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Algae to Liquid Biofuels - State of Industry and Technology Literature Review

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Algae to Liquid Biofuels - State of Industry and Technology Literature Review

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ABSTRACT

Decarbonizing transport is crucial for Europe's GHG reduction goals, with biofuels expected to play a key role, particularly in aviation and maritime sectors, where electrification is challenging. Among the Annex IX biofeedstocks in the Renewable Energy Directive (RED), algae initially drew interest due to their rapid growth and CO_2 utilization. However, economic and technical barriers have hindered commercialization. In Europe, algae production is mainly for food, feed, and cosmetics, while biofuels remain at an experimental stage. This report reviews the state of the algae industry, evaluating the economic feasibility, and sustainability performance of different algae-to-liquid biofuel pathways.

Algae are categorized into macroalgae and microalgae based on their cellular structure. Macroalgae, commonly rich in carbohydrates, have been mostly explored for ethanol production, but conversion efficiencies are low (<10%), with a statistically averaged minimum ethanol selling price of 1.4 €/L, based on the available techno-economic publications. However, the limited research on macroalgae pathways makes these economic estimates uncertain.

Microalgae, which can accumulate lipids (typically 20–45 wt%), are more relevant for biodiesel production via lipid extraction followed by transesterification or for renewable diesel and sustainable aviation fuel (SAF) via direct hydrotreatment of extracted oil. However, large lipid concentrations constrain biomass productivity and seasonal variations in composition occur. For this reason, there has been a growing interest in hydrothermal liquefaction (HTL) alternative, a non-lipid-targeting thermochemical process, which does not require energy-intensive drying before processing.

Techno-economic studies indicate that biofuels from microalgae are significantly more expensive than oil-based and lignocellulosic biofuels. After harmonizing key technical and economic assumptions across various techno-economic models, the statistically averaged minimum fuel selling price (MFSP) is 2.2 €/L for lipid extraction routes and 3.4 €/L for HTL. However, these figures are based on future algae productivity targets (a standardized biomass productivity of 25 g/m^2-d) set by NREL, rather than current technological capabilities. With the highest state-of-the-art productivity at 18.6 g/m^2-d, actual fuel prices would be higher. The upstream processes, including microalgae production and harvesting, are identified as the primary cost bottlenecks. Strategies to improve competitiveness include increasing productivity to 25–30 g/m^2-d and enhancing lipid yields (~50%). Additionally, multi-product biorefineries, co-producing polyurethane and other valuable chemicals, have been explored as a strategy to improve biorefinery economics, but the relatively smaller market size of these co-products could be a challenge for large-scale commercialization.

According to the literature, GHG emissions vary widely depending on the accounting methodology and biorefinery setup, particularly in how co-products and their credits (e.g., electricity, fertilizers) are accounted for. Achieving GHG reductions comparable to lignocellulosic biofuels remains challenging, primarily due to the high energy demand of algae cultivation and harvesting. Due to the lack of a consistent GHG calculation framework, further research is needed to establish a harmonised GHG accounting approach (aligned with RED), and the exploration of more sustainable solutions, such as integration with renewable energy infrastructure (e.g., solar panels), is recommended.

KEYWORDS

Literature review, macroalgae (seaweed), microalgae, algae applications, algae production, algae to biofuels, macroalgae to ethanol, microalgae to biodiesel, microalgae to renewable diesel, combined algae processing, techno-economic assessment, production costs, energy efficiency, green-house gas emissions

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SUMMARY

Decarbonising the transport sector is a crucial step towards meeting Europe's GHG reduction goals outlined in the 2015 Paris Agreement. Biofuels are anticipated to play a significant role, especially in aviation and maritime transport. Among the eligible biofeedstocks for advanced biofuels listed in Annex IX of the Renewable Energy Directive, aquatic biomass, particularly algae, is included. However, the use of algae for biofuels has sparked debate. In the early 2010s, algae garnered interest from researchers and fuel manufacturers as a promising solution for sustainable biofuels, given that they do not compete with food and feed supply chains and grow rapidly using carbon dioxide. Predictions at that time foresaw a flourishing algae industry post-2020, a progress that has not materialized due to various technical and economic challenges. In Europe, algae production is currently minimal, and the main consumers are the food, animal feed, and cosmetic sectors, while biofuel production from algae remains at experimental stage. This report reviews the current state of the algae industry, summarizing algae-to-liquid biofuel pathways and evaluating their economic and sustainability performance based on recent technological advancements and scientific studies.

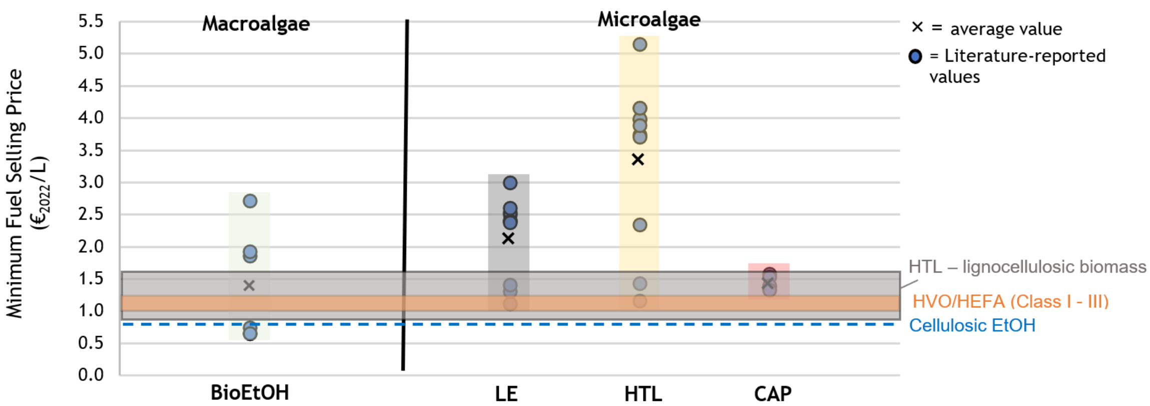
Algae fall into two primary categories based on cellular structure: macroalgae and microalgae. Macroalgae, or seaweed, are large, multicellular aquatic plants typically rich in carbohydrates (40-60% by weight), hence they have mainly been studied for ethanol production through fermentation. However, traditional fermentation processes typically achieve less than 10% conversion of algal biomass into ethanol. In contrast, microalgae, which can have a high lipid content (20-45% by weight), have been the focus of extensive research for biofuels production. Microalgae are cultivated in controlled environments like open ponds or photobioreactors. Considering the projected or the currently highest achievable productivity of each system, open ponds are generally preferred for biofuel production due to their lower costs. However, in cases where open ponds face frequent contamination or low productivity due to limited sunlight, closed systems may prove to be more economically favourable. Although open ponds offer higher productivity than lignocellulosic crops (up to 6 times), they still require substantial space and must be situated close to industrial facilities for logistical reasons. Lipid extraction from microalgae for biodiesel production via transesterification or renewable diesel and SAF through direct hydrotreating are the most explored process routes. However, as the increase of lipids during the cultivation stage reduces algal biomass productivity and seasonal variations in composition occur, the alternative of non-lipid targeted thermochemical processes has also been explored. Due to the high content of water in harvested biomass (over 99%), only hydrothermal liquefaction (HTL) is suitable, eliminating the need for extensive drying.

For the economic potential of algae-to-biofuel pathways, the minimum fuel selling price, calculated through discounted cash flow analysis, is the economic indicator used in most techno-economic studies. Research on the economic performance of converting macroalgae to ethanol is limited, and existing studies have varying assumptions, leading to different minimum selling prices and making it difficult to reach clear conclusions (see Figure 1). While some studies suggest that the minimum ethanol price could compete with biofuels from other biofeedstocks, these estimates rely on optimistic assumptions, such as near-ideal conversion rates that do not reflect the current technological progress. Contrary, the studies that use more realistic assumptions yield the least favourable results. Nevertheless, all studies indicate that ensuring macroalgae production costs below 80 €/t and further improving biomass conversion efficiency to ethanol are essential for achieving economic competitiveness.

Opposite to the less explored macroalgae, more research has been conducted on biofuel production from microalgae, focusing on either lipid extraction or hydrothermal processing. To reduce the uncertainties from varying study assumptions, this report relies on the recent harmonization assessment by Cruce et al. (2021) for reporting minimum fuel selling prices. Cruce et al. performed a literature review and harmonised key factors such as biomass productivity (set at 25 g m^2d^{-1}), battery limits, and economic parameters. Despite this harmonization, results still vary, especially for the HTL pathway, which is at a lower technology readiness level (TRL), hence variations in parameters like biomass-to-biocrude yield, which were not harmonized, contribute to these discrepancies.

The results reveal that most techno-economic studies report minimum selling prices for algae-based biofuels that are significantly higher than those of other biofuels (see Figure 1). For lipid extraction pathways, the minimum fuel selling price frequently exceeds 2 €/L (average = 2.2 €/L), and for hydrothermal pathways, it surpasses 3 €/L (average = 3.4 €/L). This occurs despite assuming relatively high biomass productivity levels, which align more with future targets set by the National Renewable Energy Laboratory (NREL) rather than current technology (annually average maximum = 18.6 g m^2d^{-1}). Studies indicate that capital cost for microalgae production is the primary cost driver (indicative fraction: 30% of total costs). Techno-economic assessments suggest that scaling up pond sizes, increasing biomass productivity (to 25-30 g m^2d^{-1}), and enhancing lipid content (close to 50 wt%) are essential strategies to lower costs and improve economic competitiveness. Additionally, NREL has introduced and recently evaluated a multi-product biorefinery approach (CAP), which co-produces valuable materials like polyurethane, improving economic performance. However, the relatively smaller market for these co-products may pose challenges to scaling up the multi-product concept.

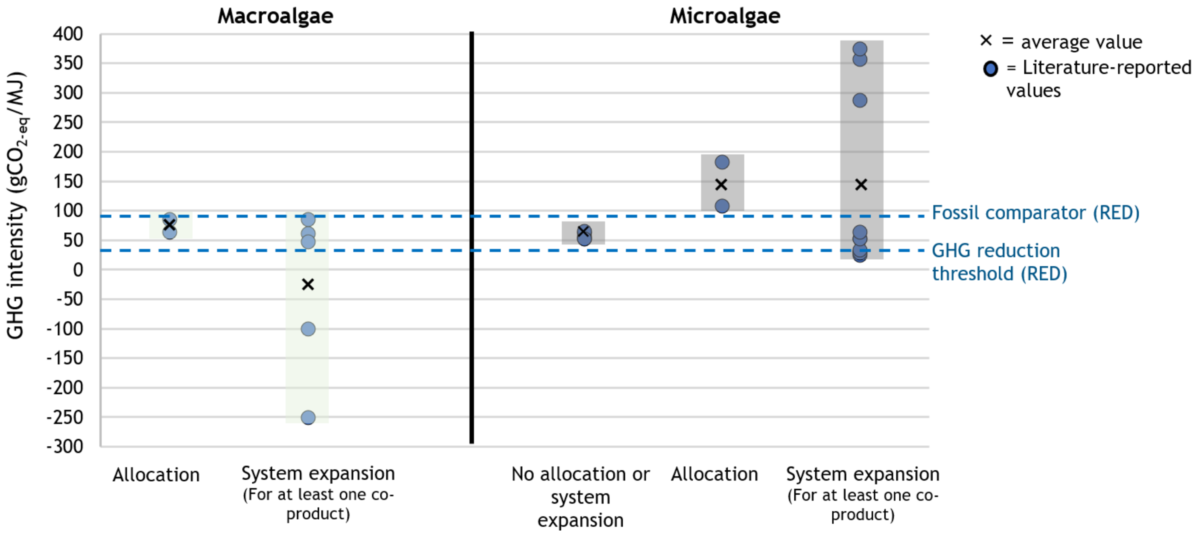
Figure 1. Distribution of literature-reported values for the minimum fuel selling price (MFSP) across various algae-to-biofuel pathways explored in this report. Pathways included: BioEtOH = biochemical pathway to ethanol, LE = lipid extraction for renewable diesel or biodiesel, HTL = Hydrothermal liquefaction to renewable diesel, CAP = Combined algae processing - multi-product biorefinery (i.e., polyurethane co-production). The coloured boxes represent the economic ranges reported across multiple studies, each employing different techno-economic assumptions



The sustainability of using algae for biofuel production was assessed through a literature review of the reported energy efficiencies and GHG intensities (gCO2-eq/MJ_{fuel}). The results were categorized based on the GHG calculation methodology (allocation, system expansion) used in each study. While information for macroalgae-to-ethanol is limited, the sustainability of microalgae pathways has been more extensively explored, and the same study by Cruce et al. was used as the basis for reporting sustainability metrics, due to the harmonization they applied regarding the battery limits in the different LCA assessments. The results show significant divergence due to the varying assumptions and GHG accounting methods employed in each study (see Figure 2). For instance, studies that consider credits from co-producing electricity and fertilizer, thereby displacing fossil-based equivalents (system expansion) report much lower emissions. These results highlight the significant impact that GHG methodological choices have on the final results and underscore the importance of process configuration and targeted co-products in achieving low GHG intensities. Nonetheless, on the same GHG calculation basis, achieving GHG intensities comparable to advanced biofuels from other biofeedstocks (e.g., lignocellulosic) is challenging, primarily due to the substantial energy required for upstream processes, including microalgae growth and harvesting.

Due to the lack of a consistent calculation framework for GHG emissions, more research using a harmonized approach, particularly in alignment with the Renewable Energy Directive methodology, is recommended. Additionally, updating case studies and evaluating pathways under a more sustainable framework, such as considering the projected future carbon intensity of the electricity grid or employing more sustainable energy and material solutions, can better showcase the sustainability potential of algal biofuels, an aspect that has not been investigated sufficiently so far.

Figure 2. Distribution of literature-reported values for the GHG intensity of the different algae to biofuel pathways explored in this report. The fossil comparator and GHG reduction threshold set in RED III are disclosed in the Figure[1]. The results are categorized based on the GHG accounting methodology (allocation, system expansion) used in each study.



[1] 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 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.

1. INTRODUCTION

1.1. BACKGROUND

The European Union has made a commitment to significantly reduce greenhouse gas emissions in the coming decades. By aiming to decrease emissions by 55% in 2030 compared to 1990 levels and reaching climate neutrality by 2050 (European Climate Law), the EU aligns with international ambitions to limit the temperature increase to 1.5°C above pre-industrial levels. To achieve these ambitious goals, it is crucial to address the emissions generated by the transport sector. The use of biofuels is expected to play a pivotal role in both the short-term and long-term decarbonisation of transport. While road transport is expected to shift for an important share to electrification, especially for personal cars and light commercial vehicles, the hard-to-abate aviation and maritime sectors, and potentially heavy-duty road transportation, present unique challenges and will heavily rely on sustainable fuels [1], [2]. The Renewable Energy Directive is the legislative framework that sets binding targets for the use of renewable energy in the EU. To prevent any competition for land use, the Directive imposes a cap (7% of total energy consumption) on the use of food and feed crop-based biofuels in the transport sector, while also establishing a minimum subtarget for advanced biofuels and renewable fuels of non-biological origin. The Annex IX part A of the Directive lists the eligible advanced biofeedstocks, with algae cultivated on land in ponds or photobioreactors being included as one of the approved feedstocks.

Microalgae, with many species to be known for their high lipid content, has received significant attention as a feedstock for biofuel production. These single-celled photosynthetic microorganisms, which are abundant and vital to our planet, offer numerous advantages over traditional biomass sources. With their rapid growth rates, ability to thrive in various water conditions, and capacity to absorb CO_2 and use it for their growth, microalgae could be a promising solution for the future of biofuels [3], [4]. In fact, their potential generated great excitement in the previous two decades, leading to substantial investments in algae technology companies such as Algenol, Sapphire Energy and Solazyme and start-ups on the promise of engineering the algae of the future [4]. In 2010, market projections were made for algae indicating a promising future. For example, SBI energy among others forecasted an annual growth rate of 43% for algal biofuels, estimating a $1.6 billion total market size in 2015. However, these projections can be traced back to a few publications using highly optimistic assumptions regarding the biological potential of microalgae. For example, publications at that time indicated the feasibility of producing microalgae with lipid concentrations up to 70 wt% and productivities in the range of 50-460 $g\ m^{-2}\ d^{-1}$ in the coming years [4]. Moreover, several EU-funded projects took place in 2010s, and oil & gas companies invested in the development of microalgae technologies.

Despite the hype that was plagued at that time and the considerable progress made on dedicated technologies, the technology readiness level of these systems did not advance beyond pilot scale and the market projections were not realised. The reasons for the market stagnancy are the bottlenecks regarding the productivity of microalgae, the lipids mass balance, maintaining stable cultivation conditions in open ponds and the immense volumes of water and CO_2 that are needed to keep these systems running [4], [5]. All the aforementioned barriers result in very high cultivation and harvesting costs relative to producing biofuels from terrestrial biomass. Most of the companies working on algal biofuels in 2005-2012 have been driven out of business or shifted their focus to the production and supply of algae to markets such as dietary supplements, food additives, and cosmetics. Today, only a few companies, such as Viridos (formerly Synthetic Genomics Inc.), are still working on the development of microalgae for biofuels [6], [7]. One by one the oil & gas companies have dropped out from investing in the development of algal biofuels, with the last one, ExxonMobil, announcing its withdrawal in 2023, as despite advances in the science thanks to years of committed effort, the breakthrough to reduce the cost of wide-scale deployment has not materialised [6]. Moreover, there is currently no EU-funded project on algal biofuels. Despite the dramatic decline of interest and financial flows, technology developers like Viridos claim that oil productivity in microalgae “has increased seven-fold” during the latest years, and “reaching the economic targets is only a matter of time” [6]. In Europe, the European Algae Biomass Association (EABA) exists and aims to foster collaboration among scientists, industry, and policymakers to advance research, technology, and industrial capacities in the field of algae. Their working groups focus on areas such as food and feed, cosmetics, and biofertilizers, but notably, there is no dedicated group specifically for biofuels.

To address the economic constraints on the commercialising microalgal biofuels, different researchers such as the National Renewable Energy Laboratory, devoted substantial resources to algae research, and have started investigating the option of a multi-product biorefinery wherein valuable co-products are generated along biofuels [4]. In addition, researchers have started looking at the potential of macroalgae, known also as seaweed. Given that seaweeds are already commercially harvested for food and chemical purposes, the viability of using them as a source of biofuels is currently in its nascent stages of investigation. It is imperative that more intensive research is carried out to obtain a more comprehensive understanding of its prospects [4].

1.2. SCOPE AND REPORT STRUCTURE

The purpose of this report is to provide a comprehensive overview of the various pathways for converting algae into liquid biofuels. Starting with a demonstration of the current market status and the tested technologies for the production of algal biofuels, the ultimate objective is to explore the economic and sustainability performance of the different pathways. Given the claimed bottlenecks on the economic viability of microalgal biofuels that led to a massive withdrawal of investments, this report draws upon the latest technical reports and scientific publications to shed light on these challenges and unveil whether a future market rollout for algal biofuels could be possible. While the majority of research has focused on microalgae, this report also explores the potential of macroalgae (seaweed), which has recently gained attention. It is important to note that the current definition of eligible feedstocks in Annex IX of the Renewable Energy Directive (RED) specifically excludes macroalgae harvested directly from the sea, focusing instead on algae cultivated in systems such as ponds and photobioreactors[2]. However, since the revision of Annex IX is an ongoing process, this report encompasses all methods of algae production and harvesting to provide a comprehensive overview.

In 2015 and 2017, JRC and IEA respectively published reports that provided a literature review of the economics and GHG emissions associated to the various algae-to-biofuel pathways [3], [4]. These reports, summarising the available data at that time, highlighted significant variations in the values of the economic and sustainability metrics, which arise from differences in assumptions and system boundaries adopted in each study. Notably, the deviations in GHG emissions may be attributed to varying carbon accounting methodologies, although this aspect was

[2] Definition in RED – Annex IX: Algae if cultivated on land in ponds or photobioreactors

not explored in these reports. This report, published eight years after the most recent literature review, aims to reassess the economic and sustainability potential of these pathways by incorporating the latest data in the literature. It places particular emphasis on studies that have gathered and harmonized techno-economic assumptions from different sources, and explicitly mentions the methodological differences to enhance the clarity of conclusions.

The report structure is set out in the following chapters:

Chapter 3: Introduces the biological characteristics and composition of the different types of algae and provides an overview of the algae market state and applications both on a global and EU level.

Chapter 4: Presents and analyses the status of the different technologies involved in the upstream (algae cultivation and harvesting) of the macroalgae and microalgae to liquid biofuel pathways (while biogas production is a potential alternative pathway, it is not included within the scope). Particular focus is given on the different technical parameters and operating conditions affecting the performance of the processes.

Chapter 5: Presents and analyses the current status of the different technologies involved in the downstream (algae conversion to biofuels) of the macroalgae and microalgae to liquid fuel pathways. The production of biodiesel, renewable diesel and ethanol through chemical, thermochemical and biochemical processes are the different process routes explored. The technical performance of the processes is reported based on experimental results that are available in the literature.

Chapter 6: Presents the economic potential of the different macroalgae and microalgae to liquid fuel pathways by collecting and illustrating the available literature data. The minimum fuel selling price is the indicator being used to assess economic performance.

Chapter 7: Presents the sustainability potential of the different macroalgae and microalgae to liquid fuel pathways by collecting and illustrating the available data in the literature. Energy efficiency and GHG emissions are the two metrics being used to assess sustainability.

2. EXPLORING ALGAE AS A FEEDSTOCK

2.1. BIOLOGY AND PROPERTIES OF ALGAE

Algae are eukaryotic[3] microorganisms, with most of them being photoautotrophs and found in aquatic ecosystems. Photoautotrophs grow with the uptake of carbon from atmospheric CO_2 and the conversion of sunlight into chemical energy through the process photosynthesis: $6CO_2 + 6H_2O$ + light energy → $C_6H_{12}O_6$ (sugars). Exception to this are certain heterotrophic algal species, which usually grow in the absence of light and utilising organic carbon substrates (e.g. glucose, acetate and fructose). Additionally, a group of mixotrophic algae exists that possess both phototrophic and heterotrophic metabolisms. The produced sugars play a vital role in sustaining life, as they are further metabolized to form biomolecules including carbohydrates, lipids, and proteins [3].

In general, algae can be classified according to their size into two main categories:

- Macroalgae: are multicellular forms that are found in marine environments (commonly called seaweeds)
- Microalgae: are tiny single-celled organisms that are found in both freshwater and marine environments.

In addition to their size, macro and micro algae are commonly classified based on their pigmentation, which is affected by their exposure to sunlight [3]. Specifically, seaweeds are classified into Rhodophyceae or red (living in warm shallow waters or cold deep waters), Phaeophyceae or brown (found in shallow and cold waters), and Chlorophyceae or green (found in bays, tide pools), with the latter being the majority. As for macroalgae, microalgae can be categorised into different types such as green Chlorophyceae (green), Cyanophyceae (blue-green, cyanobacteria, which are prokaryotic rather than eukaryotic), and Chrysophyceae (diatoms and golden-brown).

The class to which algae belong affects their molecular composition. Yet, it is important to note that even within the same class, distinct differences exist. Finally, seasons and climate play a significant role to the variation of their composition [3].

2.1.1. Chemical Composition

Figure 3 demonstrates the composition range of biomolecules found in macroalgae and microalgae. Upon closer look at the compositions, it is evident that there are significant differences between the two different groups of species. Specifically, macroalgae can be rich in carbohydrates, have high ash contents, and relatively lower concentration of lipids. The high carbohydrate levels coupled with the low presence of cellulose and lignin make seaweeds suitable resources for the production of ethanol/ butanol via alcoholic fermentation, a process traditionally applied for starches such as corn [8].

Table 1 lists some examples of different seaweeds and their carbohydrate levels that have been experimentally measured. Furthermore, a significant drawback of seaweed is their high ash composition, as their minerals cannot be utilised for biofuels production and constrain the performance of fermenters [9].

[3] **Eukaryote**, any cell or organism that possesses a clearly defined nucleus. Eukaryotic cells also contain organelles, including mitochondria (cellular energy exchangers), a Golgi apparatus (secretory device), an endoplasmic reticulum (a canal-like system of membranes within the cell), and lysosomes. (Eukaryote | Definition, Structure, & Facts | Britannica)

On the other hand, the metabolism of microalgae follows a different path that prioritises the production of proteins [3]. Furthermore, a significant portion of the overall biomass can be composed of lipids. It must be noted that the supply of nutrients in the culture plays a critical role for the final composition. For example, by subjecting certain species (such as *Chlorella vulgaris*) to growth conditions with limited nitrogen and phosphorus supply, the concentration of lipids can significantly increase [3],[10]. This is an important cultivation strategy as lipids can then be extracted and converted to biodiesel, or to renewable diesel in the same way HVO is produced. Table 2 lists examples of microalgal species that have been repeatedly tested for biofuel production. Species such as *Chlorella, Dunaliella and Nannochloropsis* have been widely studied due to their potential for a high oil content. It should be noted that for some species, a wide range of possible lipid compositions has been found. This is a result of seasonal variations and growth under nitrogen-starving conditions which can significantly increase lipid concentration.

Figure 3. Box charts of biochemical composition (carbohydrates, proteins and lipids) in A) macroalgae, B) microalgae [**11**]

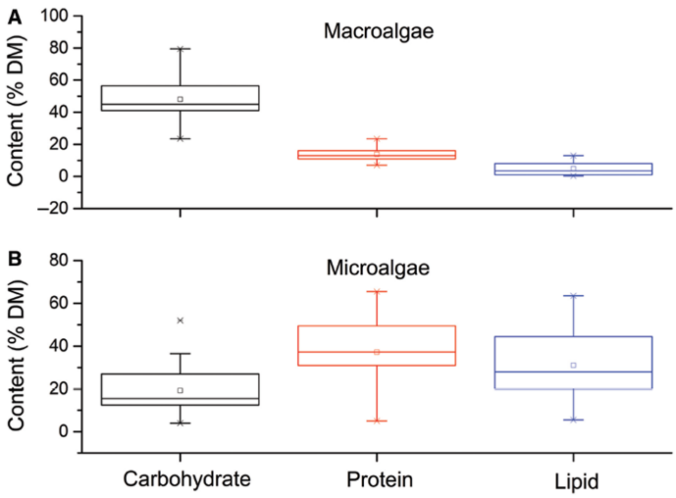


Table 1. Examples of macroalgae (seaweed) species used in different experiments for ethanol production

Seaweed species	Carbohydrates wt_{DM}%	Reference
Brown Seaweed		
Sargassum horneri	58%	[12]
Sargassum spp.	21%	[13]
Laminaria digitata	63%	[14]
Saccharina japonica	66%	[15]
Laminaria digitata	52%	[16]
Green Seaweed		
Ulva lactuca	20-24%	[17], [18]
Chaetomorpha linum	51%	[19]
Ulva intestinalis	25%	[20]
Red Seaweed		
Gelidium amansii	52%	[21]
Gracilaria verrucosa	42%	[22]

Table 2. Examples of microalgae species with high lipid content [23]

Species	Lipids wt_{DM}%
Scenedesmus obliquus	11-55%
Euglena gracilis	14-20%
Chlorella photothecoides	15-58%
Chlorococcum sp.	19%
Chlorella vulgaris	5-58%
Phaeodactylum tricornutum	18-57%
Dunaliella sp.	17-67%
Nannochloropsis spp.	20-56%

2.1.2. Water Content

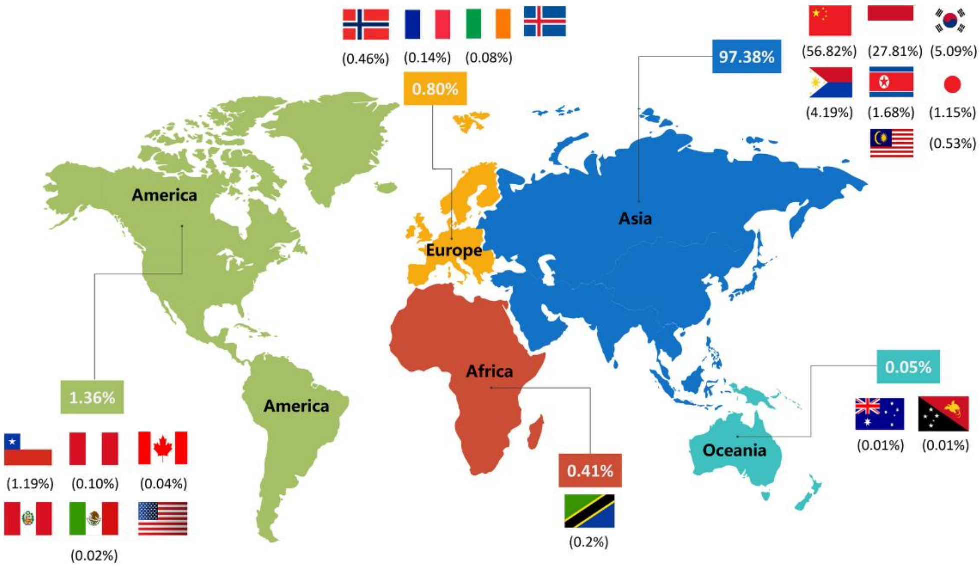
The water content of a biofeedstock is a significant property for logistics and the efficient operation of several conversion processes (i.e., thermochemical). High moisture levels can cause degradation during storage and inefficient conversion to fuels. Conversely, removing large amounts of water requires energy-intensive drying methods which can have negative economic implications. Algae, being aquatic organisms, naturally contain a large amount of water: 70-90 wt% for macroalgae and 99.5 wt% for microalgae [3], [24]. These levels are in fact much higher than other advanced biofeedstocks like forest residues (e.g., 45 wt%) and cereal straw (e.g., 15 wt%), making the pretreatment of algae very expensive [25].

2.2. STATE OF THE ALGAE INDUSTRY

2.2.1. Global Production of Algae

According to the data released by the Food and Agriculture Organization (FAO) of the United Nations in 2021, the global seaweed production in 2019 amounted to 36 million metric tonnes (on a wet basis), with 81% coming from aquacultures [26]. Notably, the production of red and brown species dominates the industry as their components are utilised as sources of food, fertilisers, hydrocolloids, and animal feed [3], [27]. Asia stands at the forefront of the industry, accounting for 97% of the global production, as seaweeds are important for the region's culinary tradition and pharmaceutical sector.

Figure 4. Global seaweed production map for 2019 (the production share of continents and counties is displayed) [26]



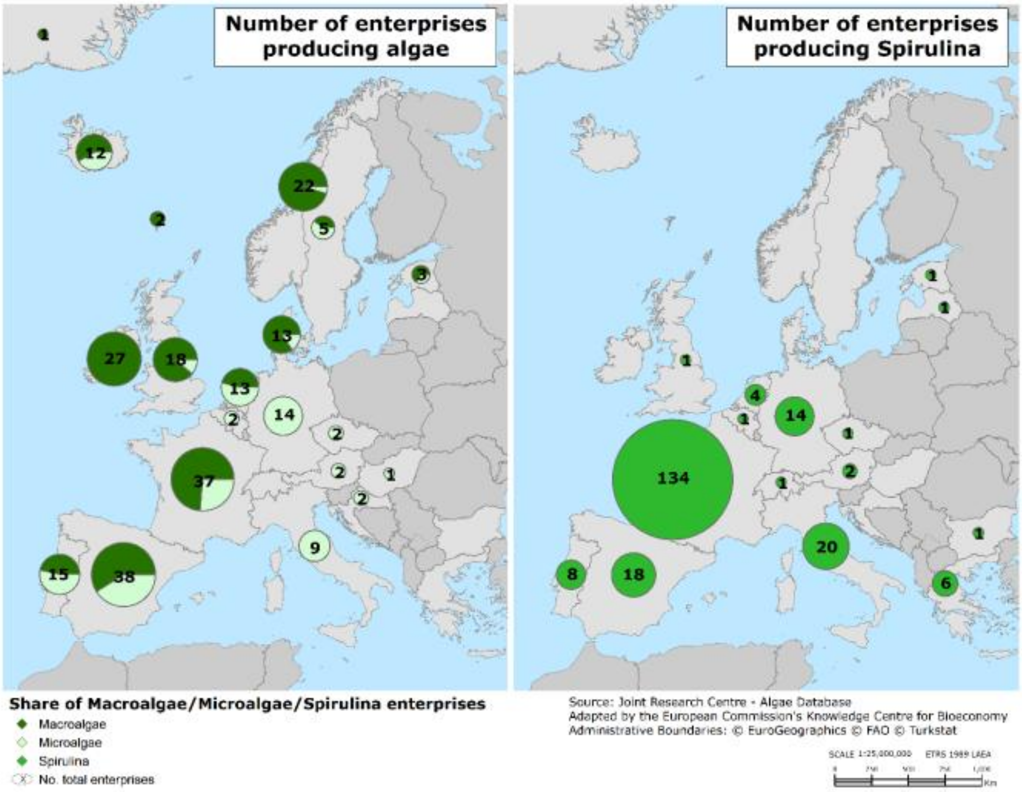
According to FAO, the production scale of microalgae is relatively small as it amounts to 56.5 kt globally. China stands as the leading producer (97% of global production). However, almost none of these quantities is currently used for biofuel production. It should be noted that in the microalgae accounting, spirulina is included [26]. From a biology perspective, spirulina belongs to the family of cyanobacteria, but they are frequently defined, from the industry and consumer perspective, as "microalgae" (e.g. "Algae and Algae Products-Terms and Definitions". CEN/TC 454 - Algae and Algae Products. European Committee for Standardization") [28].

2.2.2. State of Industry in Europe

Due to the small production volumes of algae compared to other bio-feedstocks, there are currently no national obligations requiring the collection and reporting of relevant data. Especially for the production facilities of microalgae in Europe, data availability is claimed to be scarce and sometimes challenging to access [28]. For this purpose, the Joint Research Centre (JRC) launched a study in 2020 to fulfil these gaps by gathering and revising relevant information provided by the European Algae Biomass Association (EABA) and other sources. The findings of this study were visualised and made available through the European Marine Observation and Data Network (EMODnet) Human Activities Portal.

Based on the results from JRC (see Figure 5), macroalgae production accounts for 67% of the total, while microalgae make up the remaining 33%. The primary production centres for macroalgae are located in North and Western European countries, such as Ireland, France, Spain, and Norway, with facilities extending along the Atlantic coastal region. Several of these facilities have roots in family-run operations, aiming at the production of seaweed for food, feed and fertilisers [28]. Concerning the microalgae and spirulina production landscape, this is concentrated in the inland of Europe, with France, Spain and Germany emerging as the leading producers [28].

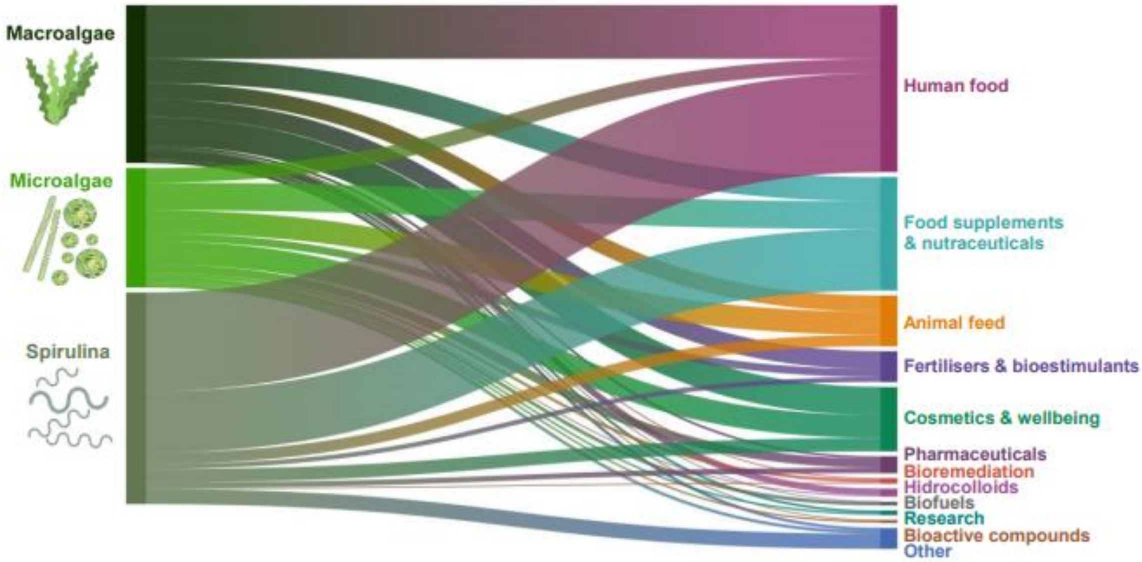
Figure 5. Macro, microalgae and spirulina production facilities in Europe [28]



2.2.3. Applications for Algae in Europe

The flows of the produced macroalgae and microalgae to the different industries in Europe have been identified and reported by JRC, as depicted in Figure 6. It should be noted that the illustrated flows represent the number of European algae-producing companies in Europe selling their products to the different industries, and not the actual volumetric flows. Seaweeds, with their high nutritional value (rich in proteins, low lipid levels), find primary application in the food and food supplements sector as well as in animal feed. Additionally to the food industry, cosmetics is an important destination for the produced seaweed. Likewise, microalgae are primarily used in the food, feed and cosmetics sectors. The use of microalgae for biofuels has been a topic of extensive research in the last decades, however, the production for this purpose remains at experimental scale due to the associated economic challenges. The performance, bottlenecks, the potential development and improvement of these algae to biofuel pathways are some key aspects addressed in the following Chapters of this report.

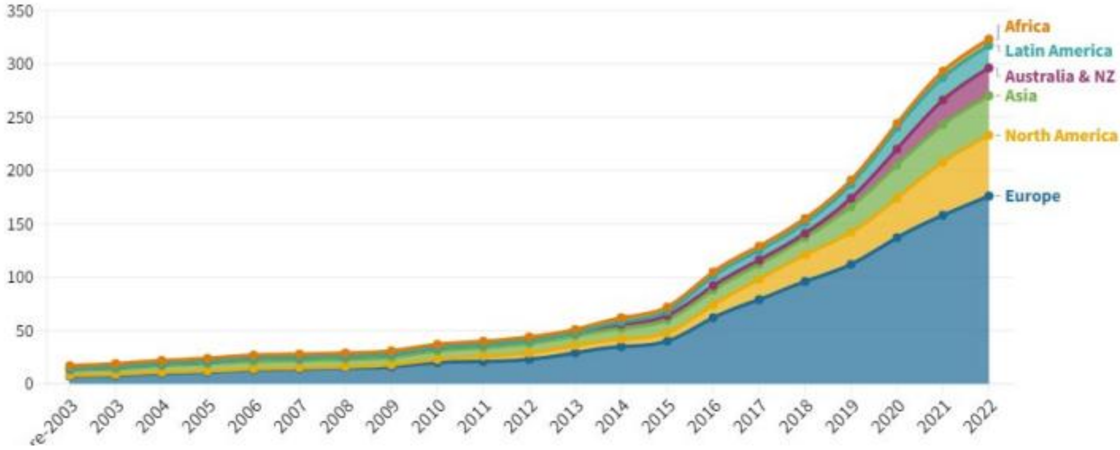
Figure 6. Flows of macro and micro algae to different applications in Europe. The illustration depicts the number of companies and not the volumetric flows [28]



2.2.4. EU Algae Start-ups and Projects

Despite that the EU making up only 1% of the global algae production, the highest number of start-ups are found in Europe. Figure 7 shows the number of start-ups in the different continents over the last 20 years. A significant increase in the number of start-ups appears since 2015. Most of the start-ups work on the seaweed sector with France and Norway being the frontrunners in Europe [29].

Figure 7. Global development of algae start-ups by founding year, 2003 - 2022 (for all applications) [29]



Despite the increase in the number of start-ups, the opposite trend is observed for projects or initiatives focusing on algae to biofuel pathways. Although numerous EU projects conducted on the production of algal biofuels over the 2010-2019 period such as FUEL4ME (2013-2016, microalgae to biofuels), DEMA (2012-2017, microalgae to ethanol), BIOFAT (2011-2015, microalgae to biodiesel), MacroFuels (2016-2019, seaweed to butanol/ethanol), INTESUSAL (microalgae to biodiesel), currently, to our knowledge, to our knowledge, only two projects are running at EU level, named FUELGAE and SusAlgaeFuel. FUELGAE focuses on the development of microalgae strains and the production of biofuels through hydrothermal processing and fermentation while SusAlgaeFuel aims at producing sustainable aviation fuel (SAF) from microalgae. Both projects target a pilot-scale demonstration. The poor economic performance of these pathways has been the main factor for discouraging further research efforts and investments in scaling up these technologies. All the existing projects now focus on the efficient and sustainable production of algae, with a strong emphasis on their use in sectors like food, feed, and cosmetics. If the inefficiencies of algae to biofuel route can be addressed, this can support the development of the industry in the future as the EU Commission targets within the coming years (see section 3.2.5.) to support large-scale algae farming initiatives and address algae to biofuel challenges.

2.2.5. EU Algae Initiative

In November 2022, the EU Commission finalised and made public the **EU Algae Initiative** communication which sets out actions for increasing the sustainable and safe production of algae towards bio-based products in Europe. The objective is to help to harness the untapped potential of algae as part of the Blue Bioeconomy and contribute to the targets of the European Green Deal. The communication describes the benefits of growing the algae sector, and acknowledges in parallel the challenges for its realisation. To tackle the challenges, the communication proposes a plan consisting of four overarching aims and a total of 23 actions. A progress report regarding the implementation of the proposed actions was announced for the end of 2027 [29].

The contribution of algae to food security by providing an alternative plant-based source of protein, the regeneration of oceans and seas by removing excess nutrients and preventing eutrophication, and the removal of carbon from the atmosphere are some of the most important benefits mentioned in the Commission's communication. However, there are several bottlenecks that prevent the algae industry from growing. One of the major issues is the substantial difference in licensing procedures and integration of seaweeds into Marine Spatial Planning (MSP). Currently, there is no uniformity among Member States in licensing, therefore, the process is reliant on national marine spatial planning procedures. Other important challenges are the current low production levels, the low consumer awareness of algae-based products, as well as the knowledge gaps on production techniques and environmental impact [29].

To address the challenges, the EU Commission proposed the following four aims:

- Aim 1: Improving the governance framework and legislation.
- Aim 2: Improving the business environment.
- Aim 3: Closing knowledge, research, technological and innovation gaps.
- Aim 4: Increasing social awareness and market acceptance of algae and algae-based products in the EU.

The aims are supported by 23 actions. Many of the actions focus on enabling the scale-up of algae farming, better understanding and standardising the ingredients contained in algae and facilitating partnerships between Members States. Concerning biofuels production from algae, the following actions are stated:

- Action 4: Development of algae biofuel standards and certification
- Action 19: Address algae biofuel specific challenges

3. TECHNOLOGIES FOR ALGAE PRODUCTION (UPSTREAM)

3.1. UPSTREAM TECHNOLOGIES FOR MACROALGAE

3.1.1. Seaweed Production and Harvesting

Seaweed can be harvested directly from wild stocks or produced in aquacultures. In contrast to the global trend, wild stocks currently comprise the primary source of seaweed in Europe, making up 68% of seaweed production [28]. The traditional manual harvesting of wild stocks involves using trawls. For instance, in Norway, trawlers have been reported to harvest 50-150 tonnes of seaweed per day [30], [31]. Mechanical harvesting is an alternative method offering faster removals making it more suitable for large seaweed (e.g. kelps and wracks) or seaweed living in deep sea beds. It is important to note, however, that mechanical operations come with higher costs. After a yearlong harvesting period, a 4 or 5-years period is always left to provide enough time for the marine plantation to regenerate. While mechanical methods have their benefits, they may have undesired impacts on other marine structures and overharvesting can lead to biodiversity losses as it has already been indicated for some regions [30], [31]. It is important to note that the current definition of eligible feedstocks in Annex IX of the Renewable Energy Directive (RED) specifically excludes macroalgae harvested directly from the sea, focusing instead on algae cultivated in systems such as ponds and photobioreactors[4]. However, since the revision of Annex IX is an ongoing process, this report encompasses all methods of algae production and harvesting to provide a comprehensive overview.

Figure 8. Wild seaweed harvesting via trawls [32]

In response to increasing environmental concerns concerning wild stocks overharvesting, aquacultures are promoted as an alternative solution. In fact, Norway has employed a national strategy that aims at the promotion of sustainable seaweed farming which has led the country to possess the most seaweed aquacultures in Europe [31]. However, in Norway as well as in other European countries, only a part of the aquaculture units has obtained an operation permit. As a result, large-scale cultivation of seaweed has not become a reality yet.

Seaweed can be cultivated in offshore, near shore and land-based farms, with near-shore systems being the most common due to their simplicity and low labour costs [33]. However, the competition for these areas with other economic activities (e.g. tourism, fishing), coupled with rising upper pelagic ocean temperatures, is expected to change the dynamics between the different farming methods [33]. However, for

[4] Definition in RED – Annex IX: Algae if cultivated on land in ponds or photobioreactors

large scale offshore, systems, there are still challenges to be addressed. For example, apart from the difficulty in accessing farms, colonization of other organisms in the farms must be prevented, and negative impacts on the biodiversity of oceans (i.e. interference in migration routes, entanglement due to infrastructure, disruption of nutrients balance) must be avoided [33]. For land-based systems, tanks are used, which allow for better control of conditions and biochemical processes. However, this comes at higher costs, restricting their use to high-value (food uses) applications [33].

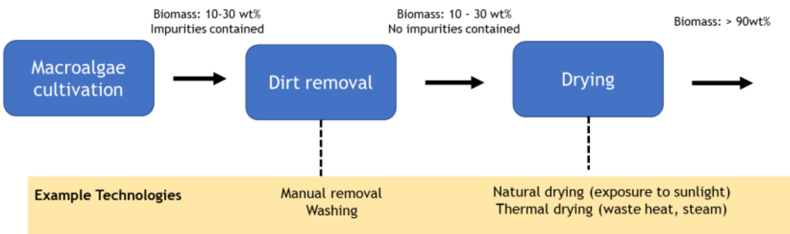
Figure 9. Rows of seaweed in a farm [34]

When considering the growth rates of algae, there are numerous factors that affect it including the particular species, location, salinity, and climate. It is reported that the average growth yield of macroalgae produced in onshore farms is usually lower than 16 g m^{-2} d^{-1} [11]. However, when cultivated in tanks, the yield can significantly increase typically up to 30 g m^{-2} d^{-1} with some species such as Ulva to be able to reach productivity levels of 38 g m^{-2} d^{-1} [11]. Looking at the growth potential of all the different advanced biofeedstocks that can be mobilised to produce biofuels, seaweed seems to have an advantage. For example, Miscanthus, one of the most widely considered lignocellulosic energy crops, is reported to grow at a significantly lower rate (with 1.5 up to 6 g m^{-2} d^{-1} being a representative range) [35] [36].

3.1.2. Macroalgae Pretreatment

Harvested seaweed contains large amounts of water (70-90 wt%) and many other solid objects such as stones, and debris. Before further processing or transportation, all this dirt and usually a significant amount of water needs to be removed. Figure 10 gives an overview of these pre-treatment steps, with more information to be given below. Although drying can be important for logistical and storage reasons, technologies such as fermentation to alcohols, can process macroalgae with high water levels.

Figure 10. Overview of the different seaweed preparation processes that can be applied



- Dirt removal

Prior to any processing, all dirt found in harvested seaweed needs to be removed. This can be done either manually or more quickly via water washing. This treatment step is not expected to cause considerable changes in the material properties, only with some small increases in the moisture levels (by 4%) and a drop in the ash concentration (by 6%). No effect on the following processing stages is reported [37].

- Water removal and storage

Reducing water content in seaweed (from 80-90 wt% to 20-30 wt%) is important when it comes to transportation and storage, as high levels of moisture can lead to degradation in storage and excessively high logistical costs [3]. This can be carried out either naturally or via thermal drying. The natural method involves solar drying, an inexpensive method but comes with challenges such as, land space requirements potential material degradation due to excessive radiation, and odour issues. It may also cause the loss of sugars in the removed water lowering the carbohydrates content [38]. Furthermore, natural drying cannot be practical in every place, like Northern Europe. Thermal drying, on the other hand, needs a heat source, which in an integrated aquaculture with a biorefinery, could be ideally provided in the form of waste heat from boilers or other exothermic processes.

Even after reducing the amount of water, long storage can lead to microbial fermentation and consumption of sugars. To address this issue, experiments have been conducted to find ways to maintain optimal sugar levels, which is crucial for the efficient functioning of bioethanol/biobutanol fermenters. Storing seaweed under acidic conditions has been proposed as an efficient and inexpensive solution. More specifically, storage of brown algae in sulphuric and formic acid solutions ($pH<4$) has been tested for over 6.5 months storage time, and no carbohydrate losses were observed [39].

3.2. UPSTREAM TECHNOLOGIES FOR MICROALGAE

Microalgae are cultivated in open or closed reactor configurations. Among the open cultivation systems frequently employed are open ponds, and closed tanks. On the other hand, closed systems are biochemical reactors such as, tubular reactors, bubble columns and flat plates, engineered to deliver high production yields.

In 1970, countries in Eastern Europe, Israel and Japan embarked on the commercial production of microalgal species in open ponds for food end-products [40]. Over the course of the last decades, open ponds remain the most widely used technology for microalgae production due to their lower investment costs [41], [42]. To avoid operational challenges linked to open systems such as the contamination of culture, research has been directed towards the advancement and scale-up of closed photobioreactors.

This section presents the operating parameters and conditions that are important for the growth of microalgae. Furthermore, an overview of the different reactor technologies is given and their characteristics and bottlenecks are highlighted. Finally, the pretreatment technologies that can be used to remove water and bring biomass to the required specifications for transport and conversion are discussed.

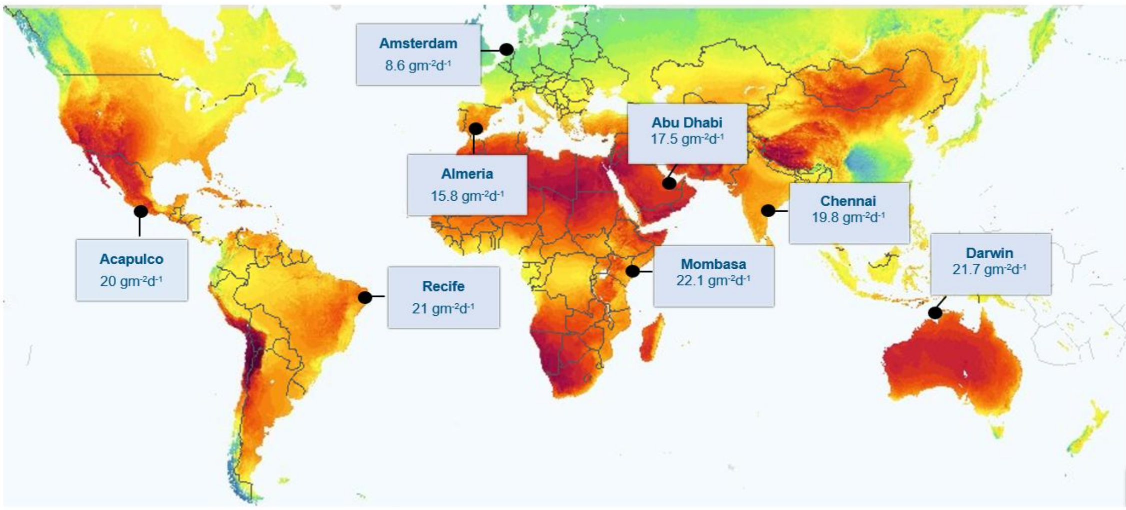
3.2.1. Microalgae Cultivation: Operating conditions

The growth rate and specifications of microalgal biomass are strongly affected by operating parameters such as light availability, temperature, pH, nutrients concentration, sterility and flow regime. For this reason, these parameters need to be carefully considered.

- Light Availability

Light availability is of utmost importance when it comes to the growth of microalgae. The light reaching the reactor is usually measured with the average irradiance variable, the order of magnitude of which can be up to 2000 μE/(m^2s) [10]. In general, the higher the energy inflow via light, the faster microalgae will grow. This is why open pond systems are traditionally installed in regions abundant in sunlight such as the southern regions of the United States, Central Africa and Australia and productivity reaches its peak during summer. However, it must be noted that excessive exposure to light (above 500 μE/(m^2s) can harm the cultivation of most species [10], [43]. The map in Figure 11 was generated via simulations by Roles et al. and shows a theoretical productivity distribution worldwide.

Figure 11. Global solar radiation map and microalgae productivity in specific locations based on simulations. Maximum productivity approximates 22 g/(m^2-d) [44]



- Temperature

The optimal temperature range for most species is between 20-35 ⁰C, with a few exceptions of mesophilic species that can grow in temperatures as high as 40 ⁰C. Lower or higher temperatures can significantly inhibit productivity. Due to irradiance, temperature elevation is expected if no actions are taken. Controlling temperature in closed systems is easily accomplished as cold air can be supplied around the photobioreactor. Water spraying or heat exchangers can prevent overheating in large outdoor ponds [43].

- pH

Similar to temperature, an optimal pH exists for all the species, usually falling within the slightly alkaline environment range (pH = 7-10). Any deviation from this range has a negative effect on productivity. In addition, pH is essential for the absorption efficiency of supplied CO_2, which is the primary nutrient for growth [43].

- Supply of Nutrients and carbon fixation

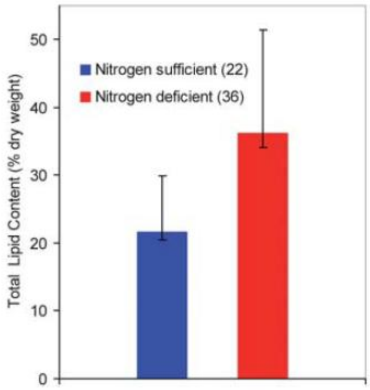
Carbon fixation:
Over the years, various carbon sources have been explored for use in cultivation systems, including acetate and glucose for heterotrophic cultivation and carbon dioxide (CO_2) for autotrophic cultivation. Among these, autotrophic cultivation has been the most extensively studied and favoured, primarily due to its greenhouse gas (GHG) reduction benefits [3]. Capturing CO_2 from flue gas can also serve as a carbon sequestration solution for hard-to-abate sectors.

While autotrophic cultivation can face productivity challenges in low-light conditions, heterotrophic systems offer more reliable biomass yields and higher lipid concentrations. However, heterotrophic cultivation is also more susceptible to contamination by other microorganisms, has higher operating costs, and provides a lower environmental benefit. These factors have made it a less favourable option for biofuel production [3].

For microorganisms to utilize CO_2, it must first dissolve in the aqueous phase, undergo hydrolysis to carbonate and bicarbonate, and then be transported to algal cells. However, CO_2 solubility is thermodynamically limited, meaning that only a fraction of the supplied CO_2 is ultimately dissolved and available for biological uptake. Concerning CO_2 fixation, researchers claim that the capture potential of microalgae can be 10-50 times higher than that of terrestrial plants [45]. The efficiency of CO_2 capture varies, ranging from 40% to 90%, depending on factors such as the species used, the cultivation conditions, and the CO_2 concentration in the flue gas. For example, Doucha et al. measured that in a 55 m^2 outdoor pond with Chlorella sp., up to 50% of CO_2 in the flue gas was removed. Herzog and Golomb estimated that in a 1457 ha open pond, 80% of the CO_2 initially contained in the waste flue gas from a natural gas-fired power plant can be captured [46], [47], [48]. If open ponds were to replace a conventional post-combustion CO_2 absorption unit of 100 kta capture capacity, assuming a microalgae productivity of 55 t ha^{-1} (= 15 g m^{-2} d^{-1}) with 50% carbon content as reasonable estimations according to the literature data, then 1000 ha of land would be needed [49]. To visualise the scale of this, it is approximately equivalent to one third of the City of Brussels, making the substantial space requirement for the construction of such facilities easily understood.

Nitrogen (N_2):
Nitrogen can be supplied as urea, nitrate or ammonium because most microalgae cannot uptake atmospheric N_2. For all these substances, careful control of their concentration is required as after a threshold, they can become toxic and inhibit biomass growth (e.g., > 100 mg/L for ammonium) [43]. Nitrogen starvation has been experimentally proven to trigger lipids or carbohydrate accumulation (see Figure 12). A spike in the concentration of lipids (about 50-60%) is observed only for specific species, as carbohydrate levels are the molecules usually increased for most species [43]. Although lipid increase is favourable for biodiesel and renewable diesel production, usually this comes at the expense of lower biomass productivities [4], [50].

Figure 12. The effect of nitrogen limitation on the lipid content of eukaryotic algae. The values in parenthesis are number of observations from which the mean value was derived. The upper error bar is the standard deviation, the lower the standard error [50]



Other nutrients:
Phosphorus (P) is important for the growth of microorganisms, usually supplied as phosphate (10 to 100 mg/L) [43].

- Sterility

Keeping sterile growth conditions in open photobioreactors can be a challenging but critical task, especially when the products are directed to the food industry. Contamination can be caused by bacteria, viruses, fungi, and protozoa. Usually, this is tackled by running open ponds in batches and not continuously. In addition, if the cultivated microalgae can sustain it, an alkaline (pH = 9-11) or very saline environment can be created [40].

- Mixing

Mixing is important to ensure good distribution of nutrients, keep cells in suspension, eliminate thermal stratification and reduce photoinhibition. For this purpose, in open ponds, a turbulent flow is created using paddlewheels. On the other hand, in tubular photobioreactors, airlift is usually applied to enhance mixing. Mixing in photobioreactors can be very energy consuming accounting for a significant share of the operating costs [43].

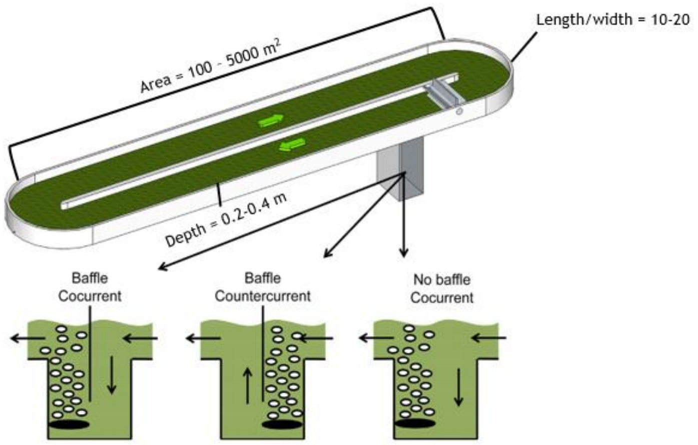
3.2.2. Microalgae Cultivation: Reactor Technology

Microalgae production can be carried in two different systems: open pond (i.e., raceway) reactors and closed (tubular, flat plate designs) photobioreactors. Below, the different reactor types are presented.

- Open ponds (Raceway)

Raceway is the simplest and most commonly employed open pond reactor design in the industry due to its lower investment cost compared to the other alternatives (0.08 M€/ha for a multi-pond system, 2000 ha in total) [51]. The biomass concentration is usually adjusted at 0.5 g/L to facilitate light penetration, but on the other hand, this low concentration poses challenges during the harvesting process [43]. According to different literature sources, the state of art annual average biomass productivity goes up to 18.6 g m^{-2} d^{-1} (based on experimental trials in open ponds at AzCATI) [52]. The exact production rate depends on different parameters such as the cultivated species, the operating conditions and the supply of nutrients. The standard dimensions of a single raceway reactor reported in the literature are illustrated in Figure 13. For large scale facilities, a series of ponds are installed.

Figure 13. Illustration of a single raceway reactor. The indicative dimensions of the reactor are given in the Figure [43]

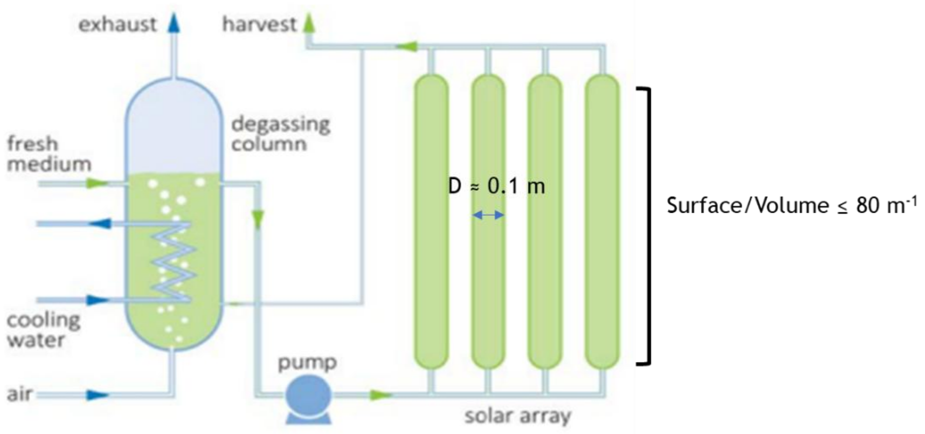


Another important consideration in the design of these open reactors is how to maximise the mass transfer of CO_2 and O_2. Specifically, the design strategy must ensure CO_2 supply and O_2 removal rates that keep microalgae at their maximum growth rate. If the O_2 removal rate is lower than the optimum, then, O_2 accumulates and degradation reactions occur. If the CO_2 supply rate is lower, mass transfer becomes the rate limiting step, preventing maximum growth. To maximise CO_2 and liquid contact time, a sump is used and CO_2 is supplied from the outer side of it [43].

- Closed Tubular Photobioreactors

This is the most common closed reactor design employed in the industry. These reactors are composed of very thin tubes (diameter ~ 0.1 m), designed to provide optimal light regime and fast growth. In addition, due to their structure, they allow high biomass productivity 12-38 g m^{-2} d^{-1} [51]. The reactor unit is always divided into two subunits: 1) the photosynthesis loop, 2) mixing (retention). In the former, photosynthesis, microalgae growth and biochemical reactions take place, while in the mixing tank, the produced O_2 from photosynthesis is degassed. In the reaction tubes, microalgae are circulated using pumping or airlift equipment.

Figure 14. Illustration of a simple tubular photobioreactor configuration. Indicative dimensions of the reactor are depicted [43]



The reported power consumption ranges between 10-100 W/m^2, being 10 to 100 times higher than what is applied to the open ponds. The liquid velocity is kept within 0.1-0.8 m/s. Higher velocities should be avoided, otherwise, the process becomes more energy-costly and cell damage may occur [43].

Concerning the liquid-gas separation vessel, it is designed in such a way as to maximise O_2 removal rates. Oxygen is removed with the flow of air. The same principles elaborated for CO_2 supply in raceway reactors apply in this case as well, as sufficient CO_2 supply is needed to avoid growth inhibition.

In general, tubular reactors can be subdivided into different groups: 1) serpentine, 2) manifold, and 3) helical. These different designs follow the same principles discussed above. As the tubes can be very long, all these reactors are very compact designs aiming at minimising space requirements. Serpentine is the oldest applied type resembling the structure of U-tube heat exchangers and reaching lengths up to 400 m per unit [43]. For manifold, parallel tubes are connected at the end by manifolds. Manifold type is characterized by reduced mass transfer but lower head losses (and power consumption) and O_2 concentrations in the liquid.

Concluding, tubular photobioreactors can deliver high quality biomass, but with a high cost (an indicative estimation 0.1 M€/ha for horizontal tube design of a 2100 ha scale) [51]. For this reason, these designs are usually favoured for producing high-value end products.

Figure 15. A) serpentine, and B) manifold photobioreactor designs being used for microalgae production [43]

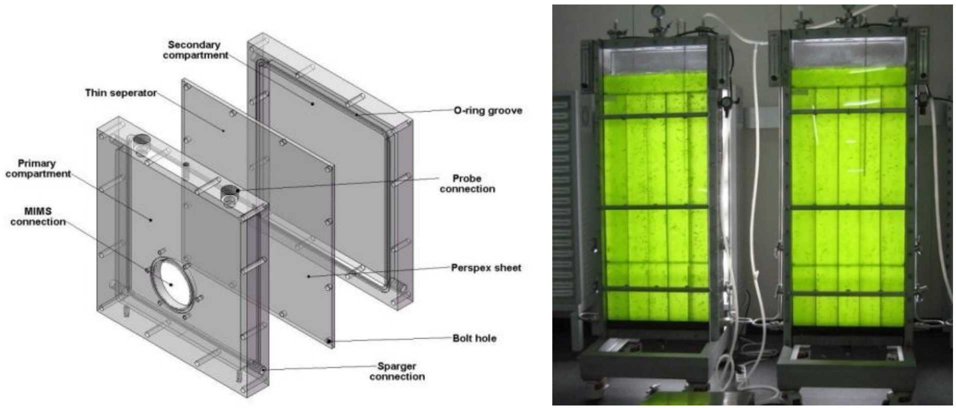
A. B.

- Closed Flat-Plate Photobioreactors

Flat-plate photobioreactors are manufactured with transparent materials that effectively enhance exposure to light, resulting in very high biomass productivities (reported range: 20-40 g m^{-2} d^{-1}) [51]. The fundamental design principle incorporates two parallel panels with a thin layer in between in which cells are suspended. This simple design makes it easy to scale them up (put many of them in parallel or increase liquid height). Mixing between the plates is pump driven. Separation of O_2 and supply of CO_2 can be carried out either in a separate gas exchange unit or in the reactor itself. Finally, their orientation to the sun can be easily adjusted maximising the amount of radiant energy reaching the panels [43].

A constraint that has been observed in these reactors is that due to their shape, high temperature spots are formed. As a result, a dedicated cooling system needs to be installed. Furthermore, scaling up this design can be expensive (indicative investment → 1.3 M€/ha for a 1000 ha scale), and in many cases, fouling on the walls and cells damage caused by hydrodynamic stresses have been reported [51].

Figure 16. Illustration and picture of a flat-plate photobioreactor [53], (DOGA Limited)



3.2.3. Harvesting and Pretreatment

Once microalgae have reached the stationary growth phase (very slow growth), they need to be removed from the water medium where they are suspended. Typically, solids concentration is very low, ranging from 0.05 wt% (0.5 g/L) in open ponds to 0.3-0.4 wt% in closed photobioreactors [43]. This means that a large amount of water needs to be removed before transport, storage or processing.

Different solid-liquid separation technologies can be used for water removal. First, the cultivation product stream is usually thickened to a concentration of solids equal to 6-10 wt%. This can be achieved with a single or a combination of different processes. Properties such as the size, shape, hydrophobicity and electric charge of microalgae play a crucial role in the process selection and design. Even after thickening, the final product still contains a significant amount of water and further dewatering to a concentration of solids of 20 wt% is needed before biomass storage or processing [3], [42].

Figure 17 gives an overview of the different thickening/dewatering technologies. Their strengths and weakness are summarised in Table 3. In commercial plants targeting high-value end products, centrifugation is the process typically used. However, this is an energy intensive process, the use of which creates economic challenges in pathways with low priced end-products (e.g., biofuels) [3]. As different microalgae have different characteristics, there is not a fit for all solution, and the process must be carefully chosen based on the species that are cultivated.

As large amounts of water are used in reactors which are then removed, it is important to recycle them back to the reactor and minimise water consumption. Therefore, downstream processing is essential to target high solid recovery efficiency and not interfere with or degrade water quality (e.g., use of chemical additives).

Figure 17. Overview of the most common dewatering technologies reported in the literature [43], [54], [55], [56], [57]

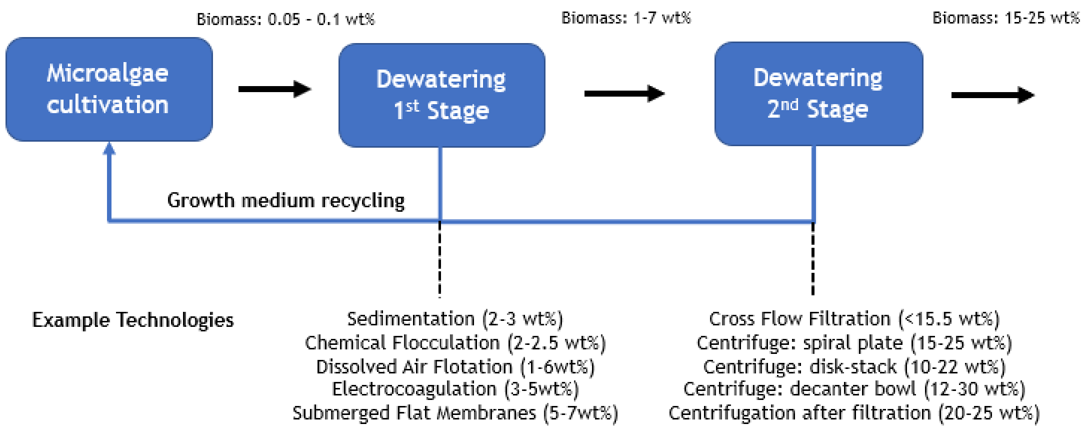


Table 3. Strengths and weaknesses of technologies used for dewatering of harvested microalgae [3], [43], [54], [55]

Technologies	Strengths	Weaknesses
	Flocculation	
Chemical flocculation	Low energy demand Low equipment costs	Difficult recovery of chemicals High chemical costs Biomass contamination (potential)
Electrocoagulation	High biomass recovery No chemicals required opposite to chemical flocculation Non-species specific	Limited application: more suitable to marine water microalgae Regular maintenance and replacement of electrodes High equipment costs Low TRL, not fully investigated
	Gravity-based	
Sedimentation	Easy application Low energy demand	Slow process → biomass deterioration, large equipment Low biomass recovery (it is recommended as a concentration step after flocculation) Limited application → suitable only for a few large strains (> 20 μm)
Air Flotation	Low energy demand compared to other technologies	Low biomass recovery (often implemented after flocculation) Limited application: suitable to small and hydrophobic microalgae (easier attached to air bubbles) High power consumption (pressurize air)
Centrifugation	Efficient for large scale processing (commercially established) High recovery even within a single step Most widely used technology	High capital and operating costs making it only suitable for high value end products Risk of cell destruction
	Filtration	
Membranes	High biomass recovery Efficient for small scale processing Low water footprint (water recycling)	Fouling High capital costs

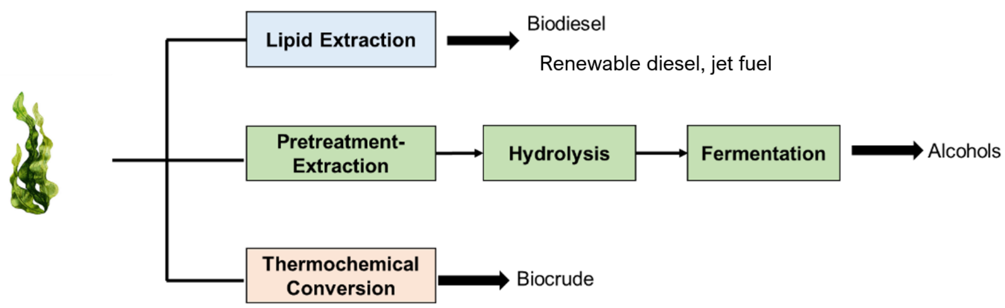
4. TECHNOLOGIES FOR BIOFUEL PRODUCTION FROM ALGAE

4.1. BIOFUELS FROM MACROALGAE

As discussed in the previous chapters, macroalgae are characterised by high carbohydrate concentrations, making them suitable feedstocks for bioethanol or biobutanol production via fermentation. The valorisation of seaweed for biofuel production is presently confined to experimental level due to the limited conversion efficiency of sugars to alcohols in the fermenter [58]. Figure 18 depicts the different macroalgae to biofuel routes. Complementary to the main route of ethanol/butanol production, lipid can be extracted and converted to diesel-like fuels. However, this pathway has not received the same attention, primarily due to the low lipid concentrations in macroalgae [4],[59].Thermochemical routes have been also given less priority due to the high moisture levels in the feedstock [4],[59].Hydrothermal processing could be an exception due to its ability to process wet feedstocks, however the research in this area is limited. For this reason, this report focuses on the more explored macroalgae to bioethanol pathway.

For the production of bioethanol in the fermenter, as applied for first generation and second generation biofeedstocks, prior to fermentation, chemical hydrolysis using acidic/alkali solvents is applied to break down cell walls, release polysaccharides and convert them into fermentable sugars. However, the typically low sugar yields in the hydrolysate stream, have recently led researchers to propose a two-stage approach where a pretreatment stage for the extraction of polysaccharides precedes the hydrolysis of polysaccharides to sugars.

Figure 18. Diagram of the different macroalgae to biofuel conversion pathways



4.1.1. Process Technologies: Macroalgae to Ethanol

4.1.1.1. Hydrolysis Process

Polysaccharides are structural and energy storage components found within the area limited by the cell walls and consist of the substrate for bioethanol production. A list of different polysaccharides and their sugar molecules (monosaccharides) found in green, red and brown macroalgae is given in Table 4. According to the literature, brown species have garnered most attention due to their higher carbohydrate content, and rapid growth rates [59], [60].

Table 4. List of polysaccharides and their reduced sugars in macroalgae [61]

Macroalgae type	Polysaccharides	Sugars
Green	ulvan, starch, xylopyranose, glucopyranose, xyloglucan, glucuronan, cellulose, hemicellulose	glucose, xylose, uronic acids, rhamnose, galactose
Red	agar, carrageenan, agaropectin, cellulose, xylans, mannans	D-galactose, D-fructose, glucose, 3,6-anhydro-D-galactose
Brown	Fucoidan, laminaran, alginates, cellulose	mannitol, glucose, guluronate, mannuronate, glucuronate, sulphated fucose

Hydrolysis concerns the decomposition of cell walls, extraction and depolymerization of polysaccharides to their monomers – sugars. Compared to the resistant-to-degradation lignocellulosic biomass, the advantage of macroalgae is that carbohydrates are typically found in the form of polysaccharides and lignin content is minimal, hence less intense operating conditions in hydrolysis units are needed [24].

The conventional hydrolysis method is based on the use of strong acid/alkali catalysts which decompose cell walls, release polysaccharides and convert them to their sugars within a single stage. However, this process is usually characterized by intense operating conditions that may lead to partial degradation of constituent sugars and the formation of fermentation inhibitors such as hydroxymethylfurfural (HMF), furfural and levulinic acid [59]. In addition, to mitigate the environmental hazards associated with these chemical methods, costly detoxification processes need to be considered [59].

Sugar yields using chemical methods are reported to be limited to 60% (less than 60 g/L in the hydrolysate), restrictive results for the scale up of these technologies [62]. In order to enhance sugar yields in the hydrolysate stream, coupling hydrolysis with a preceding pretreatment process step targeting at the extraction of polysaccharides has been suggested in studies. The hydrolysis agent can be an acid, but in the most recent studies, enzyme-assisted hydrolysis has been proposed as a green alternative to chemical treatments. Using enzymes for hydrolysis has also the potential to enhance sugar productivity. However, the slow biochemical reaction rates consist of a significant bottleneck for large scale applications as they entail high residence times, and high capital costs [24], [27].

An overview of indicative experimental results on the pretreatment and hydrolysis of macroalgae reported in the literature, is given in Table 5. In the most recent experimental studies, pretreatment with dilute sulfuric acid followed by enzymatic hydrolysis is employed.

Table 5. Yields of macroalgae hydrolysis as reported in different experimental studies available in the literature

Algae	Pretreatment process	Hydrolysis type	Yield	References
		Brown Seaweed		
Saccharina japonica	Dilute Acid: 40 mM H_2SO_4, T= 121 ºC	Enzyme: *Basilicus sp.*	69% of total carbohydrates	[59]
Saccharina latissima	-	Enzymatic hydrolysis	79% of glucose	[63]
Saccharina latissima	Thermal treatment after pressing	Enzymatic hydrolysis	89% of the total sugars	[64]
Sargassum spp.	Dilute Acid: 4% H_2SO_4 T = 115 ºC	Enzymatic hydrolysis	25.5% of total biomass	[59]
Sargassum muticum	Hydrothermal: T =130-180 ºC	Enzymatic hydrolysis	89-94% glucose	[24]
Laminaria japonica	Dilute acid: H2SO4 (0.02-0.14%) Temperature: (150-180 ˚C)	Enzymatic hydrolysis	83% glucose	[24]
Laminaria digitata	-	Acidic Hydrolysis: 5% H_2SO_4	65% for al sugars	[62]
Laminaria digitata	Dilute acid: 0.75 M H_2SO_4 , T= 121 ºC	Enzymatic hydrolysis	110-219 mg of glucose per g of biomass	[58]
Alaria crassifolia	Dilute acid: 2% H2SO4, T = 121 ºC	Enzymatic hydrolysis	28% glucose and 21% galactose	[59]
Eucheuma cottonii cellulosic residue	Dilute Acid: 1% w/v H_2SO_4 T= 120 ºC	Enzymatic hydrolysis	80-99.8% glucose	[24]
		Red Seaweed		
Gracilaria salicornia	Dilute Acid: 2% H_2SO_4 T= 120 ºC	Enzymatic hydrolysis	17.4 g glucose/ kg algae	[59]
Kappaphycus alvarezii	Dilute acid: 200 mM H_2SO_4, T= 120 ºC	Enzymatic hydrolysis	30% reducing sugar	[59]
Kappaphycus alvarezii	Dilute Acid: 1% H_2SO_4 T= 120 ºC	Enzymatic hydrolysis (cellulase)	81 g/L of sugars	[59]
Gelidium amansii	Dilute Acid: 4% H_2SO_4 T= 120 ºC	Enzymatic hydrolysis	69% glucose	[59]
Gelidium amansii	Ionic liquids T= 30-100 ºC	Enzymatic hydrolysis	33-56% galactose	[24]
D. carnosa	Auto-hydrolytical T = 121 ºC	Enzymatic hydrolysis	229 mg glucose/g biomass	[58]
		Green Seaweed		
Ulva lactuca	Dilute acid: H_2SO_4 T= 150 ºC	Enzymatic hydrolysis	75-93%	[59]
Ulva pertusa Kjellman	T= 150 ºC, P = 150 bar	Enzymatic hydrolysis	99% glucose	[59]
Zostera marina	Hydrothermal: T= 160 - 180 ºC, oxalic acid: 0-2wt%	Enzymatic hydrolysis	30-53% glucose	[24]
Ulva linza	-	Acidic Hydrolysis: 5% H_2SO_4 water	69% sugars	[62]

4.1.1.2. Fermentation for Alcohols Production

Following hydrolysis, the rich in fermentable sugars hydrolysate is fed to the anaerobic fermenter where sugars are converted to alcohols such as ethanol or butanol. On a property basis, butanol demonstrates benefits such as higher energy density and better blending with gasoline compared to ethanol. When butanol production is targeted, anaerobic bacteria are used, in a fermentation process that forms ethanol and acetone as co-products. However, ethanol is the most widely produced biofuel worldwide, with the pure form of it or blends with gasoline having been used in many regions such as Brazil, the EU and the US for years. Moreover, ethanol fermentation is more mature and efficient compared to butanol fermentation [24]. For this reason, the vast majority of experiments have focused on optimising bioconversion to ethanol.

Although ethanol production from macroalgae is claimed to be the pathway with the highest potential, its large-scale production is yet not economically viable. The main bottleneck concerns the inability of the well-known ethanologenic yeasts/ bacteria (e.g., *S. cerevisiae*) to metabolise all the different sugar molecules other than glucose. For example, brown seaweed, a favourable feedstock due to its higher polysaccharide concentration, contains sugars such as uronic acid (main constituent of alginate) which cannot be metabolised by *S. cerevisiae* [24]. Based on the experience with ethanol production plants, the rule of thumb for an economically feasible process is that ethanol concentration in the broth should be at least 4-5 (v/v) % to prevent excessive energy consumption in the subsequent ethanol-water distillation [58].

In Table 6, the results of different experimental studies targeting at the production of ethanol or butanol via the hydrolysis of seaweed and fermentation of hydrolysates are listed. Fermentation process can be designed to run either separately to saccharification (hydrolysis) (SHF) or simultaneously (SSF). Operating the two processes separately allows a better control and optimisation of the operating parameters. However, it has been shown that simultaneous operation reduces reaction time and prevents the accumulation of sugars that may inhibit microorganisms' growth [27]. As can be seen in the experimental results, the final ethanol concentration in most experiments falls below the economically recommended range. Moreover, although the largest part of macroalgae is formed by sugars, only a small part of the biomass is eventually converted to ethanol. This indicates the difficulty to metabolise seaweed sugars other than glucose.

To address these technical issues, in the recent years, the scientific community has been focusing on identifying and testing alternative bioprocessing strategies, such as the use of new yeasts with a more diverse metabolising potential of sugars, and the genetic engineering of conventional bacteria such as *S. cerevisiae* to enhance their resistance to hydrolysates inhibitors [24]. Because of the limited economic potential by focusing solely on ethanol production, promoting the cascading concept and valorising all the different products and by-products could potentially improve the economic outlook of biorefineries.

Table 6. Yields of macroalgae hydrolysis plus fermentation as reported in different experimental studies available in the literature

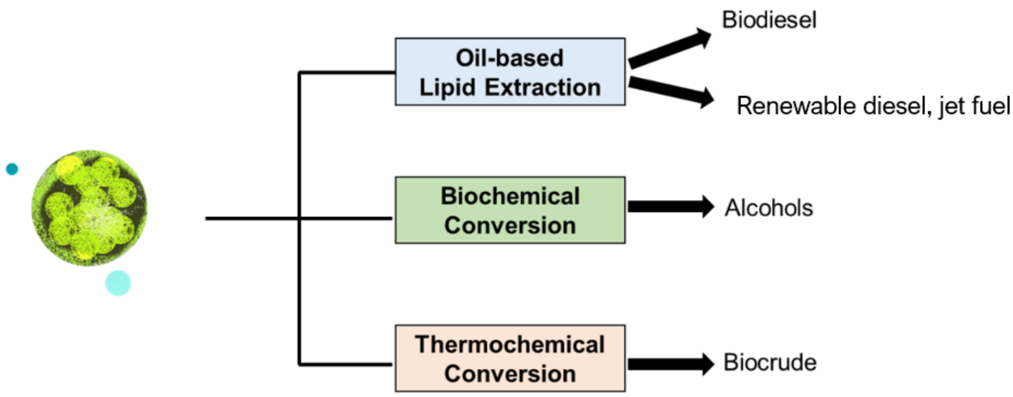
Algae	Pretreatment	Fermentation Method	Microorganism	Ethanol Concentration*	Conversion yield %**	References
			Brown Seaweed			
Saccharina japonica	Dilute Acid + Enzymatic hydrolysis	SSF	*P. angophorae KCTC 17574,*	0.8 v/v%	7.7 %	[59]
Saccharina japonica	Dilute Acid + Enzymatic hydrolysis	SSF	*S. cerevisiae (DK 410362)*	0.6 v/v%	14.3%	[59]
Alaria crassifolia Kjellman	Dilute acid + Enzymatic hydrolysis	SHF	*S. cerevisiae (IAM 4178)*	7 v/v%	22%	[59]
Sargassum spp.	Dilute acid + Enzymatic hydrolysis	SHF	*S. cerevisiae*	0.4 v/v%	2.79%	[59]
Laminaria japonica	-	SSF	*E. coli (ATCC8739)*	4.7 v/v%	28.1%	[59]
Laminaria japonica	Dilute Acid	SSF	*E. coli KO11*	3.0-3.7 v/v%	23-29%	[59]
Laminaria digitata	Dilute Acid + Enzymatic hydrolysis	SHF	*S. cerevisiae NCYC2592*	0.4 v/v%	2.2%	[58]
			Red Seaweed			
Gracilaria salicornia	Dilute acid + Enzymatic hydrolysis	SHF	*E. coli KO11*	0.2 v/v%	7.9%	[59]
Kappaphycus alvarezii	Dilute acid	SSF	*S. cerevisiae (CBS1782)*	8.4 v/v%	19%	[59]
Kappaphycus alvarezii	Dilute Acid	SHF	*S. cerevisiae*	0.4 v/v%	3.3%	[59]
Gracilaria verrucosa	Caustic solution + Enzymatic hydrolysis	SHF	S. cerevisiae (HAU strain)	1.9 v/v%	14.9%	[59]
Dilsea carnosa	Dilute Acid	SHF	S. cerevisiae NCYC2592	0.7 v/v%	1.5%	[58]
			Green Seaweed			
Ulva lactuca	Dilute acid + Enzymatic hydrolysis	SHF	*C. beijerinckii*	-	40% (ABE)	[59]
Ulva pertusa Kjellman	Hydrothermal+ Enzymatic	SHF	*S. cerevisiae (ATCC 24858)*	1.6 v/v%	12.4%	[59]
Ulva linza	Strong acid	SHF	*Wickerhamomyces anomalus M15*	6.2 v/v%	9.6 %	[62]
Chaetomorpha linum	Enzymatic hydrolysis	SSF	*S. cerevisiae (ATCC 96581)*	-	18%	[59]

* The results are presented in the form of volumetric concentration. For the conversion to this unit, ethanol density of 776 g/L was assumed (density at T = 35 ºC, with 35 ºC being an indicative fermentation temperature)
** Ethanol conversion yield = $kg_{EtOH}/kg_{biomass\ (dry)}$

4.2. BIOFUELS FROM MICROALGAE

Over the years, the scientific community has put forth different pathways for the conversion of microalgal biomass to biofuels, which could contribute to the decarbonisation of the transport sector. Among these pathways, the fermentation of sugars to alcohols, the thermochemical treatment (pyrolysis, gasification, hydrothermal liquefaction) of biomass to biocrude, the extraction and conversion of lipids to biodiesel, and the extraction followed by the hydrotreatment of lipids to drop-in fuels are the most extensively investigated approaches [3], [4], [65]. As discussed in the previous chapters, although producing biofuels via these routes has been a subject of research for a long period, their energetic and economic limitations have hindered their application on industrial scale.

Figure 19. Diagram of the different microalgae to biofuels conversion pathways



The extraction of lipids for the production of biodiesel (FAME) or renewable diesel and jet fuel has been the most explored and promising from the aforementioned pathways [3], [4]. High lipid concentrations in microalgae (≈ 15-60 wt%, see Table 2), have brought them into the foreground as an attractive alternative to traditional oil-based biofeedstocks such as animal fats and vegetable oils.

Concerning the rest of the pathways, ethanol is a fuel of less interest compared to oil-based and middle distillate biofuels, and its production via fermentation is less investigated and not as favourable due to the low levels of carbohydrates which some of them are not readily metabolised by most microorganisms [3], [66]. Hence it is not further explored as a standalone pathway in this report. However, it needs to be noted that producing ethanol could become more interesting in the future as it serves as a feedstock in the ethanol-to-jet fuel process. Regarding thermochemical processing, it does not take into advantage the lipid-rich nature of microalgae but instead converts the entire biomass into biocrude under high thermal stresses. This approach allows for the processing of algal biomass with a wider range of specifications. However, research on these processes is limited to hydrothermal liquefaction due to the ability of this technology to efficiently process wet feedstocks such as microalgae [4], [67]. Other thermochemical processes, such as pyrolysis and gasification, require a dry feedstock (< 15 wt% of water) and considering the large amount of water in the microalgal biomass, makes the application of these technologies energy inefficient and expensive [4], [68], [69]. The process yields of the different conversion to biofuel technologies are reported in the following sections.

4.2.1. Lipid Extraction based Pathways

4.2.1.1. Lipid Extraction Technologies

Lipid extraction from pretreated algal biomass consists of the first process step in the downstream operations of oil-based pathways. Apart from lipid content, lipid composition is another factor that needs to be considered. For instance, only neutral lipids, such as triacylglycerol (TAG), can be easily converted to biodiesel [70]. For this reason, lipid extraction must be selected and designed in a way that maximises the recovery of the lipids with the desired properties [70]. A list of indicative yields that have been experimentally measured for different extraction methods and reported in the literature is given in Table 7. At present, there is no standardised oil extraction technology tailored for algae. Below, the different lipid-extraction technologies are discussed.

- Organic Solvent Extraction

Using organic solvents is the most common lipid extraction process, and it has already been successfully employed for biofeedstocks like soybeans. Folch (chloroform: methanol, 2:1 v/v), Soxhlet (n-hexane) and Blingh and Dyer (chloroform: methanol, 1:2 v/v) are the most well-known organic solvent extraction methods [70]. Ideally, a nonpolar solvent targeting only the hydrophobic nonpolar lipids is needed. However, there is evidence that although more polar solvents do not have a high selectivity to the targeted lipids, they allow a more effective penetration of the cells, and a higher concentration of lipids in the extract [70]. Furthermore, water removal to a 50-98 wt% solid content prior to extraction favours the efficiency of the process but it comes with a considerable additional expense [70]. Another reported limitation is the slow extraction rate which can be accelerated by increasing the temperature at the expense of higher operating costs [70]. These economic drawbacks coupled with the moderate efficiencies (see Table 7) and the safety and environmental risks in the use of these chemicals have driven researchers to investigate alternative extraction methods [70].

- Supercritical (SC) Fluid Extraction

As an alternative to the extraction using chemicals, SC fluid extraction has been proposed and tested. Supplying inert components such as carbon dioxide (CO_2) at SC conditions can provide faster and higher extraction rates than organic solvents without the addition of any toxic or flammable chemicals. Both the nonoxidizing nature and low critical temperature of CO_2 allow the efficient removal of lipids without their degradation [70], [71]. Opposite to organic solvents, SC-CO_2 extraction is not sensitive to water, hence drying process and its costs can be avoided [71]. Despite these advantages, this process is reported to have a number of drawbacks that impede its industrial application such as the low solubility of polar lipids, the use of expensive equipment that are resistant to high-pressure environments, and the high energy input needed for condensing CO_2. Lastly, SC-CO_2 is nonpolar and in order to increase its affinity towards the medium-polarity lipids, the additional use of a polar solvent such as ethanol is recommended [70].

- Additional extraction methods

Other cutting-edge extraction methods that have been proposed as greener solutions are microwave-assisted, ultrasound-assisted extraction and ionic liquids. Cells are lysed by electromagnetic radiation in the case of microwaves and sound-induced vibration for ultrasound technology. Both methods have not been significantly explored and are usually suggested in synergy with a conventional method, but it is important to note that electromagnetic waves can generate high temperatures damaging thermosensitive products whereas ultrasound is a technology of low efficiency and high energy input [70]. Concerning ionic liquids, these are salt solutions that can be modified according to the composition of the used biofeedstock. However, more research on these extraction methods is needed [70].

Table 7. Experimental lipid yields for different extraction techniques as summarised in different publications

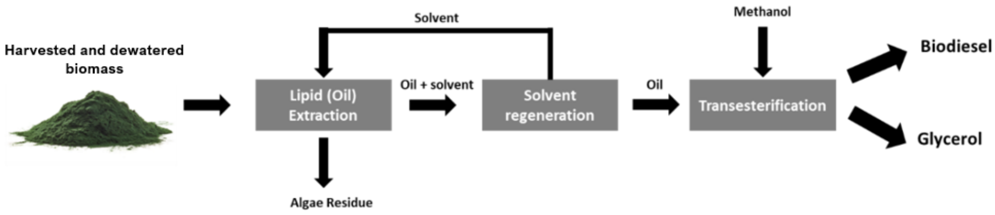
Extraction method	Solvent/Parameters	Biofeedstock	Lipid Yield* (wt%)	Reference
ORGANIC SOLVENTS	-	Dry biomass	5.0 %	[70]
	n- hexane, room temperature, ultrasonically shaken, 900 min	Dry biomass	13.5%	[70]
	n-hexane, 50 ºC	Wet biomass	4.0%	[70]
	Hexane, 25 ºC, 180 min	Dry biomass	4.0%	[70]
	Compressed hexane, 235 ºC, 31 bar, 5min	Dry biomass	16.3%	[70]
	n-hexane, bead beating + room temperature; ultrasonically shaken	Dry biomass	15.3%	[70]
	Chloroform: methanol (1:2), ultrasound pretreatment, 25 ºC, 10 min	Dry biomass	19.6 %	[70]
	Chloroform: methanol: water (1:1:0.9), 25 ºC, 120 min	Dry biomass	14.5%	[70]
	Chloroform: methanol (1:2), Ultrasound pretreatment, 25 ºC, 10 min	Dry biomass	28.6 %	[70]
	Ethanol, 1440 min	Dry biomass	6.3 %	
SUPERCRITICAL CO_2	50 ºC, 450 bar, 2 h	*Chlorella vulgaris* (dry)	3.1%	[72]
	50 ºC, 450 bar, 3.5 h, ethanol co-solvent	*Chlorella vulgaris* (dry)	24.2%	[72]
	50 ºC, 450 bar, 3.5 h,	*Nannochloropsis oculata* (dry)	33.1%	[72]
	Lysozyme treatment, 500 bar	Wet biomass	12.5%	[70]
	60 ºC, 306 bar	Dry biomass	10.4%	[70]
	65 ºC, 300 bar, 5% EtOH co-solvent	Dry biomass	18.1%	[70]

* Lipid yield: (weight of lipids)/ (weight of dry biomass)

4.2.1.2. Microalgae to Biodiesel Pathway

Biodiesel (FAME) can be produced from microalgae according to the process block flow diagram presented in Figure 20. This is the process route that is also applied for biodiesel production from other conventional biofeedstocks. Following the extraction of oil and its separation from the extraction mean, the oil is fed to the transesterification unit where oil molecules (TAG) react with methanol to form FAME (viscous fuel with poor cold flow properties and, frequently blended with diesel) and glycerol [73]. To minimise waste disposal and enhance the economic outlook of the biorefinery, the residual biomass can be either valorised for energy generation or the formation of by-products. More information on the main processes for biodiesel production following oil extraction is given below.

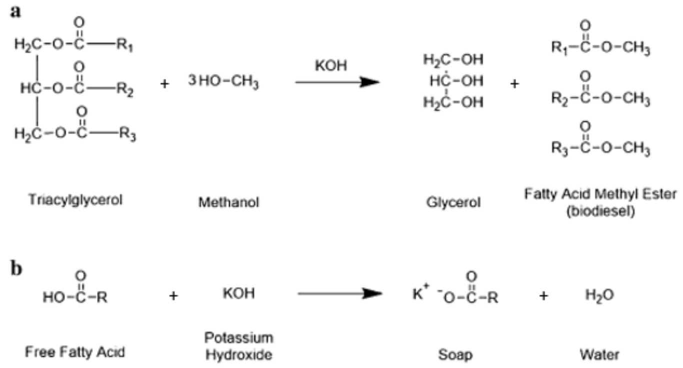
Figure 20. Block diagram of the main process units comprising biodiesel production from microalgae



- Transesterification

The most commonly used process for biodiesel (FAME) production from the extracted oil is the homogenous catalytic transesterification [70]. The process can run under mild operating conditions and usually requires methanol (in excess) and an alkali catalyst such as potassium hydroxide (KOH) to yield FAME and glycerol as a by-product (see reactions in Figure 21). In parallel with TAG conversion to biodiesel, free fatty acids in the oil undergo a side reaction to form soap which reduces the overall conversion to biodiesel, causes gelling in the reaction mixture and more importantly makes the separation of products challenging. To circumvent this, an initial free fatty acids concentration of 0-2 wt% is recommended [70]. The overall conversion yield to biodiesel for the conventional transesterification is equal to 100% for TAG while for other lipids, such as phospholipids and glycolipids, does not exceed 65% and 56% respectively [74].

Figure 21. Reactions occurring in the homogeneous alkali transesterification process [70]

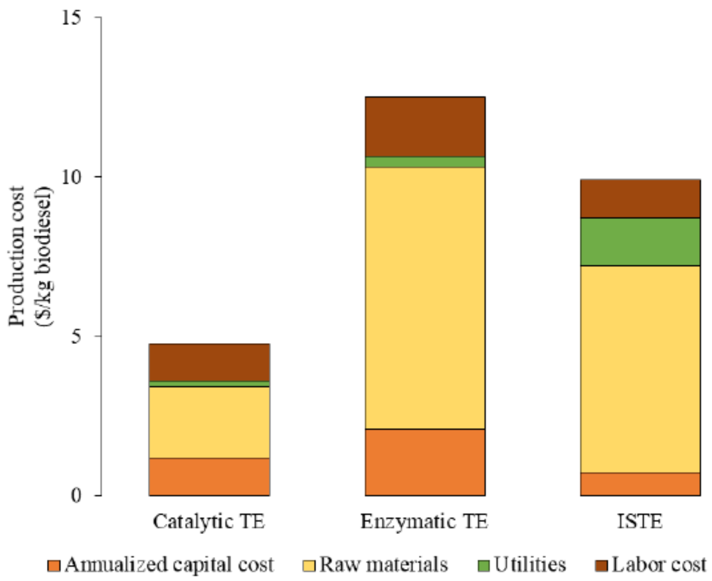


Alternative transesterification technologies have been proposed to address soap formation. For example, saponification cannot occur when acidic catalysts are deployed. However, acidic conversion comes with other challenges such as corrosion issues, and very slow reaction rates (4000 times slower than alkali conversion) [70]. Direct (or in situ) and enzymatic transesterification are further solutions under investigation. Enzymatic catalysis enables transesterification with high specificity under low temperatures but at the expense of high enzyme costs and deactivation of enzymes by the alcohol and glycerol molecules. On the other hand, direct transesterification aims at minimising capital cost by combining lipid extraction and conversion into biodiesel in a single step. This can be implemented by using supercritical methanol (> T = 241.6 ^{0}C, P = 62.7 bar). However, the disadvantage of the direct method is the high energy consumption required for reaching the high operating temperature and pressure [70].

To conclude which is the economically most favourable transesterification process, a techno-economic evaluation of the different processing options is necessary. However, only a few pertinent studies are available in the literature. Heo et al. (2019) simulated and costed biodiesel manufacturing for three different cases, with each of them representing one of the following transesterification processes: 1) a homogeneous catalytic chemical process, 2) enzymatic bioprocess, 3) In-situ (direct) process (integrated SC oil extraction and transesterification) [75]. The annual production cost (annualised CAPEX + OPEX) calculated for the three cases is presented in Figure 22.

The results show that the chemical catalytic process (4.77 $/kg) is significantly less costly compared to the other two alternatives (9.52 $/kg for the in situ and 12.53 $/kg for the enzymatic process). The increase in the costs for the enzymatic process is primarily attributed to the expensive enzymes that are needed to catalyse bioreactions. Finally, employing an in situ (direct) process approach, the high solvent flowrates combined with the intense operating conditions outweigh the capital cost benefits.

Figure 22. Production costs of biodiesel from microalgae (30 wt% lipids) for three different transesterification technologies: 1) Catalytic transesterification (TE), 2) Enzymatic transesterification (TE), 3) In situ transesterification (ISTE) as calculated and reported by Heo et al. [75]

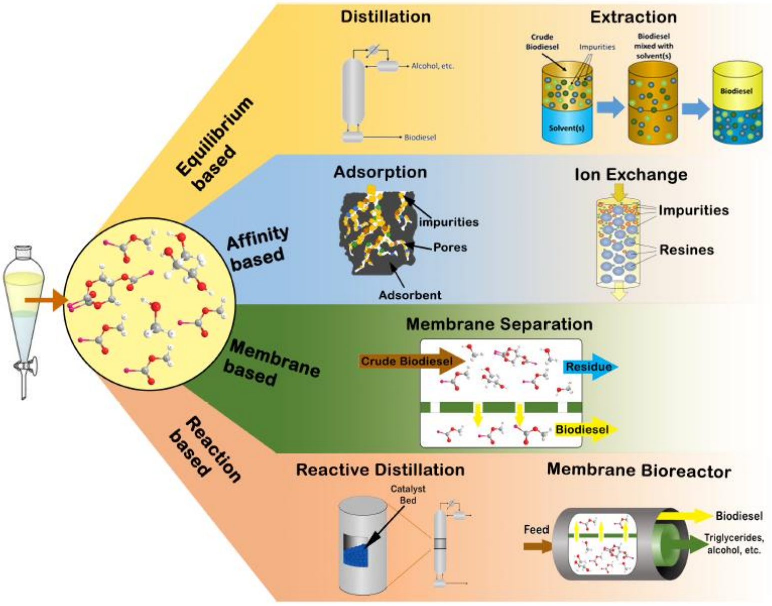


- Biodiesel Separation and Purification

The product stream of transesterification contains the formed biodiesel together with glycerol, unreacted methanol, and other contaminants. Opposite to the biorefinery's upstream, product separation and purification processes have not been explored to the same extent. First, methanol can be recovered at the top of a vacuum distillation tower while biodiesel and glycerol are retrieved at the bottom [70]. Separation of biodiesel from glycerol can be accomplished in a centrifugation unit due to the distinct difference in the density of the two components [76].

To produce biodiesel of commercial quality, further purification is needed. H. Bateni et al. reported that the different possible process options are the following: 1. wet washing, 2. organic solvent extraction, 3. adsorption followed by ion exchange, 4. membrane separation (see Figure 23) [76]. Purification via conventional adsorption and wet washing along with membranes are the mostly explored technologies in the literature.

Figure 23. The different possible biodiesel purification processes [76]



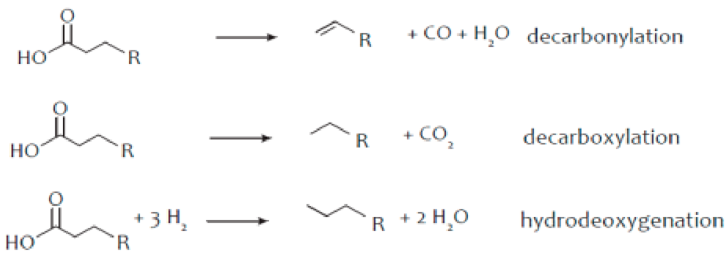
4.2.1.3. Microalgae to Renewable Fuels (Diesel and Jet Fuel)

The direct utilisation of the fatty acid molecules (lipids) for the production of renewable diesel, jet fuel and naptha is an alternative biofuel production route. Rather than undergoing transesterification, which is used for biodiesel production, oil extracted from microalgal biomass is subjected to a hydrotreatment process similar to the one used for diesel production from oilseeds. Hydrotreating is a traditional refinery operation, intensively used for the hydrogenation of olefins and aromatics, and the removal of sulphur and other impurities to improve the quality of petroleum products. Biofeedstocks such as algae do not contain sulphur but other heteroatoms such as oxygen that need to be removed. The upgraded renewable diesel resembles fossil diesel, in terms of its long-chain alkane composition and properties [4], [77].

- Hydrotreatment of algal lipids and Isomerisation

Following its extraction from biomass, algal oil is sent to a hydrotreating unit where with the addition of hydrogen and under elevated temperatures and pressures (280-450 ⁰C, 10-50 bar), saturation of double bonds, hydrodeoxygenation and hydrodenitrogenation take place [77]. Due to the presence of long organic chains (C16-C18) in microalgal lipids, hydrotreatment forms alkanes (C15-C18) that are solid at room temperature (freezing point > 15 ⁰C). For this reason, branching via isomerisation can be introduced after the hydrotreatment process or in the hydrotreater. The amount of hydrogen needed for upgrading strongly depends on the catalyst and the composition of the biofeedstock (saturation of fatty acids). Catalysts such as NiMo/g-Al_2O_3 or CoMo/g-Al_2O_3 are commonly used for hydrotreating [4], [78]. During hydro-processing, propane is formed together with water, carbon monoxide (CO) and carbon dioxide (CO_2). Water and acid gases can be easily removed in a flash/decanter separation vessel while light products such as propane are removed from the top of a distillation tower. It needs to be noted that, depending on the feedstock composition—particularly the presence of inorganic contaminants like phosphorus and metals—pretreatment of the feed stream prior to hydrotreatment may be required to prevent catalyst contamination [79].

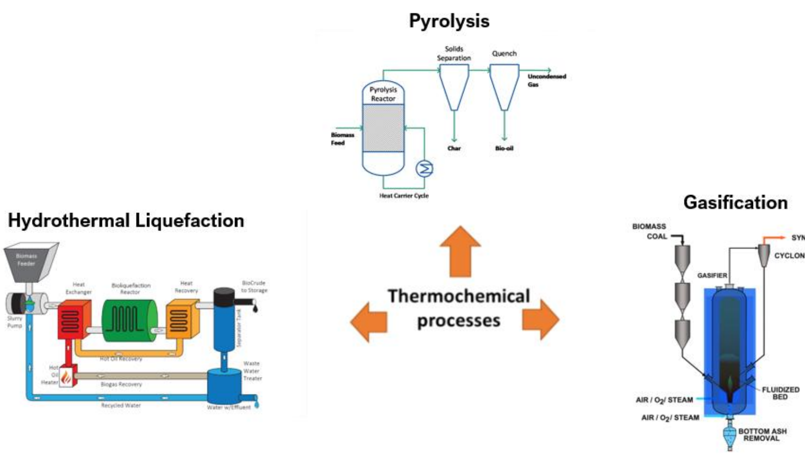
Figure 24. Reactions occurring during the hydrotreating process [78]



4.2.2. Thermochemical Pathway (Biomass to Liquid Fuels)

Thermochemical processes offer distinct advantages compared to oil-processing routes. They are not strongly dependent on the composition of the feedstock and are designed to treat the entire microalgal biomass, regardless of its lipid concentration. For this reason, it could be preferred for algae with a low lipid content. Another advantage of thermochemical processing is that no stringent optimisation of lipid concentration during cultivation is required; instead, the focus can be on maximising microalgae growth yields (an inverse relationship has been shown in many cases between biomass productivity and lipid content) [4]. As shown in Figure 25, thermochemical treatment can be divided into three primary processes, namely pyrolysis, gasification and hydrothermal liquefaction. The output for all of them is an intermediate product that needs further refinement so it obtains the desired fuel properties.

Figure 25. Thermochemical processes that can be used to convert microalgae to intermediate products (biocrude, syngas) from which liquid fuels can be produced via further upgrading or conversion [126], [127]], [128]

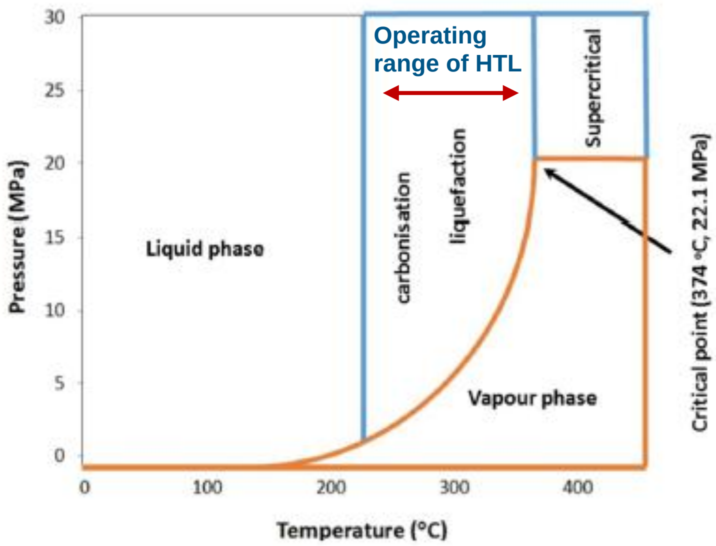


From the aforementioned processes, pyrolysis and gasification are dry-based. This means that in order to ensure efficient conversion, biomass of low moisture content (< 10 wt_{water}% for pyrolysis, < 15 wt_{water}% for gasification) is needed. The presence of water in the reactor acts as a heat sink [80]. This requirement poses a significant challenge when it comes to converting microalgae into biofuels, as harvested microalgae contain a high amount of water (99.5 wt%), and it requires a substantial amount of energy and cost to bring the feed up to the desired specifications [4]. HTL, on the other hand, has the advantage of accepting wet feedstocks (typically at 80 wt_{water}%). Furthermore, the small size of microalgae is well-suited for HTL since they promote heat transfer in the reactor [81]. The advantages of HTL are widely recognised by the scientific community, therefore most research efforts have focused on testing and optimising hydrothermal processing. Yet, HTL is currently at low TRL (from pilot to demonstration), even for conventional biofeedstocks [80]. More information on the technical characteristics of HTL is given below.

4.2.2.1. Hydrothermal Liquefaction (HTL) of Microalgae to Biocrude

Hydrothermal liquefaction involves the conversion of microalgae in a slurry feed (10-20 wt% solids) to biocrude using hot compressed water (300-350 ºC). Water is mostly used as a solvent in the process and high pressure is needed to retain water in its liquid phase during this high temperature operation (see Figure 26). Under these thermally intensive conditions, biomass goes gradually through a series of complex reactions such as the breakdown of biomolecules into smaller compounds via hydrolysis, and further polymerisation of these compounds to biocrude and solids (catalyst has been tested in some setups). Research indicates that biocrude mainly consists of constituents derived from the liquefaction of lipids at temperatures <250 ºC whereas higher temperatures (> 300 ºC) promote the conversion of proteins and carbohydrates and increase the formation of gas [81]. Residence times in the range of 30-60 min are normally held [81]. Table 8 gives an overview of the conversion to biocrude yields as measured in different experimental setups.

Figure 26. Phase diagram of water and operating window for hydrothermal liquefaction



HTL of biomass leads to the formation of biocrude along with gas and solid by-products. The obtained biocrude has a significantly lower oxygen content (usually in the range of 10-20 wt%) compared to the biofeedstock, but it still exceeds the concentrations found in petroleum crude oil. Experiments have measured high concentrations of nitrogen (usually in the range of 5-9 wt%), whereas sulphur amount falls usually below the concentration of 1 wt%. As far as the by-products are concerned, in the gas, CO_2, CH_4 and H_2 are the most abundant components while the formed solids (ash, char) have a relatively low energy content [81].

Table 8. A list of experimental results for the conversion of microalgae to biocrude via HTL using water as solvent

Species	Catalyst	Temperature [ºC]	Time [min]	C/H ratio	C/O ratio	Biocrude yield (wt%)	Reference
Chlorella vulgaris	-	300	60	8.4	8.1	46.6	[81]
Chlorella vulgaris	-	350	60	8.2	4.8	36.0	[81]
Dunaliella tertiolecta	Na_2CO_3 (5%)	300	60	7.9	7.9	42.0	[81]
Desmodesmus sp.	-	375	5	8.9	7.1	49.4	[81]
Kirchneriella sp.	-	300	30	-	-	45.5	[82]
Microcystis viridis	Na_2CO_3 (5%)	340	30	8.3	3.2	33.0	[81]
Nannochloropsis	-	350	60	7.7	3.6	35.0	[81]
Nannochloropsis	-	350	60	7.4	8.4	43.0	[81]
Nannochloropsis sp.	-	320	30	-	-	54.1	[81]
Picochlorum celeri		350		8.0	17	33	[83]
Scenedesmus dimorphous	-	350	60	8.9	5.8	27.1	[81]
Scenedesmus obliquus	Novel catalyst from clam shells	300	60	-	-	39.6	[82]
Spirulina	-	350	60	8.0	7.0	29.0	[81]
Spirulina		350	-	7.9	15.0	31.0	[83]
Spirulina platensis	-	350	60	8.3	6.3	39.9	[81]
Spirulina platensis	CeO_2	250	30	-	-	26.0	[82]

*Biocrude yield = (weight of biocrude)/ (weight of dry biomass)

- Biocrude Upgrade

Following the formation of biocrude, gas and solids in the HTL reactor, solids are separated from the liquid phase (biocrude + aqueous phase) and recycled back to the microalgae cultivation ponds to be used as a source of nutrients. The formed biocrude may be used as heavy fuel oil, but significant upgrading is required if it is intended to be used as transport fuel. For this purpose, after its separation from the aqueous phase, biocrude needs to be catalytically hydrotreated in order to reduce oxygen concentration and acidity. Experiments using fossil oil hydrotreating catalysts (CoMo) at 400 ºC and 130 bar have shown that an O_2 reduction to 0.8-1.8 wt% is feasible [4].

In the aqueous stream, 25-40% of the carbon molecules, ~ 50% of nitrogen and other soluble minerals contained initially in the feedstock have been dissolved, therefore it is important to develop a process strategy that minimises waste disposal and enhances sustainability and economic potential [4]. The aqueous stream could be directly recycled to the HTL reactor to increase conversion to biocrude or to the microalgae cultivation system as a nutrients source. However, this should be carefully tested before considered as experimental studies have shown that the concentration of components (i.e., phenols, fatty acids) in the aqueous by-product are significantly higher compared to the standard growth medium which has an inhibitory effect on the growth of biomass [4]. Further research on HTL is recommended to identify potential opportunities for optimization – process and by-product use.

5. ECONOMICS OF ALGAE TO BIOFUEL PATHWAYS

The objective of this Chapter is to provide insights into the economic potential and challenges of the algae to liquid biofuel pathways, analysed in the previous Chapters. A literature review was conducted to collect and demonstrate the results from scientific publications and technical reports focused on this particular topic. Minimum fuel selling price (MFSP), calculated with a Discount Cash Flow (DCF) analysis, is the indicator most commonly used in these studies to assess the economic performance of a certain technology or pathway. MFSP is the lowest selling price for the produced fuel to make the plant break-even (zero net present value) at the targeted operating year. For the calculation of MFSP, financial parameters such as income tax rate, and internal rate of return need to be adjusted.

Due to the uncertainty of many technical and financial parameters, different assumptions are taken in each study, which are expected to create significant discrepancies in the final results. Therefore, for the purposes of this report, prioritisation is given on studies which have harmonised the techno-economic models of different case studies to recalculate the results on the same basis.

5.1. BIOFUELS FROM MACROALGAE

In this chapter, the techno-economics surrounding biofuel production from macroalgae is assessed. The process technologies for this pathway are currently at experimental level. A literature review was conducted focusing on techno-economic case studies that assess bioethanol production. Similar to traditional biofeedstocks like corn, macroalgae possess a high carbohydrate content, making them ideal for ethanol production via fermentation. Although the number of studies evaluating macroalgae to liquid biofuel pathways is relatively limited, the existing research has mainly revolved around the production of fuel ethanol.

Most of the studies analyse the case of producing bioethanol as the only end-product (only-to-fuel approach) [84], [85], [86], [87], [88]. However, in order to tackle the economic challenges caused by the low conversion yield of macroalgae to bioethanol (see Table 6), some researchers have evaluated alternative process configurations for a multi-product biorefinery [85], [87]. The following section will present the available techno-economic findings and explore the economic aspects of the different biorefinery approaches.

5.1.1. Biochemical Pathway: Economics of Ethanol Production

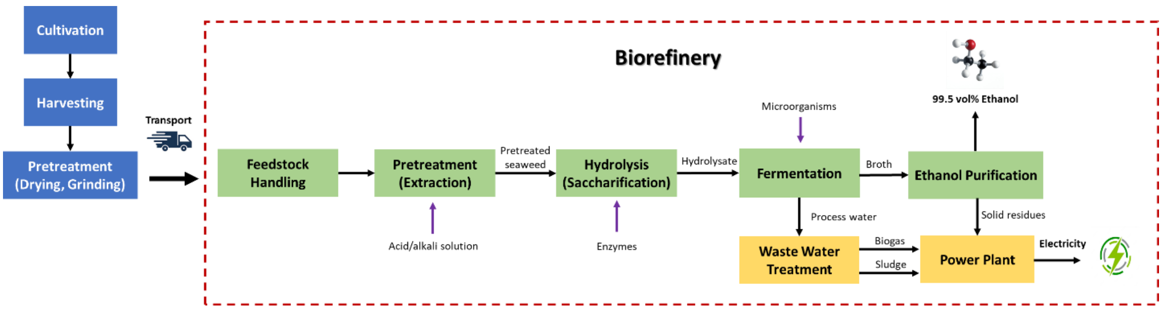
- **Process Description**

An indicative block diagram considered in the different techno-economic assessments (TEAs) is given in Figure 27. For all the TEAs, macroalgae farming, harvesting and pre-processing are placed outside the battery limits with the associated costs of these processes being reflected in the price of feedstock delivered at the biorefinery's gate.

The process starts with the delivery of the pre-processed macroalgae (grinded and dried) to the biorefinery which are unloaded and stored in the handling units. The biomass is then transferred to the pretreatment unit where either hot water or a mild acidic solution are used to extract polysaccharides from the algal cells. Should acidic pretreatment be employed, it is necessary to neutralise the produced slurry using ammonia before proceeding with the next units. The mixture then goes under enzymatic hydrolysis to convert polysaccharides to fermentable sugars. The use of enzymes instead of chemical solutions is used in most TEAs as a more environmentally friendly solution. Therefore, hydrolysate is separately fermented and sugars are converted to ethanol. The product stream of fermentation is a dilute in ethanol broth. To meet the commercial purity specification for ethanol-fuel (> 98.7 wt%) [89], the ethanol broth undergoes a purification process including distillation and the use of molecular sieves.

To minimise waste disposal and maximise economic potential, solid residues and wastewater coming from the ethanol purification units are commonly harnessed to generate energy for the plant. More specifically, in a dedicated wastewater treatment facility using anaerobic digestion, biogas and sludge are formed and together with the solid residues of the ethanol recovery processes, these components are burnt in a combined heat and power plant (CHP).

Figure 27. Block diagram of bioethanol production from macroalgae for the only-to-fuel process configuration (cultivation step may not be necessary as opposite to microalgae, seaweed can be harvested directly from sea)



- **Economic performance**

A small number of TEAs have evaluated ethanol fuel production from macroalgae and calculated the associated minimum fuel selling price. Multiple results come from the same publication as some studies evaluated the system under different scenarios (e.g., Fasahati et al. assessed two pretreatment configurations). Some important assumptions used in these analyses are listed in Table 9. It is important to highlight the lack of harmonisation in the assumptions across the studies, which makes it challenging to draw conclusions about the techno-economic performance. For example, Fasahati et al. assumed an optimistic conversion yield (25%), while Konda et al. and Soleymani et al. based their calculations on more conservative yields taking into account the impact of seasonal variations and moving from experimental to large scale processing. Furthermore, the variations in the assumed biomass prices among the studies is another important cause for the observed differences in the final results.

Table 9. Technoeconomic assumptions used in the different macroalgae to ethanol case studies that are available in the literature

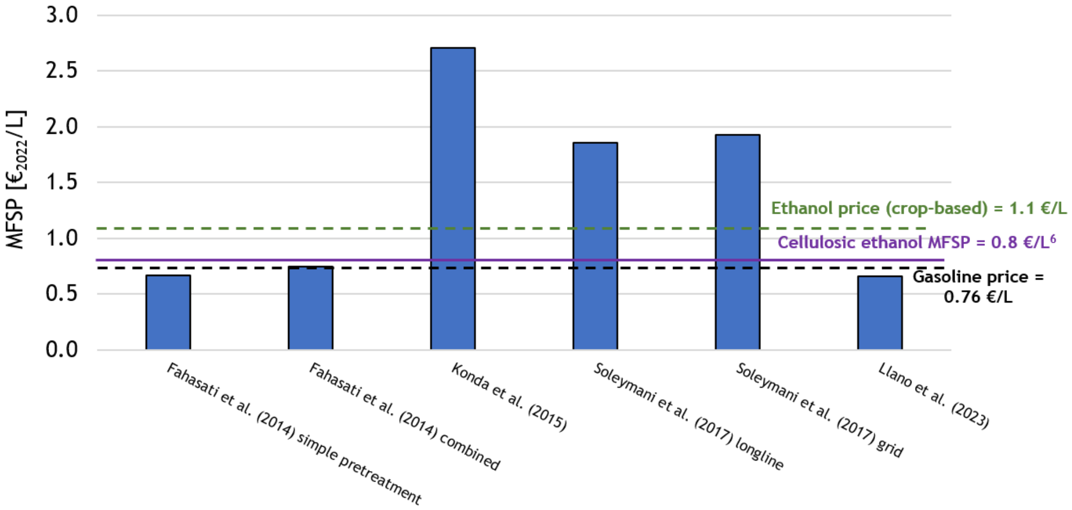
Parameters	Fahasati et al. (2014) [84]	Konda et al. (2015) [85]	Soleymani et al. (2017) [86]	Llano et al. (2023) [88]
Technical assumptions				
Feed capacity [kt/y]	400	700	1000	413
Carbohydrate yield wt%	-	65%	-	54%
Conversion yield [$kg_{ETOH}/kg_{biomass\ (dry)}$]	25.4%	15.5%	7.5%	16%
Solid loading in the feed wt%	20 wt%	5 wt%	22 wt%	-
Economic assumptions				
Project lifetime (NPV=0) [years]	20	-	10	8
Biomass price [$€_{2022}$/t]	82	120	~ 120[5]	20
Income tax rate	35%	-	-	20%
Discount rate	10%	10%	-	-%

Upon evaluation of the results (see Figure 28), it becomes apparent that there are significant differences in the reported selling prices for ethanol. These disparities stem from the different assumptions applied in the feedstock cost, process design and subsequent calculation of capital costs, operating expenses and sales revenues. One example are the differences in the assumed fermentation yields, an important parameter as it determines the amount of fuel that can be produced and sold from a given amount of biomass. Considering the current state of technology (see Table 6), we can conclude that the low ethanol minimum selling price reported by Fahasati et al. is based on a degree of conversion that is very optimistic and may not reflect the dynamics a current biofuels plant would have. Another reason that can be identified after an in-depth examination of the studies is that Konda et al. assumed the external supply of hydrolysis enzymes rather than their on-site production which increases the operating expenses. Finally, disparities in the supply cost of biomass and the scale of the plant are key factors for the economics of a biofuels plant.

When examining the MFSP of macroalgae-based ethanol compared to the commercial price of ethanol from crops (1st generation biofuel), and the MFSP of cellulosic ethanol from corn stover (2nd generation biofuel), it becomes clear that the existing uncertainty in the available studies does not allow to reliably conclude if producing ethanol from macroalgae is economically competitive. However, considering that Konda et al. employed a more realistic approach that takes into account the effect that seasonal variations in chemical composition and scaling up technologies from experimental to industrial scale could have on conversion efficiency, we can see that for this particular study, the MFSP of bioethanol is much higher than the commercial price of corn ethanol and the MFSP of ethanol from lignocellulosic biomass.

[5] Opposite to the other studies, Soleymani et al. considered macroalgae cultivation as part of the evaluated system. 120 €/t refers to the algae production costs calculated by Soleymani et al. (and indexed to 2022) using the long-line method.

Figure 28. Minimum fuel selling price of ethanol from macroalgae as calculated in different techno-economic studies available in the literature. The price of corn-based bioethanol, gasoline and the MFSP of advanced bioethanol from lignocellulosic biomass are included in the bar chart as a comparison point [90], [91][6]. All the prices were indexed to 2022[7]

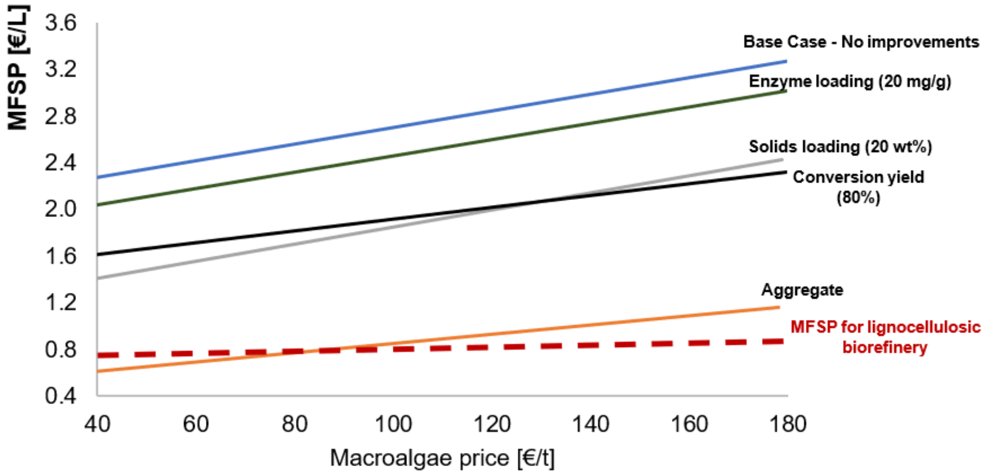


The importance of the fermentation yield and biomass price on economics can be confirmed by the sensitivity analysis conducted by Konda et al (see Figure 29). This figure also highlights the innovations that are needed to improve the economic outlook of this pathway. They calculated that for every 50 €/t macroalgae price reduction, the selling price drops by 0.34 €/L. However, relying only on lower feed prices may not be sufficient to make ethanol production from macroalgae comparable to using lignocellulosic biomass. To overcome this, improving the current process technology is necessary. On that basis, increasing the conversion yield to 80% of the theoretically maximum shows to have one of the strongest positive impacts on profitability as it increases sales revenue and decreases waste volumes and management costs. Along with conversion yield, increasing solid loading can play an equally important role and lead to a fuel price reduction of 0.85 €/L. Finally, using lower enzyme quantities does not seem to have as significant an effect as the other two process parameters, however, the economic benefit cannot be ignored. Taking into account all these factors, only a collective improvement of the process parameters has the power to make the pathway economically competitive (break-even at ≈ 80 €/t).

[6] Indicative MFSP: The MFSP of cellulosic ethanol refers to the statistical average price of ethanol produced from various lignocellulosic feedstocks through fermentation, as calculated by Aui et al. This analysis is based on a review of numerous case studies. The MFSP corresponds to an average biomass input capacity of ~ 700 kta (or 236,093 m^3 of EtOH), aligning with the scale of relevance observed in the evaluated algae-based studies.
The fossil gasoline price (Euro-super 95, without taxes) refers to the average EU gasoline price in Jan. 2022. The Brent crude price at that time was 73.9 USD/bbl.

[7] 2022 was used as the reference year because the energy crisis in Europe caused significant increases in fossil fuel and biofuel prices in 2023. However, it needs to be noted that during the first half of 2024, the prices of ethanol and fossil fuels have decreased, widening the gap with the MFSP of ethanol derived from macroalgae.

Figure 29. Sensitivity analysis performed by Konda et al. for assessing the effect that biomass price, fermentation (or conversion) yield, solid loading in the feed and enzymes use rate have on the minimum ethanol selling price. All the prices were indexed to 2022



5.1.2. Combined Algae Processing (Multi-product biorefinery)

Producing only ethanol from microalgae demonstrates an economic performance, inferior to the alternative of using lignocellulosic biomass. Macroalgae are expensive feedstocks and technical constraints such as the low macroalgae to ethanol conversion rates lead to only valorise a small fraction of the initially supplied biomass. As a means to increase the economic potential, a few researchers have investigated multi-product configuration alternatives, in which valuable and non-convertible to ethanol components are extracted, purified and sold along with ethanol [85], [87].

For example, Konda et al. built on the biorefinery model developed for the only-to-fuel approach and investigated the possibility of alginate (it can be used in the food, feed and pharmaceutical industries) recovery through a series of acidic and alkali treatment steps [85]. The results showed that ethanol and alginate can be produced at competitive prices, however, production of alginate at such scale even for a single plant exceeds the global alginate demand. For example, ethanol at a competitive price of 0.8 €/L and alginate at a price of ~ 3.7-6.0 €/kg (market value: 9-12€/kg) can be produced. However, for this biorefinery, 130-220 kt y^{-1} of alginate are produced whereas the global alginate demand was equal to 26.5 kt in 2009 [85].

Another interesting case study was conducted by Nazemi et al., who introduced a biorefinery design in which alginate, mannitol, proteins and fertiliser are produced alongside ethanol [87]. According to the results, although producing these additional materials entails additional costs, the high selling price of mannitol and alginate overcover these expenses and improve the economic potential of the biorefinery. However as for the other case study, the market size for these materials is much smaller than what industrial production of fuel ethanol would give [87].

Despite the limited number of available studies focusing on a multi-product configuration, it is clear that employing this approach can deliver fuel ethanol at more competitive prices. However, the available case studies focused on components with a relatively small market. Therefore, future research endeavours should investigate whether species are available which contain components of significant market size and value.

5.2. BIOFUELS FROM MICROALGAE

In this chapter, we assess the techno-economics surrounding biofuel production from microalgae based on a literature review. The different routes for biofuel production, such as lipid extraction based and thermochemical technologies, are analysed separately. Particular emphasis is also given on the economics linked to the microalgae production technologies in the upstream as they have been extensively studied and reportedly highlighted to play key role for the economic viability of the pathways. Finally, as for macroalgae, different biorefinery configurations targeting the production of different materials at the same time are analysed.

5.2.1. Upstream: Microalgae Production System Economics

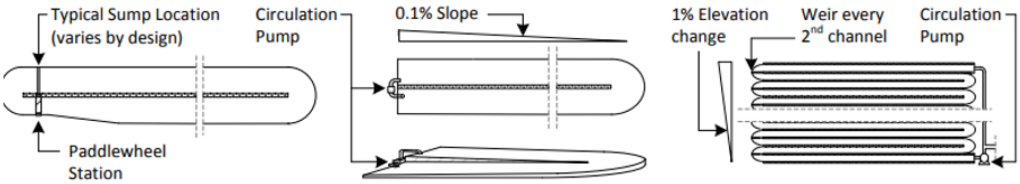
Numerous research papers were published between 2006 and 2015, focusing on evaluating the techno-economic performance of microalgae production systems [41], [92], [93], [94], [95], [96], [97]. However, these papers lack consensus and include uncertainties regarding biomass productivity (a range of 7-60 g $m^{-2}d^{-1}$ is reported as potentially feasible), dewatering methods, and respective production costs. For this reason, a comprehensive study was conducted in 2016 by NREL in collaboration with expert vendors and engineering companies in which the different open pond systems under different scenarios were designed, simulated and techno-economically assessed [42]. This study remains relevant today, and its incorporation of various future scenarios that can be used to evaluate microalgae production. Therefore, the assumptions and results of this study will be discussed to demonstrate the techno-economic performance of open ponds for different designs and scales, with the aim to identify the primary economic drivers and bottlenecks. The purpose of the assessment is not to provide absolute cost estimates, but rather to give approximate costs and identify the main cost drivers.

For the case study by NREL, a hypothetical total pond area of 5,000 acres (2023 ha) was assumed, split into modules of 100 acres each. This specific assumption was chosen as it strikes a harmonious balance between logistical challenges and production costs. While other studies have analysed larger farms spanning 10,000 acres, it is important to acknowledge the logistical constraints and controlling difficulties that accompany large cultivation areas. Conversely, opting for much smaller farms does not favour economics due to the absence of economy of scale. As it stands today, the largest farm worldwide, spanning 7,000 acres, is located in Australia [98].

The process units typically involved in the upstream and assessed in the TEA by NREL are the following:

- Production Ponds: These are the heart of the upstream and the primary source of expenses and emissions. Based on the feedback by different pond manufacturing experts, NREL proceeded to the design of different open pond types (see Figure 30) in three different sizes per single pond (2 (standard size), 10, and 50 acres) for the cultivation of *Scenedesmus acutus* (freshwater species). A productivity equal to 25 g m^{-2} d^{-1} (current max: ≈18 g m^{-2} d^{-1}) was modelled for the base case as it was the target envisioned for 2022 back in 2016. All base case designs do not use fully lined ponds as this comes with cost premiums.

Figure 30. The three different open pond designs techno-economically assessed by NREL (Left = paddlewheel raceway; centre = Global Algae Innovations (GAI) pond system with pump circulation; right = Leidos gravity flow serpentine pond) [42]



- Inoculum System: In these units, biomass inoculum is produced to cover the losses in the ponds when upsets or culture crashes occur. The inoculum units are closed photobioreactors (PBRs), covered ponds and opened ponds when larger volumes are targeted. The system was designed on the basis that the main cultivation ponds need to be re-inoculated every 20 days due to contamination incidents.

- CO_2 delivery: This part covers the delivery and injection of CO_2 to the open ponds and the inoculum. For the purposes of the NREL study, purified CO_2 (>99 vol%) coming from the flue gas of a power plant was assumed [99]. Any recycling of CO_2 from a biorefinery was not considered, hence potential recycle credits were excluded from the calculations.

- Make-up water delivery: To replenish water losses, water is supplied by a nearby local water resource.

- Dewatering: Biomass is harvested from ponds at a low concentration of 0.5 g/L (0.5 wt%). To be able to further process it or store it, dewatering is necessary. The final solids concentration commonly targeted is 200 g/L (20 wt%). Currently no standard method exists for dewatering microalgae that will be used for biofuels production. Gravity settling, membranes and centrifugation are assumed to be used in the given sequence for bringing microalgae to the desired state.

- Storage: Dewatered biomass, as well as make-up water and nutrients are stored in vessels. No transport of biomass off-site was considered.

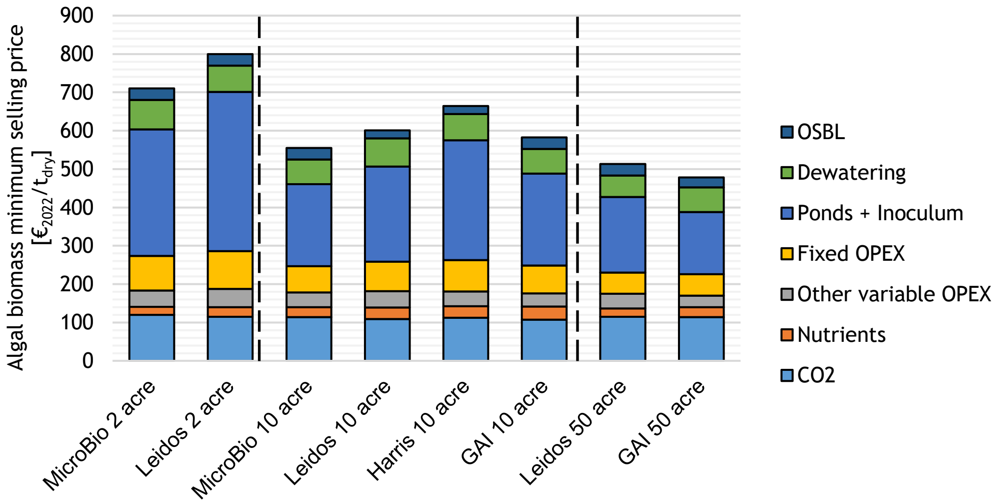
For the DCF calculations, the following assumptions considered:

- Discount rate = 10%
- Depreciation period = 7 years
- Equity = 40%
- Plant life = 30 years
- Tax rate = 35%

The calculated minimum biomass selling prices for different pond designs and sizes are shown in Figure 31 [42]. The Figure also shows the breakdown into the different costing factors contributing to the price. Upon analysing results, all the considered designs have a high capital cost which makes it the primary cost driver. This becomes even more pronounced when liners are placed (marginal inclusions for plastic liners in small targeted areas was included in the base case) [42]. Generally, for the 10-acre cases, the largest cost contributors to the pond are paddlewheels, motors, and concrete [42]. Differences in the final price for each pond design are observed. However, the reduction in price achieved through scaling up the pond size appears to be more significant than the pond configuration itself. For example, increasing the Leidos pond from 2 to 10 acres reduces the biomass price by 24%

while changing from the Leidos to the less expensive MicroBio pond leads to an 11% decrease of the price. However, such large ponds are currently not possible due to potential contamination of the culture [42]. Concluding, although dropping the price below 500 €/t is difficult to achieve, especially if we consider that 50-acre ponds are a hypothetical scenario that has not been tested, a price of 550-600 €/t_{dry} may be feasible with some advancements beyond the current state of technology.

Figure 31. Minimum biomass (ash-free dry) selling price breakdown as calculated by NREL for different designs and scales [42][8]. The prices were indexed to 2022 and converted from USD to €



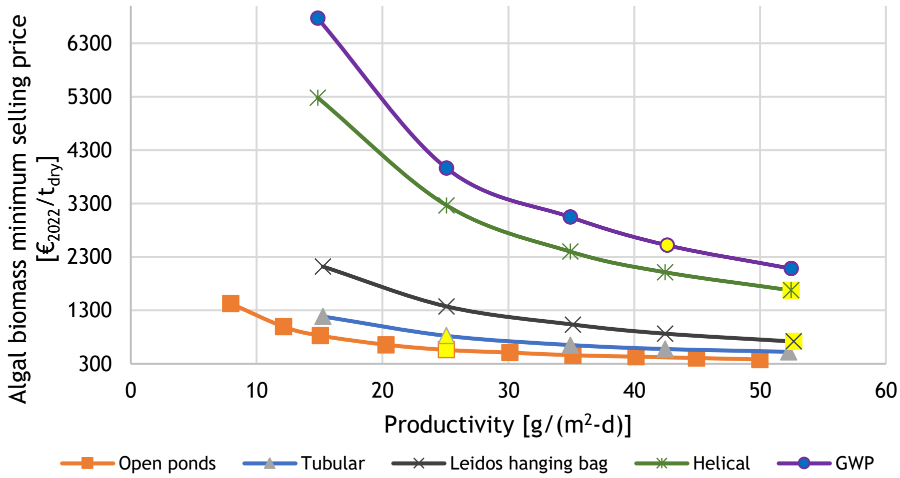
In a more recent study, Clippinger et al. used the same model for open ponds to compare their techno-economic performance with various closed bioreactor configurations [51]. The objective was to determine whether the higher potential productivities and improved control of operating conditions in closed systems could compensate for their higher capital and operational costs. Four different designs of closed reactors were analyzed: Horizontal Tubes, Helical Tubes, Green Wall Panel-II (GWP-II)—a flat panel "standing bag" system—and Leidos hanging bags made of flexible plastic.

Design and cost inputs for the closed reactors were provided by researchers and companies involved in their development. The results, as shown in Figure 32, and the projected productivities are marked in yellow. It is important to note that not all photobioreactors (PBRs) can achieve the same level of productivity. The findings reveal that, at the targeted productivity levels, open ponds are the most economically efficient system. Designs such as helical tubes and flat panels are significantly more expensive and cannot compete with open ponds, regardless of the productivity they may achieve. However, tubular reactors and Leidos bags are more comparable to open ponds in terms of cost and could potentially compete if a larger gap in productivity between them and open ponds was achieved. Even when open ponds are constrained to their currently highest productivity (18.6 g/m^2/day), they remain the most cost-efficient option. However, if higher productivities in

[8] The designs MicroBio, Leidos, Harris concern paddlewheel raceway systems. On the other hand, the design by GAI is a hybrid between a raceway and serpentine flow system, and circulation is provided by pumping. More information on the design characteristics can be found in the report by NREL [42].

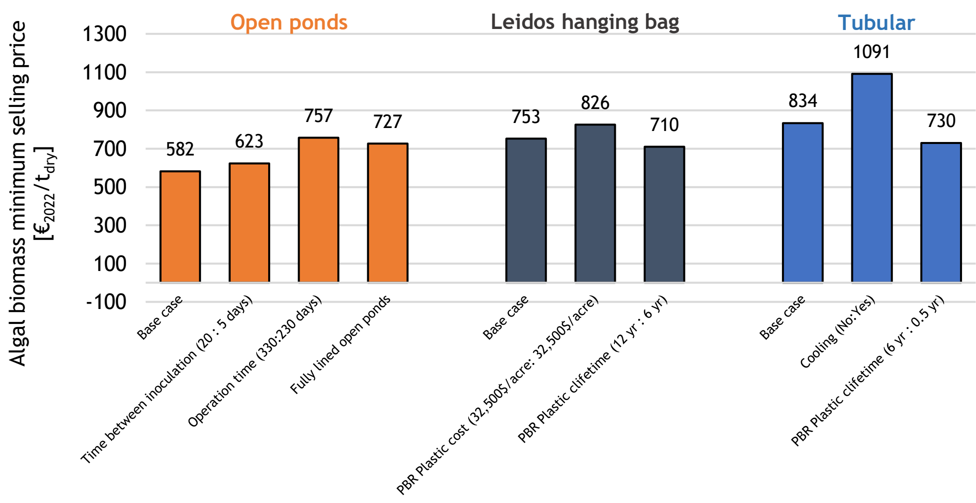
open ponds are not achievable (<15 g/m²/day), such as in locations with insufficient sunlight, then closed reactor designs may become more economically viable.

Figure 32. Minimum biomass (ash-free dry) selling price as calculated by NREL for open ponds and different closed photobioreactor designs [51]. The prices were indexed to 2022 and converted from USD to €



Clippinger et al. also evaluated the conditions under which closed photobioreactors could become more economically advantageous than open ponds at the projected productivities (see Figure 33). The analysis showed that this shift could only occur if the annual number of operating days for open ponds is significantly reduced (from 330 to 230 days) due to more frequent contamination events. Simultaneously, technological advancements in closed photobioreactors would need to be achieved for them to surpass open ponds in cost efficiency.

Figure 33. Minimum biomass (ash-free dry) selling price as calculated by NREL for open ponds and different closed photobioreactor designs for alternative scenarios [51]. The prices were indexed to 2022 and converted from USD to €



5.2.2. Pathways for Biofuel Production from Microalgae

In this section, we delve into the different studies that evaluated the production of biodiesel or renewable diesel and calculated the minimum selling price of these fuels (MFSP). For this literature review, we start from the studies that have assessed the economic performance of biorefineries, designed to produce solely fuels through 1. Lipid extraction or 2. Hydrothermal liquefaction. The objective of this section is to present the economic findings, highlighting the range of calculated results and explaining the underlying factors behind variations. Furthermore, for selected case studies, the economic drivers and challenges associated with this only-to-fuels approach are explored.

Acknowledging the limitations tied to utilising part of the biomass solely for biofuels production, we show the alternative of a multi-product biorefinery approach as modelled by different researchers. This approach focuses on re-valorising side-products and process waste streams to maximise economic gains.

Due to inconsistencies in assumptions on system boundaries, biomass productivity in the upstream and economic parameters, this literature review focuses on presenting review studies that harmonised different case studies. More specifically, Cruce et al. (2021) harmonised key techno-economic assumptions of different case studies published in 2010 or later to recalculate their economic results on the same basis [100]. For the harmonisation, only case studies with clarity on their assumptions and focusing on biodiesel or renewable diesel production were selected, while publications assessing the economics of producing jet fuel or other fuel product as the primary product were excluded. The harmonised assumptions used by Cruce et al. are summarised as follows:

Technical Assumptions

- Productivity = 10, 25, 50 g/(m^2-d)
- Include fuel upgrading in all studies
- Operating time = 330 days per year

Economic Assumptions

- Discount rate= 10%
- Working capital cost = 5% of Fixed Capital Investment FCI (excluding land)
- Depreciation period = 7 years (for general plant), 20 years for power plant
- Equity = 40%
- Plant life = 30 years
- Income tax rate = 35%
- Interest rate for debt = 8% annually

It must be noted that most TEA studies, including the harmonisation study by Cruce et al., follow an agnostic approach to the geographical location, and assume a nearly year-round operation (330 d). Moreover, TEA studies tend to overlook seasonal variations in biomass productivity in order to simplify the analysis.

5.2.2.1. Lipid Extraction Pathway: Oil-based fuels from Microalgae

- **Process System Description**

Microalgae contain a substantial quantity of lipids, rendering them a promising source for the production of biodiesel (FAME) and renewable diesel. As presented in Chapter 5, the initial process step in manufacturing of both types of diesel fuel involves the extraction of oil contained in microalgal cells, followed by either transesterification for the production of biodiesel or hydrotreatment for renewable diesel. Due to the potential of these pathways in meeting the rising demand for low carbon diesel fuel, several studies have delved into exploring their techno-economic potential. However, it is worthwhile to note that the majority of these studies were conducted prior to 2015.

An indicative block diagram of the process units involved in the biodiesel or renewable diesel production as considered in the different TEA studies is given in Figure 34. The pathway commences from the upstream where microalgae are cultivated either in open ponds or closed photobioreactors. While closed photobioreactors offer certain advantages (i.e. operational stability), the vast majority of studies opt for the significantly more cost-effective open ponds [51]. This is a strategic choice to ensure the production of biofuels at the lowest possible price point. Only in very cold climates resulting where open ponds can experience low productivities, closed photobioreactors with controlled operating conditions can be more advantageous. In addition, lipid concentration in the harvested algae is another crucial factor for the economic results of the diesel pathways. In general, high lipid concentrations favour economics, however they come with a penalty on algae growth. Increasing lipids formation via the creation of a nutrients-deficient environment is reported to impede growth rates, and a concentration of up to 35 wt% is deemed a realistic target without substantial adverse effects [101].

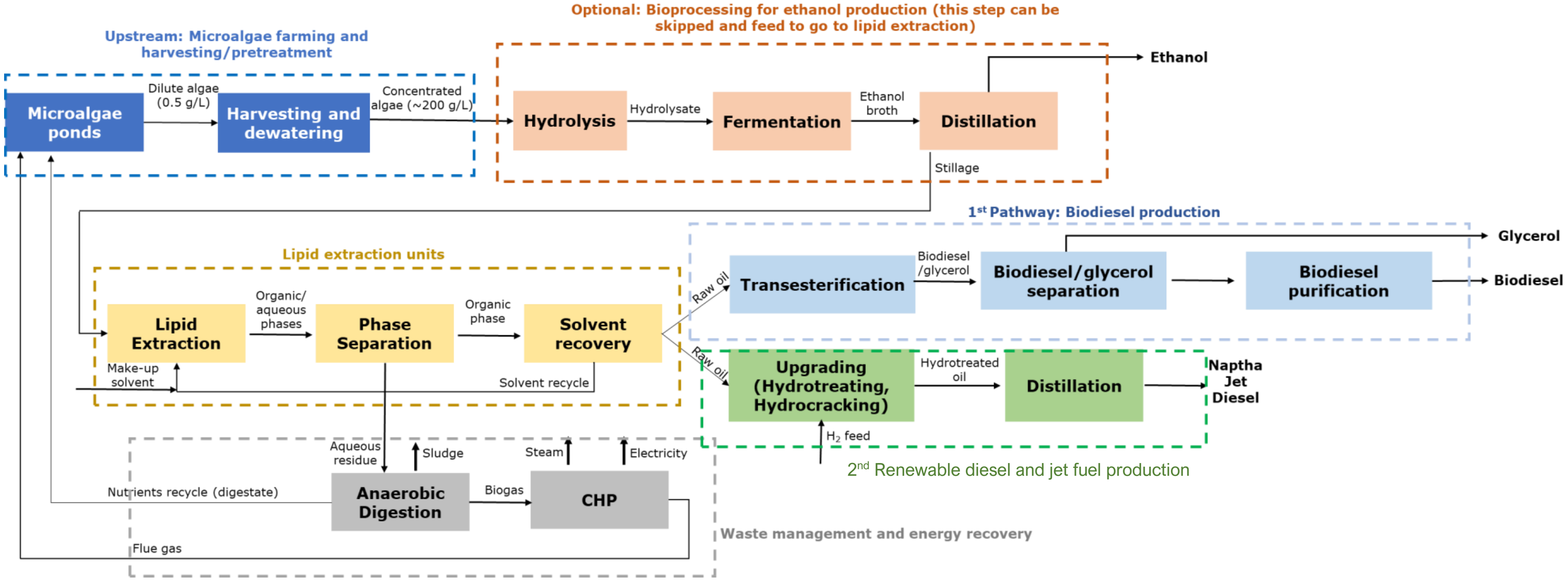
Harvested microalgae contain a large amount of water, making it necessary to remove significant quantities of it to prepare the biomass for further processing. Due to the very low concentration of solids in the harvested microalgae (0.5 wt%), drying methods are not economical [100]. In industries focusing on producing high-value products from algae, centrifugation is commonly used to concentrate biomass. However, since fuels are low-priced products, alternative methods need to be explored. One approach frequently suggested in the TEAs is the implementation of low-cost flotation technologies before centrifugation. This allows for the preconcentration of the harvested mixture, reducing energy consumption in the centrifuge, while achieving microalgae concentrations of 20-30 wt% [101], [102], [103].

Lipid extraction is the heart of the biofuel plant from where the different oil-based fuels can be formed. The TEAs that will be presented in the following section assume an extraction efficiency of 80-100% using chemical solvents such as hexane and butanol. The extracted oil can then be directed towards two different pathways depending on the desired product. When biodiesel production is aimed, the transesterification process is applied forming biodiesel and glycerol. For the case of renewable fuels (jet, diesel), the raw oil is directly upgraded in a dedicated hydrotreater. It is worth mentioning that all studies assume an external H_2 supply source.

Concerning the aqueous waste stream coming from the extraction unit, all the TEAs consider its treatment in an anaerobic digestion (AD) unit. In the digester, biogas is produced which is then burnt in a combined heat and power (CHP) plant to cover a significant part of the plant's electrical and thermal requirements. The solid residues from AD unit are rich in nutrients such as nitrogen and phosphorous, hence they are recycled back to the microalgae ponds. In the CHP plant, flue gas dilute in CO_2 is produced from biogas combustion and is recycled to the ponds to be utilised as organic substrate.

Finally, in an alternative process configuration aimed at maximizing fuel output, biomass can be pretreated and fermented before lipid extraction. This process allows for the production of ethanol in addition to the primary fuel product.

Figure 34. Block diagram of the main process units involved in the pathway of producing and processing microalgae for the production of: 1st pathway: biodiesel, 2nd pathway: renewable fuels (diesel, jet fuel, naphtha). These are the main process units that have been considered in the available TEA studies

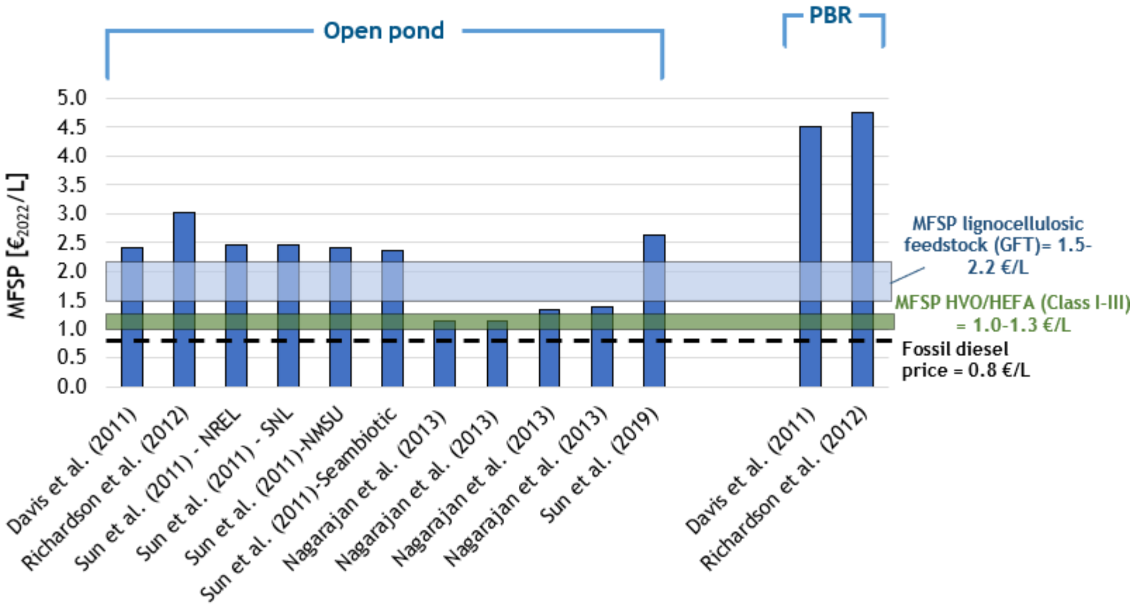


- **Economic Performance**

The minimum fuel selling prices (MFSP) of the different case studies after the harmonisation by Cruce et al. are displayed in Figure 35. Multiple results come from the same publication as some studies evaluated the system under different scenarios (e.g. using different models, cultivation processes). The reported studies encompass a broad processing scale, with dry biomass input ranging from ~ 35 to 800 kt (after the harmonisation). Although a significant variance in the MFSPs was observed in the originally reported results, the harmonisation of biomass productivity and of economic parameters narrowed down this range. The results have been calculated for a biomass productivity of 25 g $m^{-2}d^{-1}$. The MFSP, post-harmonisation, ranges from 1.1 to 3.1 €/L for pathways considering open ponds. On the other hand, replacing open systems with closed photobioreactors (PBR) leads to higher capital and operating expenditures, resulting in an MFSP range of 4.5-4.8 €/L. It is worth noting that the concentration of lipids in the harvested biomass appears to be a key factor in the differences among studies. For instance, Sun et al. (2011) and Richardson et al. (2012) reported the highest prices due to their assumption of low lipid concentrations (25 wt%) in the harvested biomass, while Nagarajan et al. (2013) considered very high lipid concentrations (50 wt%), leading to increased sale revenues and a decrease in the minimum fuel selling price [102], [104]. Nevertheless, it is important to note that such high concentrations do not reflect the current technological state and trying to increase lipid content to such high levels always comes at the expense of lower biomass productivities [105].

When considering the results in relation to the costs of established alternatives like fossil diesel, commercial HVO/HEFA and liquid biofuels derived from the gasification and Fischer Tropsch process using lignocellulosic feedstocks, it becomes evident that for the majority of cases, producing biofuel from microalgae is more expensive. The average minimum selling price for biofuel for the studies using open ponds stands at 2.2 €/L, which is twice as much as the minimum selling price of commercial HVO in the EU market.

Figure 35. Minimum fuel selling price of renewable diesel, and biodiesel from microalgae calculated after the harmonisation by Cruce et al. of the assumptions reported in the different TEA studies [100]. The results have been calculated for a biomass productivity of 25 g $m^{-2}d^{-1}$. The minimum selling price of HVO, lidquid biofuel from GFT (gasification and Fischer-Tropsch) using lignocellulosic biofeedstocks and fossil diesel price have been included in the Figure as a comparison point [90], [106], [107], [108], [109][9]. All the prices were indexed to 2022

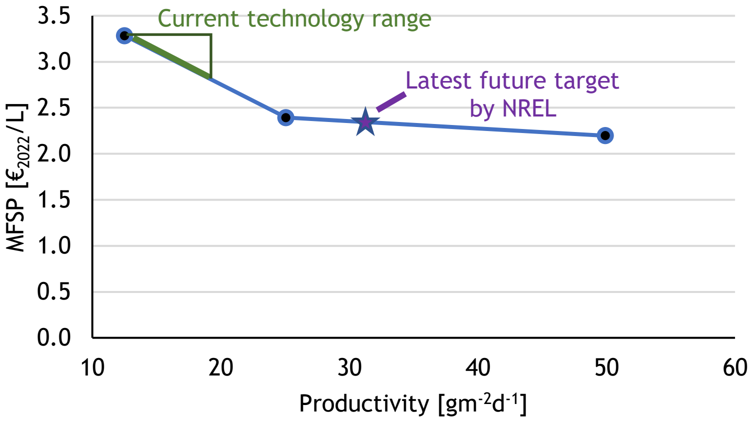


Conversion used:
1 GGE = 0.9 gallon of fuel (Gasoline gallon equivalent - Wikipedia)
1 US gallon = 0.264 L (Convert gallons to liters (unitconverters.net)
Inflation of USD calculator: U.S. Inflation Calculator: 1635→2023, Department of Labor data (officialdata.org)
1 USD (2022) = 0.95 € (2022)

Biofuel production from microalgae shows to fall short compared to the existing transport fuel production pathways even by considering an annual biomass productivity of 25 g m^{-2} d^{-1}. This value was a target set by NREL for future cultivation systems, surpassing the currently feasible annually average productivities in existing open ponds, which are no higher than 18.6 $gm^{-2}d^{-1}$ [110]. Considering the to date technology of microalgae production ponds, as shown in Figure 36 (representing an indicative model), the minimum selling price increases by ~ 40%, making the gap between this and the other biofuel pathways even larger. Another interesting conclusion coming from the Figure is that doubling biomass productivity from 25 to 50 g m^{-2} d^{-1} follows a flattening response and does not have the same positive impact as the shift from to 13 to 25 g m^{-2} d^{-1} (attributed to CAPEX changes with productivity).

[9] HVO indicative MFSP range: The range for the minimum selling price of HVO is derived from various scientific articles on the economics of HVO/HEFA production. The exact price depends on factors such as the feedstock used, production scale, and financial assumptions. The depicted range encompasses a wide variety of feedstocks, scales (feed input ~ 130 kt to 1 Mt) including, soybean oil, used cooking oil (UCO), and tallow oil [106], [107], [108], [109].
The fossil diesel price (without taxes) refers to the average EU gasoline price in 24-Jan. 2022. The Brent crude price at that time was 73.9 USD/bbl.

Figure 36. The change in MFSP for different productivities (12.5, 25, and 50 g m-^{2} day^{-1}) after the harmonization conducted by Cruce et al. The line shows the results of a model (upstream+downstream) selected by Cruce et al. as representative [100]



The capital investment for the upstream process units considered for biomass production are consistently reported to be one of the major cost drivers. For example, this can be validated by the biodiesel production cost breakdown in Figure 37, results that were calculated in another case study by Delrue et. Al [92]. It is apparent that moving from an open pond (raceway) to a PBR or even a hybrid (raceway + PBR) system, biomass production costs increase considerably. Apart from the capital expenditures in the upstream, the operating expenses for the different processes do also play a significant role, while the investment in purchasing and installing drying equipment cannot be ignored. The contribution of the other units to the total cost is calculated to be minor compared to the above mentioned.

The importance of producing rich in lipids biomass at high rates is shown by the sensitivity analysis conducted by Davis et al. for an open pond system feeding microalgae to a renewable diesel-oriented production plant [41]. Figure 38 shows the effect that the value of different parameters has on the minimum selling price of renewable diesel. Taking into account the results presented above, it can be concluded that microalgal diesel can be competitive to the commercial fossil and biofuels, only when microalgae with high concentration of lipids (→ 50 wt%) and fast growth rates (> 25 g m^{-2} d^{-1}) are produced. Therefore, the focus of development should be prioritised on the upstream sector.

Figure 37. Biodiesel production cost breakdown for three different microalgae cultivation systems: 1) Hybrid: open pond/PBR, 2) open raceway pond, 3) PBR [92]. All the prices were indexed to 2022

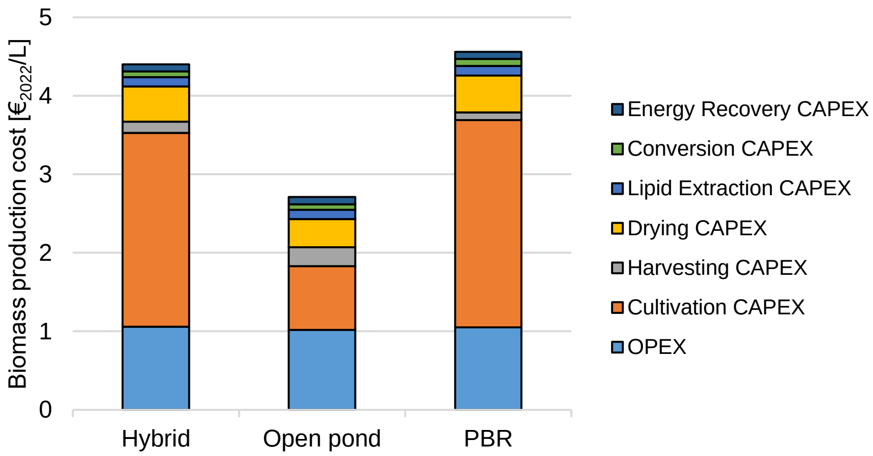
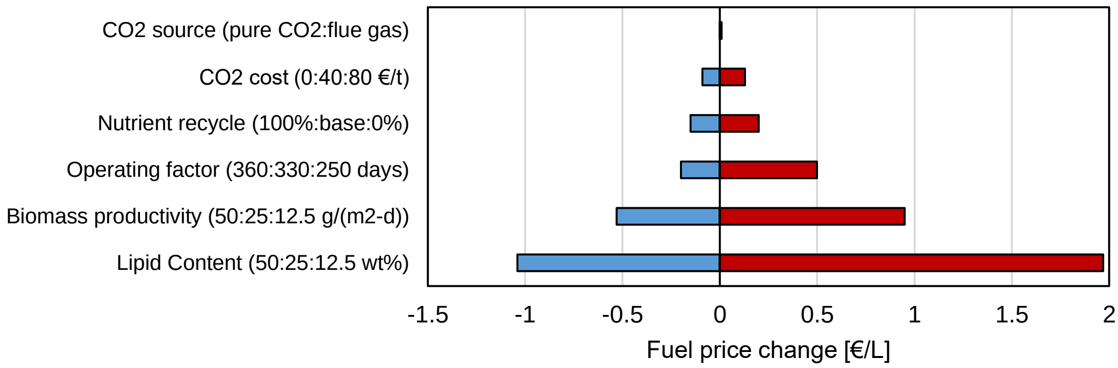


Figure 38. Sensitivity analysis conducted by Davis et. al. for renewable diesel production using open ponds for microalgae cultivation. The effect of the most important parameters on the minimum fuel selling price is displayed [41]



5.2.2.2. Thermochemical Pathway: Hydrothermal Liquefaction of Microalgae

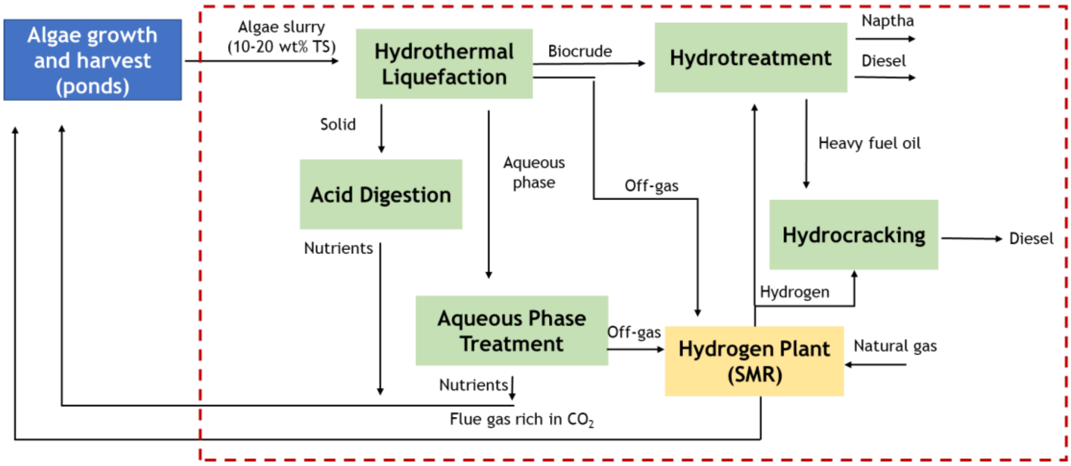
- **Process System Description**

As covered in the previous Chapters, thermochemical processes such as pyrolysis, gasification and hydrothermal liquefaction consist of alternative pathways for the production of biofuels from microalgae. Via the application of heat, not just lipids but also the other components of the biofeedstock (e.g., carbohydrates and proteins) can be turned into fuel. Under these conditions, high fuel yields are possible and as part of the cultivation strategy, maximising biomass productivity is prioritised over lipids accumulation [111]. Because harvested microalgae are diluted in water (0.1 wt%), hydrothermal liquefaction (HTL), a process converting biomass using pressurised water, has been the most studied thermochemical process as it is the only one that can handle high moisture feedstocks leading to lower drying expenses.

Freshly harvested microalgae are dewatered to form a slurry of 10-20 wt% solids as a reasonable trade-off between the capital costs for the HTL system and the dewatering costs. The slurry is supplied to the HTL reactor and under elevated temperatures (~350 ºC) and the use of pressurised water converted to a biocrude and aqueous phase, with small amounts of gas and char being also formed (see Figure 39). Once the produced char has been removed in a filter, the three different product streams (biocrude, aqueous and gas) are separated. The biocrude is primarily made up of C_{16}-C_{18} fatty acids, amides, phenols, naphthalene, substituted benzene, and some other heavy components while the contained moisture is in the range of 5-10 wt%. The aqueous phase consists of some biocrude components, small organic molecules rich in nitrogen, and dissolved CO_2 and ammonia [111]. As significant amounts of nutrients are found in the aqueous phase, it is important to treat this stream and recycle the nutrients to the algae farms. The gas phase is mostly CO_2, methane and light hydrocarbons; hence it is burnt for the generation of thermal energy. Lastly, ashes formed during the HTL reaction contain significant amounts of phosphorous making its recovery in a dedicated acid digestion unit important. The retained phosphorous is resent to the algae culture.

The biocrude is upgraded in a hydrotreater to remove heteroatoms such as nitrogen, oxygen and sulphur and form a range of hydrocarbons: mostly straight chain paraffins. For these studies, the supplied hydrogen is assumed to be produced in an on-site steam methane reforming (SMR) facility using natural gas and off-gas produced in the process units. The different cuts formed in the hydrotreater are separated in a distillation tower obtaining light hydrocarbons, gasoline/naptha, diesel and heavy fuel oil. The latter is further hydrocracked into naptha, jet fuel and diesel.

Figure 39. Block flow diagram of a microalgae to fuels HTL plant. These are the main process units that have been considered in the available TEA studies

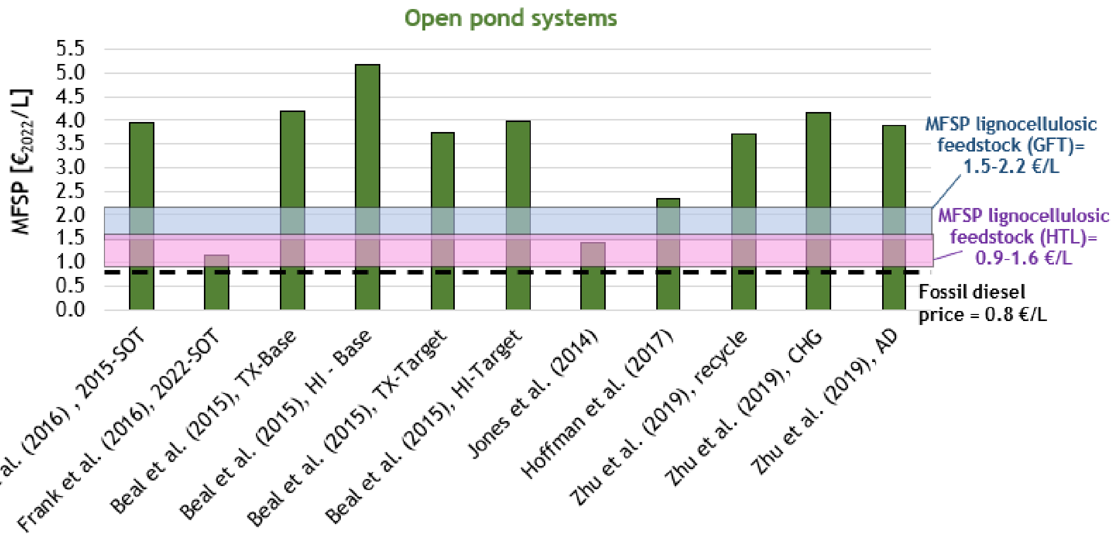


- **Economic Performance**

The minimum fuel selling prices (MFSP) of the different case studies after the harmonisation by Cruce et al. are displayed in Figure 40. The reported studies encompass a broad processing scale, with dry biomass input ranging from ~ 10 to 620 kt (after the harmonisation). When looking at systems considering open ponds for their assessment, the average price is equal to 3.4 €/L, which is higher than the average price calculated for lipid extraction pathways. In addition, opposite to what was presented for the lipid extraction pathways, the results show significant variance despite the harmonisation. This is justified by the higher uncertainty existing in the design and evaluation of hydrothermal liquefaction systems, as they are at experimental/pilot scale technology readiness. On the other hand, lipid extraction and hydrotreatment is already applied on commercial scale for biofeedstocks such as vegetable oil [112]. For example, biomass to biocrude yield is a key parameter for the economics of the biorefinery which was not harmonised by Cruce et al. Due to the uncertainty around the HTL technology, the assumed yield differs from study to study having a significant impact on the final results. For instance, the low price (= 1.2 €/L) reported by Jones et al. could be an outcome of the biocrude yield (= 59 %) used which is higher compared to the other studies (e.g. 43% and 46% assumed by Zhu et al. and Beal et al. respectively) [92], [111], [113]. However, yields over 50% have been rarely measured in experiments (see Table 8).

Moreover, multiple results come from the same publication as some studies evaluated the system under different scenarios and process configurations (e.g. using different models, cultivation processes). For instance, Zhu et al. evaluated the impact of different treatment methods for the waste aqueous phase on the economics. Specifically, they explored three different treatment configurations: direct recycling, catalytic hydrothermal gasification (CHG) and anaerobic digestion (AD). The results show that recycling stands out as the economically best method [113]. Beal et al. investigated the economics of a microalgae and HTL plant for two different locations (Texas (TX) and Hawaii (HI)) and two different scenarios; using the current state of technologies and a target case with optimistic parameters [93].

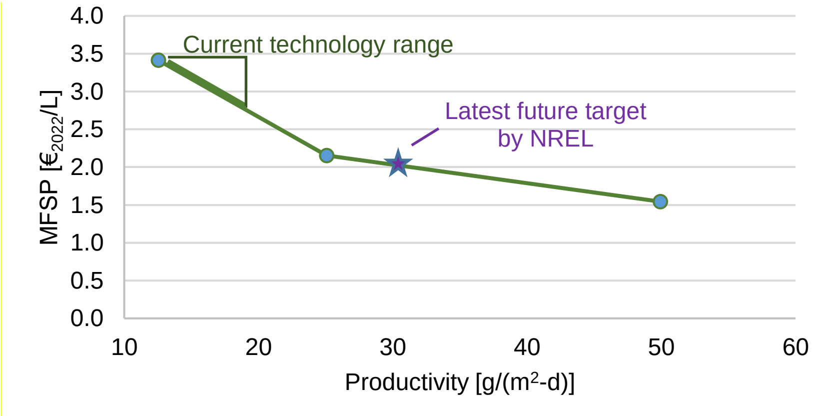
Figure 40. Minimum selling price of renewable diesel produced via hydrothermal liquefaction, calculated after the harmonisation by Cruce et al. (2021) of the assumptions reported in the different TEA studies [100]. The results have been calculated for a biomass productivity of 25 g m^{-2} d^{-1}. The price of fossil diesel as well as the MFSP of liquid fuels produced via HTL and GFT (gasification and Fischer-Tropsch) from lignocellulosic biofeedstocks have been included in the Figure as benchmark [109], [114], [115], [116][10]. All the prices were indexed to 2022



[10] The MFSP for GFT and HTL cover the economic results reported by Zhu et al. (2014), De Jong et al. (2015), Pedersen et al. (2018) and IEA (2024) for gasoline/diesel/SAF production for a range of feedstocks such as agricultural and forestry residues. The exact price depends on factors such as the feedstock used and its price, production scale (~700 to 1,300 kt dry biomass input for GFT, ~160 to 700 kt dry biomass input for HTL), state of technology and financial assumptions.

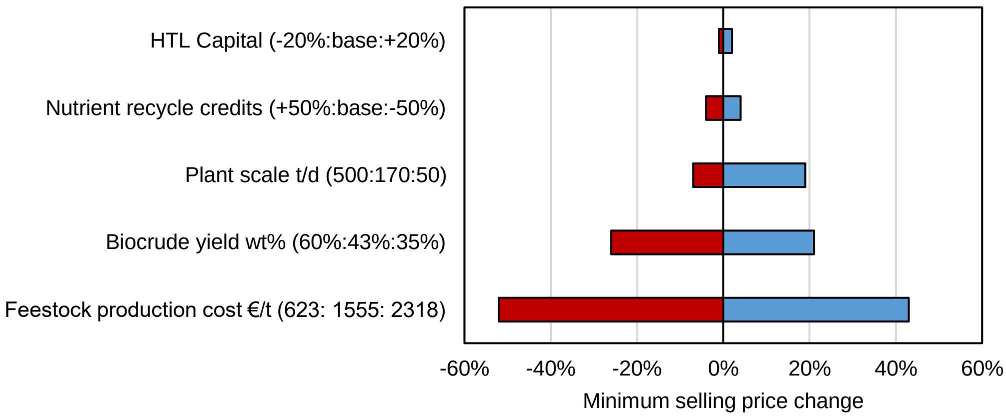
Biofuel production from microalgae via hydrothermal liquefaction is more costly than the existing commercial pathways, even for high biomass productivities (= 25 g m^{-2} d^{-1}). These productivities are not achievable with the current technological means, and as shown Figure 41 moving to values more representative of the current technology (≤ 18.6 g m^{-2} d^{-1}) leads to more unfavourable results. Even at the very high productivity of 50 g m^{-2} d^{-1}, which is significantly beyond the current technological capabilities, the minimum fuel selling price remains higher than that of pathways using lignocellulosic biomass.

Figure 41. The change in techno-economic assessment (TEA) result for different productivities (12.5, 25, and 50 g m^{-2} day^{-1}) after the harmonization conducted by Cruce et al [100]. The line shows the results of a model (upstream+downstream) selected by Cruce et al. as representative



Similar to the lipid extraction pathway, cost allocated to feedstock production (upstream) is one of the primary cost drivers along the HTL pathway. This is indicated in the tornado chart developed by Zhu et al. (see Figure 42) which shows the effect that varying key parameters have on minimum fuel selling price. Reducing biomass production costs by improving biomass productivity and systems efficiency is the primary way to make the pathway more economical, especially if it is combined with high conversion yields in the HTL reactor. The plant scale and the assumption of a 20% reduction in the capital costs of the HTL plant does not offer significant opportunity for reduction in selling price.

Figure 42. Sensitivity analysis conducted by Zhu et. al. (2019) for biofuel production *via HTL*. The effect of most important parameters on the MFSP is displayed [113]

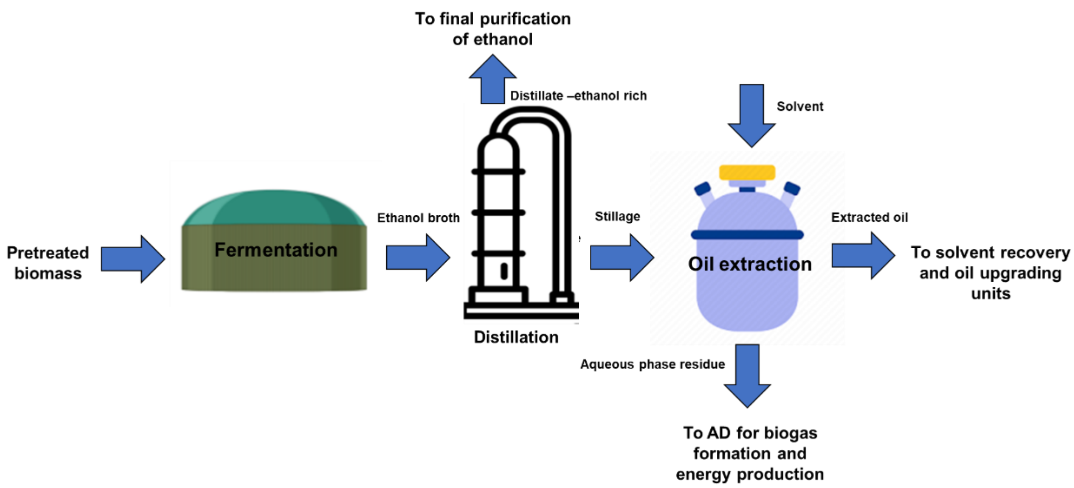


5.2.2.3. Combined Algae Processing (Multi-product Biorefinery)

As presented in the previous sections, solely producing biofuels from microalgae has proven to be economically uncompetitive compared to fossil diesel and commercial biofuels. In light of these economic challenges, some studies have been published in recent years focusing on developing, designing and assessing biorefinery alternatives where value-added co-products are produced alongside fuels. Although this multi-product approach adds complexity to the system, it offers the potential to drive down fuel selling prices and reduce the dependency on specific components such as lipids.

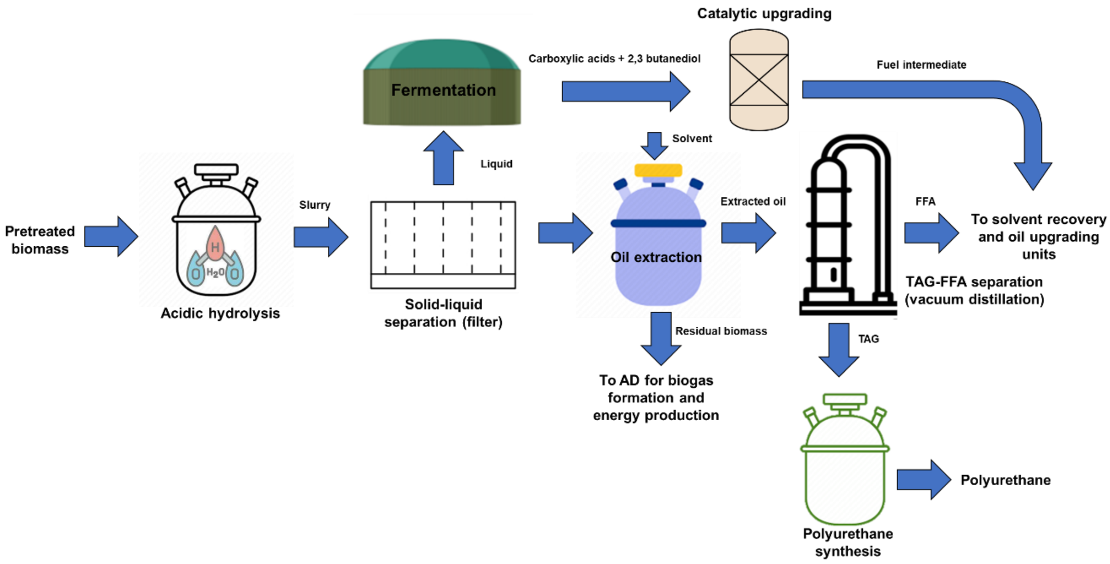
For example, NREL (Davis et al., Frank et al.) evaluated the case of maximising the utilisation of the different molecules towards fuel production. For this reason, they designed and assessed a process configuration in which both ethanol and renewable diesel are produced [66]. To achieve this, microalgal biomass is first fermented to produce ethanol and the stillage from the bioreactor is sent to an oil extraction unit. The extracted oil is then refined to high quality diesel (see Figure 43).

Figure 43. Combined algal processing (CAP) configuration proposed by NREL for ethanol and diesel production from microalgae [66]



NREL has conducted additional research on other multi-product scenarios, such as the co-production of polyurethanes [52]. Polyurethane has been a focal point for NREL due to its relatively high market price and volume. The conceptualised process is shown in Figure 44. This new process strategy starts with the hydrolysis of biomass, followed by a separation of the liquid from the solid phase in the slurry. The liquid phase, rich in sugars, is fermented to produce primarily carboxylic acid and 2,3 butanediol which can be then upgraded to fuel molecules through catalytic reactions. On the other hand, the solid phase from the slurry, after its recovery, is directed to an oil extraction unit. The recovered oil contains two main types of lipid molecules: TAG (triacylglyceride) and FFA (free fatty acid). The two lipids are separated in a distillation tower, with the TAG to be the feedstock for polyurethane formation and FFA to be used for hydrocarbon fuels production.

Figure 44. Combined algal processing (CAP) configuration proposed by NREL for polyurethane and renewable fuels production from microalgae [52]



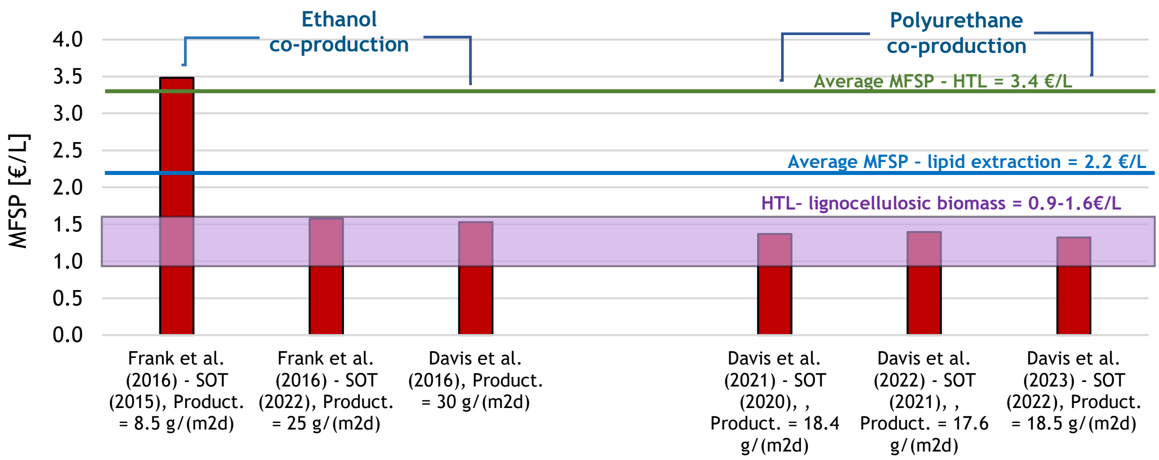
Opposite to the fuel-oriented pathways, for which the harmonised results by Cruce et al. 2021 were presented, here a different approach is followed. In the study by Cruce et al, no harmonisation of biomass productivity was carried out for the CAP case studies resulting in substantial discrepancies in the biomass production costs, and consequently in the MFSPs. In addition, their study did not incorporate the latest state of technology (SOT) reports by NREL which evaluate polyurethane co-production. For this reason, both series of studies by NREL evaluating ethanol and polyurethane co-production are presented in this report, with the differences in biomass productivity considered in each study to be indicated on the figures. It is worth noting that for some of the ethanol case studies, optimistic assumptions regarding biomass productivity (ranging from 25 to 30 g m^{-2} d^{-1}) were made, as these values exceed the current state of technology (annual average max = 18.6 g m^{-2} d^{-1}). Finally, considering the differences in biomass productivity, the results from the different case studies can be compared, as the numerical differences in economic parameters from study to study are very small, with the largest variation being (±3%) observed for the income tax rate.

- **Economic Performance**

The minimum fuel selling price (MFSP) of the three case studies evaluated and harmonised by Cruce et al. (productivity values were not harmonised) focusing on ethanol co-production are displayed in Figure 45 alongside the most recent case studies by NREL on polyurethane co-production. Compared to the cases focused solely on renewable diesel or biodiesel production, combined algae processing shows to offset the additional costs associated with co-product formation. This leads to lower MFSPs, making the multi-product business case more enticing.

Especially for the case of co-producing polyurethanes, due to the large credits coming from selling this highly priced chemical, a MFSP below 2.0 €/L is attainable. Further advancing microalgae cultivation systems to achieve average productivities in the range of 25-30 g $m^{-2}d^{-1}$ shows the potential, at least at this conceptual stage, to ensure the production of renewable fuels at prices comparable to those of other biofuel pathways.

Figure 45. Minimum fuel selling price of renewable fuels produced in a combined algal processing biorefinery reported in the different TEA studies[100], [52]. The minimum selling price of advanced biofuels from lignocellulosic biofeedstocks are included in the Figure as benchmark. All the prices were indexed to 2022



6. LIFE CYCLE ASSESSMENT OF ALGAE TO BIOFUEL PATHWAYS

6.1. INTRODUCTION TO METRICS AND METHODOLOGY

The objective of this Chapter is to assess the sustainability of algae to biofuel pathways through the literature review of scientific publications reporting values for two key sustainability metrics: Net Energy Ratio (NER), and GWP – global warming potential. Life Cycle Assessment (LCA) is the systematic and international standard framework being used to holistically analyse the sustainability and environmental impact throughout the supply chain of a certain product or service. Regarding the metrics, NER indicates the energy efficiency of a system and is calculated according to the equation below. A NER < 1 indicates a favourable energy balance for the system. GHG intensity is linked to the environmental impact of emitting carbon dioxide, methane and nitrogen oxides. The standardised method calculates GHG emissions over a 100 years horizon (GWP 100 – $gCO2_{eq}$). The functional unit used is $gCO2_{eq}$ /MJ_{fuel}.

$$NER = \frac{Energy\ input\ (= consumption)}{Energy\ output\ (products)}$$

A number of studies have evaluated the life cycle performance of algal biofuels production and use, especially of those derived from microalgae. To obtain these results, specialized tools such as SimaPro and GREET and inventories like Ecoinvent are used. However, it is important to note that many of these assessments, although they are commonly referred to as LCA, do not account for indirect emissions associated with the construction and maintenance of facilities. Moreover, indirect land use changes are not included in the scope of analysis, though land-use is considered in line with the ISO standard.

For multi-functional production systems, such as biorefineries, some studies follow an attributional approach, allocating GHG emissions to products based on energy content (lower heating value, LHV), in line with the GHG calculation methodology of the Renewable Energy Directive (RED). Other studies use a system expansion, where the GHG credits are attributed based on replacement of conventional products with biorefinery co-products (i.e. animal feed, bioelectricity). The reason for this is that some co-products (e.g. fertiliser) would be underestimated if they were considered on an energy basis, because their low energy content do not depict their effect on the whole-system emissions [117]. According to RED III, the fossil fuel comparator is equal to 94 $gCO2_{eq}$ /MJ, and a GHG reduction threshold of 65% for new installations producing biofuels is in place (33 $gCO2_{eq}$ /MJ_{fuel}).

Despite the availability of data regarding the energy efficiency and GHG emissions of microalgae to biofuel pathways, the different assumptions across studies have a significant impact on the final results and do not allow in many cases to draw conclusions. For example, considering different boundaries for the system (well to wheel or well to pump approach) and GHG accounting methods for the co-products, as well as using different biomass productivities or conversion yields can impact the outcome of the LCA. For this reason, in order to minimise uncertainty and provide reliable conclusions, wherever it is possible, this report places emphasis on literature review studies that have attempted to harmonise the varying assumptions to review the sustainability performance.

6.2. LCA - BIOFUELS FROM MACROALGAE

The scientific community has investigated the production of fuel-grade ethanol from seaweed that are rich in carbohydrates. Therefore, this particular pathway is the one we will focus on for our analysis. Ethanol can be produced based on two different biorefinery process strategies: either in a biorefinery targeting only fuel production, where the remaining materials are considered waste and utilized for energy purposes, or in a process configuration in which non-fermentable components, such as proteins are extracted and sold.

Based on the literature review, a sparse number of case studies assessing the GHG intensity of macroalgal liquid biofuels have been identified. Landscape, climate, harvesting practices and energy mix may significantly vary from country to country, hence every case study assesses ethanol production from algae for a specific part of the world. The regional differences as well as the different technical assumptions taken in the studies can create significant variance in the final results, hence no universal conclusions shall be drawn. It is important to note that parameters like the carbon intensity of the electricity grid are not updated to the latest values but reflect the conditions when the studies were conducted. No harmonisation study is available for macroalgae, therefore further investigation is necessary to gain a comprehensive understanding of the sustainability performance of these pathways.

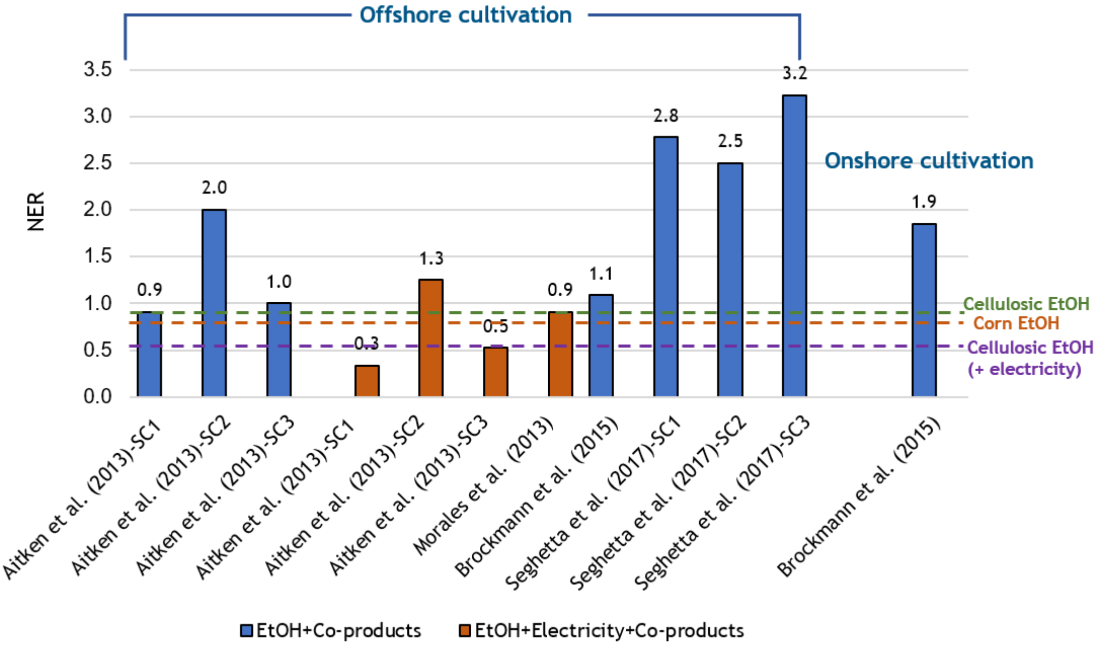
6.2.1. Energy Efficiency

The net energy ratio (NER) as reported in the different studies is given in Figure 46. The same publication is sometimes quoted multiple times as the same system was assessed for different productivities, species or cultivation techniques to cover a wide range of possibilities. Each study evaluated the pathway under different conditions and locations. For example, Morales et al. and Seghetta et al. analysed a production line placed in Denmark, Brockmann et al. a seaweed farm in France whereas Aitken focused on Chile [118], [119], [120], [121]. The geographical location has an impact on the type of seaweed which is selected and the respective productivity in the farm. Furthermore, variations in assumptions regarding the seaweed production method, biorefinery location, and conversion yields also contribute to the variability in the results. Due to these discrepancies, a wide range of values for NER (0.3-3.2) are reported in the literature.

A general trend the bar chart shows is that biorefineries designed to use biomass residues to generate electricity demonstrate higher energy efficiency (lower NER), as electricity is an energy carrier of higher exergy. According to Aitken et al. (Chile case studies), an energy-efficient system (NER < 1) may be feasible, particularly when electricity is produced alongside ethanol and fertilizer. However, many studies indicate that bioethanol production from macroalgae is not energetically favourable.

Aitken et al. found that seaweed species and cultivation method selection significantly impact cumulative energy consumption, as evidenced by the variability of energy ratios in their study. The most favourable NER scenario proposed by Aitken (scenario 1) involves cultivating *G. chilensis* at the bottom of the sea, rather than using long lines of seaweed, to minimize energy requirements. However, this method may not be feasible on a large scale due to the sea depth restrictions. The second most energy-efficient scenario (scenario 3) involves producing *M. pyrifera* using the conventional long-line cultivation method, with this species offering a conversion yield to ethanol two times higher than *G. chilensis* used in scenarios 1 and 2. Conversely, Seghetta et al. calculated the least favourable NER, as their study was the only one to consider a biorefinery located far from the shore, resulting in additional energy consumption for transporting seaweed via trucks (drying of biomass before transportation). This nearly triples total energy consumption compared to a biorefinery located onshore making this option inefficient. These results highlight that placing the biorefinery close to the algae farm, producing seaweed with energy-efficient cultivation methods, high conversion yields to ethanol and using the biomass residues to generate thermal and electrical energy are important factors for achieving an energy efficient pathway.

Figure 46. Net energy ratio (NER) of macroalgae to ethanol (EtOH) reported in the different studies available in the literature. The studies are grouped (by colour) according to the different products formed and sold along with ethanol. The scenarios by Aitken et al. are the following: SC1: seaweed = *G. chilensis* (bottom-planted), SC2: seaweed = *G. chilensis* (long-line cultivation), SC3: seaweed = *M. pyrifera* (long-line cultivation). The scenarios by Seghetta et al. are the following: SC1: *L. digitata* – base case, SC2: *L. digitata* – high productivity, SC3: digitata – high productivity – lower conversion yield. The NER of corn-based and cellulosic ethanol are also included in the figure for benchmark [122]



6.2.2. GHG Intensity

The same studies that reported the energy efficiency of seaweed to ethanol also calculated the associated GHG emissions generated throughout the pathway. However, each study followed a different GHG accounting methodology. For instance, Brockmann et al. applied an attributional method to allocate the GHG intensity to products based on energy content. Contrary, Aitken et al., Morales et al., and Seghetta et al. calculated the GHG intensity by incorporating the displacement credits of co-producing bio-based products. These important differences in the methodology among the studies hinders their direct comparison.

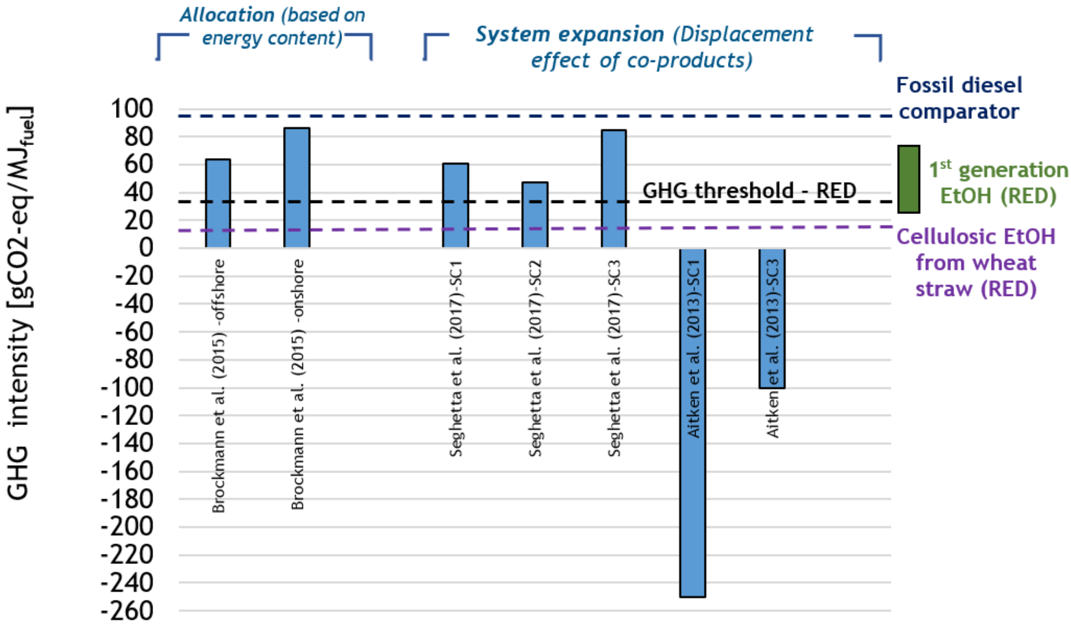
For the purposes of this review, the results of the various studies are presented in Figure 47, categorized according to the accounting method used to allocate GHG emissions to the co-products in each study (any displacement effect of primary product - fuel ethanol was excluded). All results have been normalized to the same units, $CO_{2\text{-}eq}$/MJ, with reported GHG intensities varying significantly, ranging from -250 to 86 gCO2-eq/MJ.

Factors such as the GHG accounting method used, the seaweed production method, conversion yield to ethanol, and co-products significantly influence the final results. Studies using a system expansion approach, which accounts for the displacement effect of co-products like substituting fossil electricity with electricity generated from producing and burning biogas, tend to report lower GHG intensities. For instance, Aitken et al. reported negative emissions as the largest portion biomass (94%) is not converted to ethanol and is used to produce fertiliser (recycled to the soil) and electricity, offering significant GHG credits. This, combined with energy-efficient cultivation methods, particularly in Scenario 1, leads to a negative balance of emissions. Conversely, Brockmann and Seghetta et al. reported higher emissions for seaweed growth, with most of the unconverted biomass used for animal feed production, providing lower GHG benefits. These results highlight the significant impact that GHG methodological choices have on the final results and underscore the importance of process configuration and targeted co-products in achieving low GHG intensities.

The sustainability of fuel ethanol derived from macroalgae compared to fossil diesel, commercial crop-based bioethanol, and cellulosic bioethanol is shown in Figure 45. It is important to recognize that the GHG reduction threshold and biofuel GHG intensities refer to the default values in Annex V of RED III. These values are calculated using the RED GHG accounting methodology, which differs from those used in algae studies (e.g., displacement credits from electricity surplus are not included), making direct comparisons challenging (the results by Brockman et al. are the most comparable). Nevertheless, these figures serve as a useful reference for understanding the sustainability levels of algal biofuels.

In summary, the lack of multiple results and a consistent calculation framework for GHG emissions makes it challenging to draw definitive conclusions about the GHG impact of producing biofuels from seaweed. More research using a harmonized approach, particularly in alignment with the RED methodology for the EU, is necessary to better understand how bioethanol from macroalgae compares to alternative biofuel pathways.

Figure 47. GHG intensity (gCO2-eq per MJ) of macroalgae to ethanol pathways reported in different studies available in the literature. The GHG intensity (default values) for commercial ethanol from food and feed crops (25-72 gCO2-eq/MJ), cellulosic ethanol from wheat straw, the fossil fuel comparator and the GHG emissions reduction threshold as given in RED III are included.



6.3. LCA - BIOFUELS FROM MICROALGAE

Many different studies have quantified the energetic and GHG intensity linked to the production of microalgae and their conversion to biofuels. However, the different assumptions on the system boundaries, biomass productivity, conversion yields and process optimisation across the studies creates a significance variance in the final results. To address this challenge, Cruce et al. conducted a literature review to collect case studies (published after 2010) which evaluated the LCA performance of microalgae to renewable diesel or biodiesel [100]. Following this, Cruce et al. harmonised the assumptions in the case studies regarding system boundaries and biomass productivity and re-evaluated the results on this new common basis. For the harmonised system boundaries, a Well-to-Wheel approach was applied.

6.3.1.1. Energy Efficiency

The NER (for open raceway ponds) calculated by Cruce et al. after the harmonisation of the system boundaries and productivity assumptions for the different studies is given in Figure 48. The results are given as a function of the different downstream technologies that can be used for biomass to biofuel conversion. As commented by Cruce et al., no significant change is observed in the results after harmonisation. This leads to the conclusion that biomass productivity is not the primary driver for energy efficiency, but there are other more important variables such as the conversion yield of biomass to biofuels which were not harmonised.

Multiple results come from the same publication as some studies evaluated the system under different scenarios (i.e. baseline vs. optimised). The NER varies by 2.81 between the lowest and highest values, with differences attributed to variations in process configurations, conversion yields, and the valorisation of residual biomass. To achieve an energy-efficient system (NER<1), high conversion yields of biomass to fuels are essential. For instance, Liu et al. (2013) reported the most inefficient system, probably due to low biomass-to-fuel conversion yields (20%) assumed for the HTL process. Conversely, studies that reported energy-efficient systems typically assumed conversion yields exceeding 30%.

High conversion yields alone, however, are not enough to ensure energy efficiency. The ability to process wet biomass without energy-intensive drying is consistently cited as necessary. The HTL process can convert wet biomass (with 20 wt% solids content), while lipid-based pathways require wet extraction of lipids rather than conventional dry extraction. Although all studies focusing on lipid-based pathways assume wet extraction, this process has not yet been developed to achieve efficient extraction rates and requires further research [123], [124]. Finally, all studies reporting energy-efficient systems assume the utilization of residual biomass for co-generating heat and electricity, enhancing in this way energy savings.

Figure 48. Net energy ratio (NER) of microalgae to biofuel pathways (for open raceway ponds) reported in different studies for a fixed microalgae productivity of 25 $gm^{-2}d^{-1}$. Microalgae productivity and system boundaries across the studies have been harmonised by Cruce et al. [100]. Conversion technologies are specified by colour

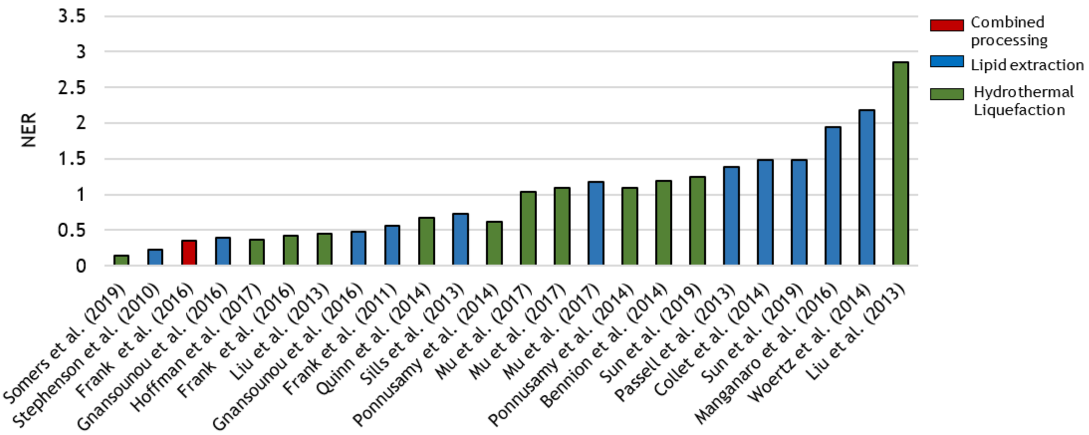
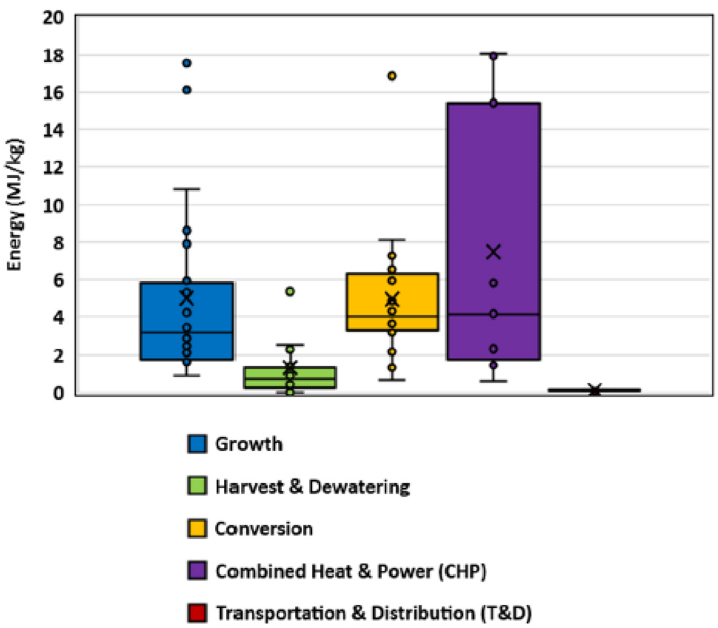


Figure 49 presents the results (range, median, mean values) of a following statistical analysis by Cruce et al. showing the energy breakdown [MJ/kg_{fuel}] into the different subunits. It is clear that the largest discrepancies among studies arise from the assumptions made for the combined heat & power (CHP) unit and then for microalgae growth (water pumping and circulation power, photosynthetic energy not included). In CHP facilities, the light gases produced in the plant as well as the biogas produced during the anaerobic digestion of residual biomass are burnt for the generation of heat and electricity. Although the assumptions concerning electricity production are relatively straight-forward, modelling assumptions for biogas production in AD and heat recovery are variable. The quality of the produced heat is an important metric for heat recovery which is not discussed in the existing studies [100].

Figure 49. Harmonized energy requirements by sub-process, normalized to a per kg algae basis. The range, median, & quartiles (boxes); mean (marked by the X); and individual data points (dots) are shown for each sub-process as calculated by Cruce et al. [100]



6.3.1.2. GHG Intensity

Cruce et al. employed the same harmonisation approach in calculating the GHG intensity. However, they found that harmonizing productivity had not an important impact on the results. Thus, variations across studies can be attributed to other factor such as GHG accounting methodology, biomass-to-fuel conversion yields and regional factors (carbon intensity of the electricity grid). The GHG intensity is directly linked to energy consumption and proportional to the energy efficiency discussed in the previous section. However, the GHG emission differences between studies are not always proportional to energy efficiencies, as the GHG accounting methodology, especially how emissions are allocated to co-products, can significantly influence the final results. For instance, some studies allocated emissions based on the energy density or market value of the primary product and co-products (attributional), while other studies considered the displacement effect of co-products, particularly when electricity is co-produced, accounting for the avoided emissions from fossil electricity substitution.

The results of the different available studies in the literature, after the harmonisation by Cruce et al., are presented in Figure 50 and categorised based on the GHG accounting method used. The harmonised results exhibit a wide range of GHG intensity, spanning from 31 to 375 $gCO2_{eq}/MJ_{fuel}$ which highlights the uncertainty that comes with drawing conclusions on the environmental performance of these pathways. However, by delving deeper into the assumptions and process configurations used in each LCA study, some useful conclusions can be drawn. Most studies reporting the lowest GHG emissions and significant savings compared to fossil fuel comparators employ a process configuration where residual biomass is treated via anaerobic digestion. The produced biogas, along with other light process gases, is burned in a CHP plant. This setup generates electricity and heat, meeting significant energy needs of the plant and reducing the reliance on external fossil-based energy. Depending on the process assumptions, some case studies produce excess electricity, which is sold to the grid, offering substantial GHG credits. Additionally, some case studies—often those reporting the lowest GHG emissions—incorporate in their accounting methodology, the GHG savings from burning the produced biogas (instead of fossil natural gas). This underscores the importance of using biomass residues for energy generation and the influence that the accounting method for GHG emissions and credits has on the final results.

Comparing the results to the fossil fuel comparator set by RED, some studies report significant emission savings, especially those employing an energy optimization approach and utilizing biomass residues for heat and electricity generation. However, in some cases, emissions are close to or even higher than the fossil comparator. This can be attributed to low conversion yields to fuels, lack of carbon credits from heat and electricity generation, or no accounting of these credits. Additionally, most case studies report emission values higher than the GHG reduction threshold set by RED III, due to these inefficiencies[11].

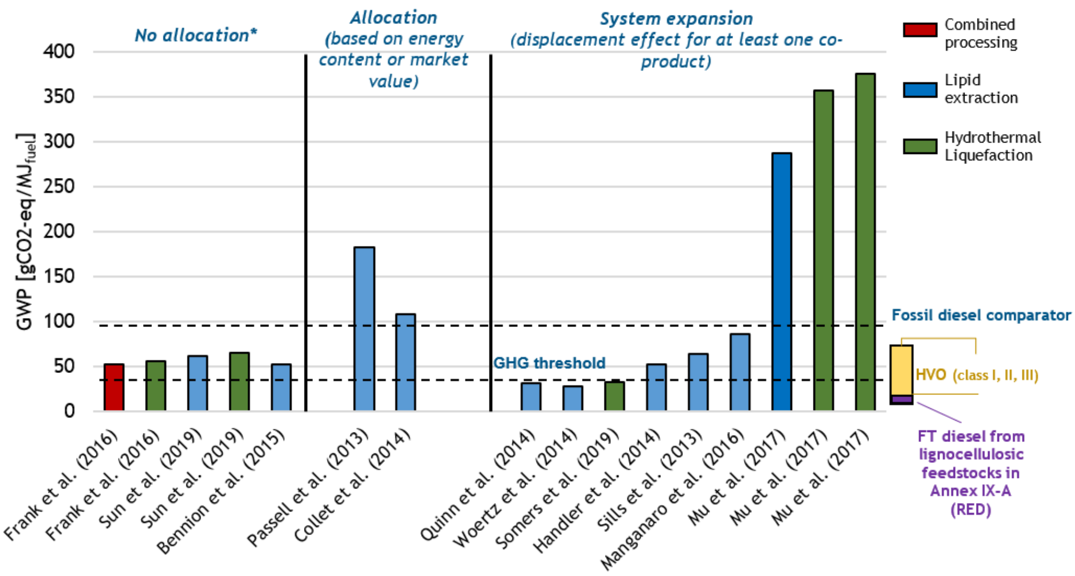
Compared to advanced biofuels from other biofeedstocks, such as the case of FT diesel included in the figure, achieving such low GHG intensities for algae-based fuels is challenging. This is primarily because significant amounts of energy are required for upstream processes, including microalgae growth and harvesting. However, there is potential for improvement, as all the case studies reviewed in this section rely on fossil energy and fossil-based material inputs to meet energy and material demands. Transitioning to a renewable and bio-based economy (e.g., using renewable methanol for transesterification, renewable electricity) could provide substantial benefits to algae production and reduce its GHG footprint.

More research on updating the case studies and evaluating the pathways under a more sustainable framework—such as using the current and the projected future carbon intensity of the electricity grid or employing more sustainable energy and material solutions—can showcase the sustainability potential of algal biofuels, an aspect that has not been investigated so far. For instance, placing algae farms next to solar panels could be an interesting case to evaluate, as microalgae productivity is favoured in regions with sufficient sunlight. The algae farms could potentially utilize the electricity generated by solar panels, creating a synergistic system that supports sustainable biofuel production. For instance, a recent study by Bradley et al. demonstrated that integrating microalgae production with solar panels could reduce emissions in biodiesel production by 54% on a direct emissions basis. When considering both direct and indirect emissions (including operation and infrastructure), the reduction potential was 38% [125].

Additionally, further investigation into the impact of various assumptions, beyond just the productivity of microalgae, on GHG emissions will help identify the conditions under which the sustainability of algal biofuels can be maximised. Finally, for the case of assessing algae to biofuel pathways under the EU framework, it is important that LCA studies using the GHG methodology of the Renewable Energy Directive are carried out, since the existing scientific work relies on different GHG accounting methodologies.

[11] Important to clarify that the presented GHG reduction threshold and biofuel GHG intensities refer to the default values in Annex V of RED III. These values are calculated using the RED GHG accounting methodology (allocation based on energy content), which often differs from those used in algae studies (e.g., any displacements credits from electricity surplus are not accounted). Nonetheless, these figures remain a useful reference point for evaluating the sustainability of algal biofuels.

Figure 50. GHG intensity of microalgae to biofuels as calculated in different studies for a microalgae productivity of 25 $gm^{-2}d^{-1}$. The assumption on microalgae productivity and system boundaries across the studies were harmonised by Cruce et al. [100]. The GHG intensity of commercial biofuels, such as HVO and FT diesel from Annex IX-A biofeedstocks, and the GHG reduction threshold for biofuels in Renewable Energy Directive are included[12]. *No allocation refers either to a single-product system or to a publication where no conclusion on the methodology used could be extracted



[12] Important to clarify that the presented GHG reduction threshold and biofuel GHG intensities refer to the default values in Annex V of RED III. These values are calculated using the RED GHG accounting methodology, which often differs from those used in algae studies. Nonetheless, these figures remain a useful reference point for evaluating the sustainability of algal biofuels.

7. CONCLUSIONS AND RECOMMENDATIONS

This report offers a comprehensive overview of the current status of algae to liquid biofuel pathways, shedding light on their economic performance and sustainability through an analysis of existing literature. Despite the early enthusiasm surrounding the potential of algae as a bioenergy source in the early 2010s, driven by their high growth rates outpacing those of terrestrial biomass, the development of these technologies has stalled at the experimental stage. This lack of progress can be attributed to significant technological and economic challenges, leading many industry players to withdraw their investments.

Among the various process routes that could be applied to produce liquid biofuels from algae, only a certain number of them can be practical and has been explored so far. When it comes to macroalgae, a feedstock typically rich in carbohydrates, the focus has been primarily on converting it to ethanol through fermentation. However, the commonly used fermentation microorganisms have not shown efficient conversion of algal sugars to ethanol, as evidenced by experimental results. On the other hand, microalgae have a different composition, with a significant portion of biomass consisting of lipid molecules. Therefore, extracting lipids from microalgae to produce biodiesel or renewable fuels have emerged as the most interesting pathway, as revealed by this literature review. Nevertheless, the lipid content of microalgae exhibits considerable variation from season to season, and increasing it to high levels (> 30% wt) typically constrains biomass productivity. These factors have prompted researchers to also explore the hydrothermal liquefaction pathway, which is well-suited for wet biomass like algae.

Regarding the economics and sustainability of using macroalgae for ethanol production, there is a limited number of techno-economic and LCA studies. These studies use varying assumptions, resulting in substantial differences in their findings. For example, reported minimum ethanol selling prices vary widely, with case studies that account for the current technological limitations calculating ethanol prices substantially higher than those for cellulosic ethanol from other biofeedstocks. Lowering biomass production costs (to below 80 €/t) and improving conversion yields to ethanol are some of the actions needed for the economic competitiveness of this pathway. Additionally, GHG intensity levels range from negative to near fossil fuel levels, depending on the GHG accounting method, co-product selection, biorefinery location, and macroalgae production methods. Key strategies to improve the system's energy and GHG performance include situating the biorefinery adjacent to macroalgae production sites and using non-convertible biomass to generate energy and produce fertilizer.

Compared to macroalgae-based pathways, there have been more techno-economic and LCA studies for producing biofuels from microalgae. It is agreed that using open ponds instead of photobioreactors for microalgae production is the economically best option considering the state-of-the-art productivity in open ponds (placed in locations with sufficiency of sunlight). Cruce et al. harmonized system boundaries, biomass productivity (fixed at 25 g m^2/day), and economic parameters across various techno-economic and LCA studies, resulting in a narrower range of economic and GHG intensity results. However, for certain pathways such as hydrothermal processing, significant variations persist in the post-harmonization results due to unchanged key process performance assumptions, like the biomass-to-biocrude conversion yield. The minimum fuel selling price for lipid extraction pathways exceeds in most cases 2 €/L (statistical average = 2.2 €/L), while for the hydrothermal pathway, it is above 3 €/L (statistical average 3.4 €/L), prices higher than the alternatives of advanced biofuels from other biofeedstocks. This economic gap is expected to be even larger if we consider that the state of art productivity in open ponds does not exceed 18.6 g m^{-2} d^{-1} which entails higher biomass production costs. All these results show the need for further development efforts on enabling more competitive production costs. Studies consistently agree that microalgae production is the primary cost driver in biofuel pathways. To make microalgal biofuels more competitive, key actions include increasing pond size and achieving high biomass productivity (25-30 $gm^{-2}d^{-1}$) while maintaining high lipid content (-> 50 wt%). In addition, the alternative of a multi-product biorefinery co-producing other materials such as polyurethanes along fuels seems to perform economically better, therefore, research groups such as NREL have shifted their focus towards this direction. As for the GHG intensity of these pathways, it varies significantly across studies even after the harmonisation due to differences in technical assumptions and the GHG accounting methodology used in the LCA models. The GHG intensity calculated for the microalgae to biofuel pathways is according to most studies lower than the reference value for fossil fuels (RED - 94 $gCO_{2\text{-eq}}$/MJ) but higher than the GHG reduction threshold set in the RED (33 $gCO_{2\text{-eq}}$/MJ).

Given the absence of a standardized method for calculating GHG emissions, further research adopting a unified approach, especially aligned with the Renewable Energy Directive (RED) methodology, is advisable. Additionally, revising existing case studies and assessing pathways within a more sustainable framework—by incorporating current and anticipated future carbon intensity of the electricity grid or exploring more eco-friendly energy and material solutions—could provide a clearer picture of the sustainability potential of algal biofuels, a dimension that is underexplored.

8. LIST OF ABBREVIATIONS

AD	Anaerobic Digestion
CAPEX	Capital Expenditures
CHG	Catalytic Hydrothermal Gasification
CHP	Combined Heat and Power
DCF	Discount Cash Flow
DM	Dry matter
EtOH	Ethanol
FAME	Fatty Acid Methyl Ester
FAO	Food and Agriculture Organisation of the United Nations
FCI	Fixed Capital Investment
FFA	Free Fatty Acid
GFT	Gasification and Fischer Tropsch
FT	Fischer Tropsch
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEFA	Hydroprocessed Esters and Fatty Acids
HMF	xymethylfurfural
HTL	Hydrothermal Liquefaction
HVO	Hydrotreated Vegetable Oil
IEA	International Energy Agency
IRR	Internal Rate of Return
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LHV	Lower Heating Value
MFSP	Minimum Fuel Selling Price
NER	Net Energy Ratio
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
OPEX	Operating Expenses
PBR	Photobioreactor
RED	Renewable Energy Directive
SAF	Sustainable Aviation Fuel
SC	Supercritical
SHF	Separated Hydrolysis and Fermentation
SMR	Steam Methane Reforming

SSF	Simultaneous Saccharification and Fermentation
TAG	Triacylglycerol
TE	Transesterification
TEA	Techno-economic Assessment
TRL	Technology Readiness Level
USD	USA Dollars
Wt	Weight
WtW	Well to Wheel
1G	1st Generation
2G	2nd Generation

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