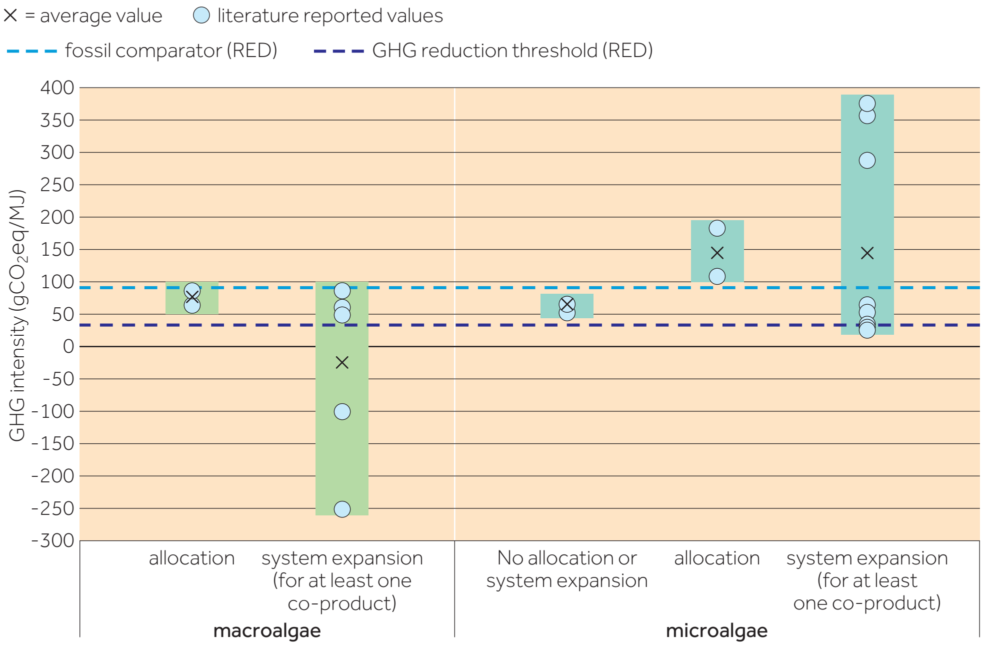
[6] Hydroprocessed esters and fatty acids/hydrotreated vegetable oil

[7] Allocation refers to distributing environmental impacts proportionally among the main product and co-products of a process (e.g. based on energy content, mass or price). System expansion attributes credits for co-products by accounting for the displacement of equivalent fossil-based products (e.g. electricity, fertiliser), thereby lowering the overall GHG intensity of the biofuel pathway.

Despite such opportunities, even under consistent calculation frameworks, achieving GHG intensities comparable to other advanced biofuels (e.g. via lignocellulosic pathways) remains challenging for algae-based systems. This is largely due to the high energy demand of upstream processes, particularly for microalgae cultivation and harvesting. The lack of a harmonised methodology for GHG accounting across studies further complicates comparison and points to the need for alignment with frameworks such as the RED methodology.

Future research should also focus on updated case studies that better reflect sustainable frameworks. For example, accounting for the projected decarbonisation of electricity grids, or integrating more sustainable energy and material inputs, could provide a clearer view of the long-term potential for algal biofuels to deliver meaningful GHG reductions—an aspect that remains underexplored.

Figure 6: Distribution of literature-reported values for the GHG intensity of the different algae-to-biofuel pathways explored



Notes:

The fossil comparator and GHG reduction threshold set in RED III are disclosed. It is important to clarify that the presented GHG reduction threshold and fossil comparator refer to the values given in RED III. To compare these values with the corresponding values for biofuels, RED discloses a specific GHG accounting methodology (allocation based on energy content), which often differs from those used in algae studies (e.g. accounting displacements credits from electricity surplus). Nonetheless, these figures remain a useful reference point for evaluating the sustainability of algal biofuels.

The results are categorised based on the GHG accounting methodology (allocation, system expansion) used in each study.

Conclusions

Over the past two decades, algae have attracted significant interest as a potential biofuel feedstock, owing to their ability to be cultivated in artificial environments. However, despite the early enthusiasm, the technological and economic challenges of scaling up algae production have led many companies to scale back or redirect their investments away from algal biofuels. Both major groups of algae, macroalgae (or seaweed) and microalgae, have been studied for biofuel applications, though research has primarily focused on microalgae due to their potentially high lipid content and their suitability for production in industrial facilities. For macroalgae, which are typically rich in carbohydrates, ethanol production is the most widely examined pathway. For microalgae, lipid extraction and upgrading to drop-in biofuels is the dominant route, followed by hydrothermal liquefaction (HTL). Other thermochemical pathways have received limited attention, as the high water content of algae renders them both energy and cost-intensive.

At present, macroalgae production is dominated by wild stock harvesting, with biomass directed to non-energy applications while microalgae production is small. Regarding microalgae production, two types of systems are available: open ponds and closed photobioreactors (PBRs). Closed systems allow tighter control of growth conditions and product characteristics, and they achieve higher biomass productivities, but their capital and energy requirements are substantial. Open ponds, by comparison, are more economically favourable for biofuel production, whereas PBRs are better suited to contexts where natural limitations, such as low sunlight, make open ponds inefficient.

From an economic standpoint, data for macroalgae-to-biofuel pathways are limited, and the studies with realistic technological assumptions report costs higher than for other biofeedstocks. For microalgae, lipid extraction generally appears more cost-effective than HTL, but both remain considerably more expensive than biofuels from lignocellulosic biomass or used oil and fat feedstocks (e.g. UCO). The high capital investment and operating costs associated with open and PBR systems are consistently identified as the main barriers. Current peak productivity for microalgae in open ponds is 18.6 $g{\cdot}m^{-2}{\cdot}d^{-1}$, with targets of 25 $g{\cdot}m^{-2}{\cdot}d^{-1}$ by 2030, though even such improvements are unlikely to ensure competitiveness. Increasing lipid content is also critical, but the inverse relationship between lipid accumulation and biomass growth creates a biological trade-off that has yet to be resolved.

From a sustainability perspective, algal biofuels face further challenges. Producing large quantities of algal biomass requires significant energy inputs, often resulting in GHG intensities exceeding those of fossil fuels or failing to meet EU reduction thresholds for eligible biofuels. Moreover, differences in assumptions and GHG accounting methodologies across studies complicate comparisons. Applying a harmonised framework, such as the RED GHG methodology, and exploring more sustainable production solutions (e.g. renewable energy integration) are critical steps that need to be further explored.

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