Louvain School of Management
and Norwegian School of Economics

Economic feasibility of microalgae as a source of biodiesel

Techno-economic and sustainability analyses

Research Master's Thesis submitted by
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List of Abbreviations

ATP	Adenosine triphosphate
CCS	Carbon capture and storage
CH_4	methane
CO_2	carbon dioxide
EER	energy efficiency ratio
ERRIN	European regions research and innovation network
EU	European Union
GHG	greenhouse gas
H_2	hydrogen
HTL	hydrothermal liquefaction
IRR	internal rate of return
LCA	life cycle assessment
LEA	lipid-extracted algae
MFSP	minimal fuel selling price
MSP	minimal selling price
N	nitrogen
NPV	net present value
P	phosphorus
PBR	photobioreactors
SDS	sustainable development scenario
SI	sensitivity indicators
SV	switching values
TEA	techno-economic analyses
WF	water footprint

List of figures

List of tables

Contents

1. Introduction

Energy is an unescapable value to support human activities and development. Since the industrial revolution in the 18th century and the exponential use of coal, the demand in energy never stopped growing. Today, the energy consumed across the world is mainly derived from fossil fuels (crude oil, natural gas and coal) and nuclear energy (BP Statistical Review of World Energy, 2020). While public acceptance of nuclear power industry will certainly remain a matter of debate for the next decade, it is now clear that non-renewable sources of energy will be depleted in a time frame that appeared to be suddenly close. In particular, considering the global demand, crude oil supply is thought to last till 2050. Although awareness among the population was initially raised by the risk of shortage, and not by the major negative impact of fossil fuels-derived carbon dioxide (CO_2) on the environment, increased temperature and consecutive weather disturbances including flooding and heat waves acted as triggers to legitimize and accelerate the search for alternative source of energy.

Plant biomass holds this potential to offer reliable alternative sources of energy (McKendry, 2002a). Bioethanol production from agricultural sources was among the first example of biofuel issued from plant biomass. In the last two decades, governmental measures were adopted all over the world to promote the use of biofuels for transport. But the increasing understanding that direct competition with food crop production was not the best option led to think about more sustainable approaches such as the production of biodiesel from microalgae cultures.

1.1 Questions

The interest of microalgae to produce biofuels originally stems from their potential to maximize productivity by converting the energy of solar photons into biomass energy during the process of CO_2 fixation. Economic feasibility of biofuel production from microalgae however requires to scale up industrial processes without compromising environmental sustainability of the production. What are the tools to explore these issues considering that the technology is still maturing and that biological parameters need to be integrated in the calculation of profitability? While models can be designed to address economic feasibility, how is the uncertainty and risk evaluated? Which directions should take the research and development based on these techno-economic models? Is the sustainability part of the techno-economic analyses? What about the impact of microalgae-derived energy on the environment and the society? What are the roles of European institutions and/or national governments in the development of a future sustainable algae sector?

1.2 Outlines

This master thesis aims to identify and discuss the issues of economic viability and sustainability of microalgae-based biofuel production. We will first position microalgae as a biomass source in the larger context of renewable sources of energy (chapter 2) and will focus on the technological issues related to this specific mode of biofuel production (chapter 3). We will then present a brief meta-study reviewing representative techno-economic analyses (TEA) published in the last years. This approach will provide us with an assessment of the most relevant productivity parameters and research priorities for future development of microalgae-related technology (chapter 4). Next, through the examination of recent life cycle analysis (LCA) studies, we will aim to address sustainability issues related to the different inputs and outputs of microalgae-to-biodiesel supply chain (chapter 5). Finally, we will summarize the current political-economic context including the current and to-be-implemented EU algae strategy (chapter 6). Finally, we will summarize the most striking issues identified in the above chapters and identify current perspectives for the microalgae sector (chapter 7).

2. Energy sources

2.1 Fossil fuels

For centuries, fossil fuels have been in abundance and economically profitable (BP Statistical Review of World Energy, 2020). They had the advantage of being easy to find and produce, and could also benefit from the presence of infrastructure allowing their distribution at low cost worldwide. However, since the oil crisis in the 70s, the world had to face a new reality, fossil fuels could become unaffordable. Since then, reserves have yet decreased, resulting in higher search costs for new deposits and higher production costs. Even though the date we expect to run out has been postponed several times and is still distant (approximatively 30 years) (Bhagea et al., 2019), this energy source is no longer considered infinite and sufficient to provide the growing population needs. What was considered as the reassuring qualities of fossil fuels namely being economical and abundant, today appears very fragile.

Although in decline, new coal, oil and gas deposits are still uncovered. Research into extraction techniques has made considerable progresses, as we have seen with fracking to release gas from rocks. This allows a stable 24/7 supply of cooling and heating, electricity, and fuel for transportation for the time being. In terms of fossil fuel fate, it is also worth considering that petrochemicals can also be extracted to produce plastic and other industrial by-products. Although we are now more aware of the dangers of using petroleum-based plastic derivatives due to the limits of recycling, their almost inescapable use in all levels of our society forces us to consider them when thinking about fossil fuels reserves.

The general population comes to understand that relying to fossils fuels do not outweigh the drawbacks of their use, making the transition to renewable energy urgent but also possible. The list of fossil fuel disadvantages is indeed long and includes dangers in the production processes, risks of explosion of refineries and oil platforms, air and water pollution, oil spills, smog, formation of acid rain, etc. Regarding their environmental impact on global warming, fossil fuels release vast quantities of CO_2 into the atmosphere during their extraction and transport processes, and when burned in power plants or engines. Transport and electricity/heat are clearly the two sectors with the greatest impact on CO_2 emissions, responsible in 2018 for 24% and 42% of the global CO_2 emissions respectively (IEA Bioenergy, 2018), thus making fossil fuels the main culprits of climate change.

During Paris Climate Conference in 2015, which has followed the Kyoto Protocol in 1996, the Paris Agreement established the goal of limiting global warming to well below 2 and preferably 1.5 degrees Celsius above pre-industrial levels (UNFCC, 2015). This agreement was a major lever in the last years for implementing measures capable of reducing global emissions and achieving the target temperatures. However, although climate policies related to the transport sector have been strengthened, their slow effects (Creutzig et al., 2011) prove that the solution is not to tighten this existing framework, which is mainly oriented towards the use of conventional fossil fuels, but to consider a modification of the fuel itself and turning to renewable energy sources.

2.2 Wind and Sun

Solar and wind are today the biggest contributors to energy consumption growth. Their first advantage as renewable technologies and energy sources is that they are freely and inexhaustibly available all over the earth. Unlike fossil fuels, they are energy sources that nature constantly renews. In addition, since most of it is available on the surface, costly and damaging techniques of extraction are not necessary. In the recent years, electricity from solar and wind energies has become more cost-effective, with a 76% drop in prices for solar panels and 34% for wind turbines between 2009 and 2017, making them increasingly competitive and even cheaper than fossil fuels (IRENA, 2017). Intrinsic efficiency of solar panels and wind turbines have been largely improved due to the development of new technologies. Their standardization that led to economies of scale in the manufacturing processes and the growing experience of the developers are also to be taken into account when considering their cost-efficiency (IMFBlog, 2019) as well as their potential for job creation (IRENA, 2020). All of this will contribute to achieve sustainable development objectives in the context of the climate crisis.

Solar and wind sources look as simple solutions, easy to implement in the short-term. However, what makes these energies renewable, meaning that they are almost inexhaustible as long as there is wind and sun, is also their greatest weakness. The evident constraint is related to the presence of wind or sun, which are to be “intermittent” by essence as they depend on natural flows without the possibility for human control. Variations in supply, partially regular for the sun but irregular for the wind, must therefore be considered in the management of the power grid and will obviously generate integration costs. A reliable energy storage system would only partially solve the intermittence of supply, yet a reliable technology to be applied at a large scale is not available at this time.

2.3 Biofuels/Biomass

Biofuels are also considered to participate in the general effort to reach sustainability in energy supply. The raw organic materials used to produce biofuels are classified into distinct categories, also called generations (**Figure 1**).

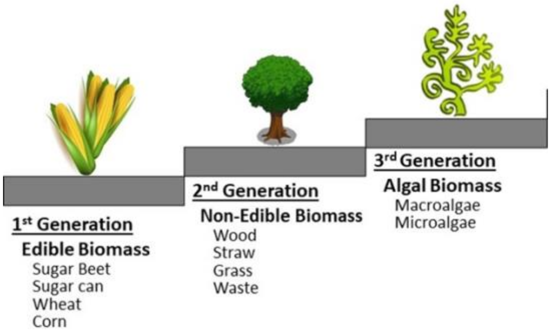


Figure 1. Biofuel generations (Alalwan et al., 2019).

- *1st biofuel generation*

The first-generation biofuel consists of products derived from **feedstock intended for human consumption** and giving rise to either biodiesel or bioethanol. Among the biofuel-generating plants, one can mention palm oil and soybean for the production of biodiesel, and wheat and sugar cane for bioethanol. Their characteristics come from the fact that they can be mixed with fuels of petroleum origin, combusted and distributed using existing equipment and facilities. It is worth to emphasize that biodiesel production from edible oils, the first-generation fuel, represented in 2016 more than 95% of the world biodiesel production (Sharma et al., 2016).

Transportation biofuel production increased by 6% year-over-year, reaching a production of 115 billion L of bioethanol and 48 billion L of biodiesel in 2019, far from what was expected to meet the Sustainable Development Scenario (SDS) target of 10% output growth required per year until 2030 (IEA Bioenergy, 2020). This low development can be explained in part by their many disadvantages. Indeed, when measured in the same units, biofuels have a lower energy density than traditional fuels, making biofuel blends (E85, B20 and E99/B100) more expensive compared to diesel and gasoline (Bhagea et al., 2019).

Another limitation is their greenhouse gas (GHG) abatement, considered as not cost-efficient compared to conventional ones (Naik et al., 2010). Finally, the greatest and most debatable disadvantage of their production is the impact on the use of land which might have been used to grow edible crops for a consumption purpose, leading to a fall in availability of these commodity and consequently higher food prices. This also leads to a progressive loss of biodiversity as more and more land is converted to produce biofuel (Fargione et al., 2010).

- *2nd biofuel generation*

The second-generation biofuels include those based on **lignocellulosic feedstocks**, i.e. the non-food crops and plant-based biomass like paper, wood, agricultural and forest residues (leaves, stems, …) (Naik et al., 2010). The fact that they are renewable makes them in theory good candidates for the production of biofuels, and in particular bioethanol.

However, although it is not competing directly with food production, this second category of biofuels produced from agricultural by-products still, indirectly, needs land for cultivation. This limitation again feeds the debate food *vs.* fuel production and makes it impossible to meet the global demand for liquid fuels using only second-generation biofuels. Together with sometimes costly pretreatment for lignin removal, drawback of land use brings them to the same category as the 1st generation (Alishah Aratboni et al., 2019). Still, the use of cellulose from waste biomass such as corn cobs, straw and wood by-products that do not require additional agricultural production represents an advantage over exhaustible fossil fuels.

- *3rd biofuel generation*

A more recent option that has been gaining more and more interest is the use of **microalgae**, capable of growing in non-agricultural land or aquatic environment. They represent the third-generation biofuel feedstock. Due to their very high photosynthetic efficiency, these unicellular or multicellular microorganisms are able to exploit solar energy radiation to rapidly transform water and carbon dioxide into biomass (Alishah Aratboni et al., 2019). This biomass is used in turn to produce valuable organic components and then industrially relevant substances as fuels and chemicals (Chum et al., 2011). Algal biofuels include methane, biodiesel, bioethanol, gasoline and biohydrogen (Abomohra et al., 2016).

Microalgae have considerable advantages compared to conventional fossil fuels and the two other biofuel generations, in terms of emissions levels and carbohydrate/lipid contents (Bhagea et al., 2019). The technology related to biodiesel production from microalgae will be described in the next chapter.

3. Microalgae: culture and technology

Algae are photosynthetic organisms that contain a diverse group of species. They range from multicellular macroalgae commonly referred to as 'seaweeds' to microscopic unicellular microalgae.

Macroalgae are mainly utilized for the production of food and the extraction of phycocolloids (alginates, agars, and carrageenan's) widely used in the food industry (Milledge et al., 2014). They contain high amounts of sugars (> 50%) and can also be used for bioethanol production. Still, the seasonal nature of macroalgae growth has so far limited their commercial development for biofuel production. By contrast, microalgae contain more lipids and are thus particularly suited to provide renewable biofuels including biodiesel.

The number of European algae producing companies has greatly increased in the last decade (**Figure 2**), one third of them work with microalgae, the rest with macroalgae (**Figure 3**). Of note, in Belgium, the two sole facilities exploit microalgae as feedstock while Norwegian plants (up to 21) mainly use macroalgae.

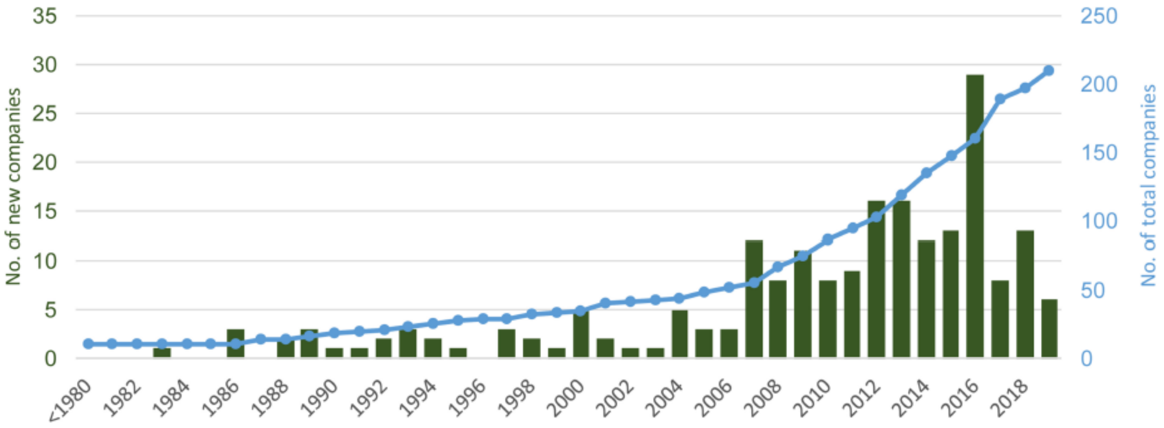


Figure 2. Number of algae-producing companies operating in Europe (cumulative figures are shown in blue, right axis) (adapted from (Araújo et al., 2021)).

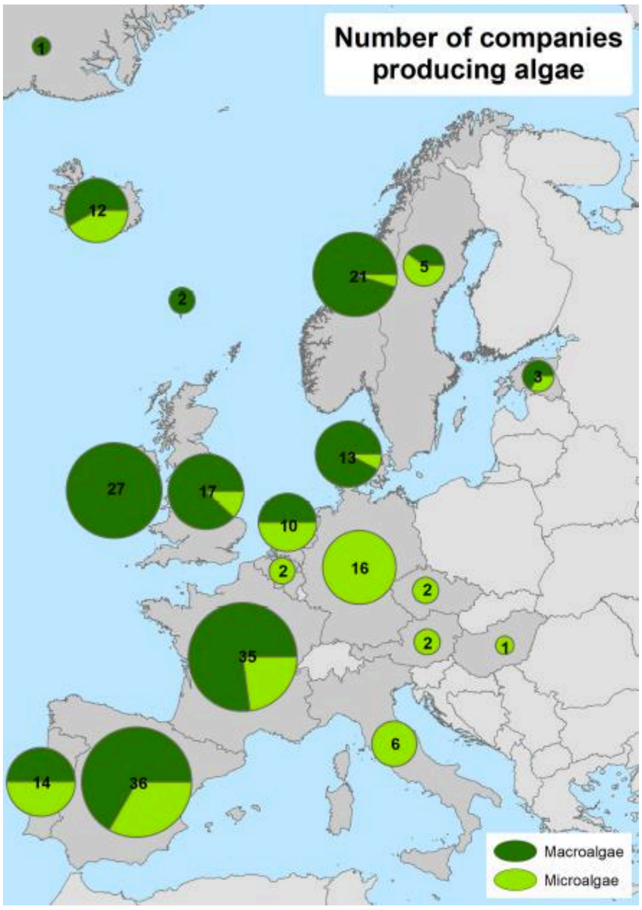


Figure 3. Number and relative distribution between macro- and microalgae-producing companies (Araújo et al., 2021).

3.1 Biomass production from microalgae

Microalgae have existed for billions of years and have actually provided suitable conditions for life to exist thanks to their ability to capture CO_2. They can produce lipids but also proteins and carbohydrates in varying proportion according to the considered species. Their capacity to synthesize around 50% of oil in biomass makes them potential champions for biodiesel production. For instance, while corn requires 1540 Mha of land to produce 172 L/ha of oil, microalgae (70% oil by wt in biomass) need 2 Mha of land area to yield 136900 L/ha of biodiesel (Chisti, 2007).

The growth of microalgae is dependent on various parameters but the two major ones for these photosynthetic organisms are light and nutrient availability. Light can either be natural and thus dependent on the time of sun exposure, or artificial (i.e., energy-consuming). Microalgae preferred nutrient-rich environment with an advantage for phosphorus (P) over nitrogen (N) when lipid content is the main objective of biomass production.

Culture of microalgae can be done in a photoautotrophic, heterotrophic or mixotrophic manner.

Photo-autotrophy is the most commonly employed method for microalgae cultivations. This type of culture operates by using light as energy source, CO_2 from the ambient air and generates bioenergetic molecules such as adenosine triphosphate (ATP), which in turn support glucose synthesis. Photosynthesis requires either day light or artificial lightning. Limitations are thus to restrict biomass formation during the day or to use another source of energy to maintain photosynthesis at night. *Heterotrophy* does not require light but the presence of an organic carbon source (e.g., glucose) in the media that is metabolized by the microalgae to yield biomass. *Photoheterotrophy* refers to an intermediate culture condition where light is needed as well as sugar as the exclusive carbon source. Finally, the term *mixotrophy* is used when photosynthesis occurs in the presence of both organic compounds and CO_2.

The industrial production of microalgae can be achieved with either open or closed systems, referred to as ponds and photobioreactors.

Open ponds. Raceway ponds usually consist of a closed and looped channel that is driven by a paddle wheel to maintain liquid flow and prevent sedimentation; circular ponds also exist with a rotating arm for culture mixing (**Figure 4**). Sunlight exposure and air CO_2 supply make these usually shallow systems easy to set up and quite economic with respect to constructions, maintenance and operation. Obvious drawbacks are contamination (bacteria or fungi), evaporation and land requirements.

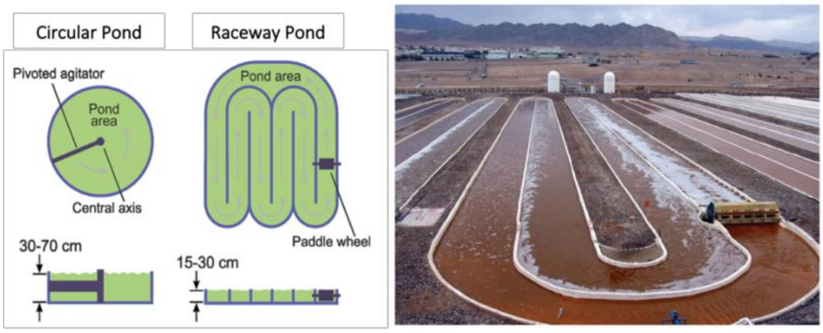


Figure 4. Open pond systems : main types (left) (Hallmann, 2016) and representative picture of a raceway pond in Arizona (Jegathese and Farid, 2014).

Closed Photobioreactors (PBRs). These closed systems are usually tubular structures with bubbling of CO_2 from the bottom (via air pump) that also ensures mixing (**Figure 5**). Advantages are a reduced risk of contamination and a well-regulated photosynthetic efficiency through either direct or artificial light exposure. Upscaling of tubular PBRs is however challenging and costly in terms of construction so that flat plate PBRs with a high illumination surface area are usually preferred for large scale production of microalgae (Dickinson et al., 2016). Temperature is however more difficult to control in these flat structures that are also more prone to biofouling.

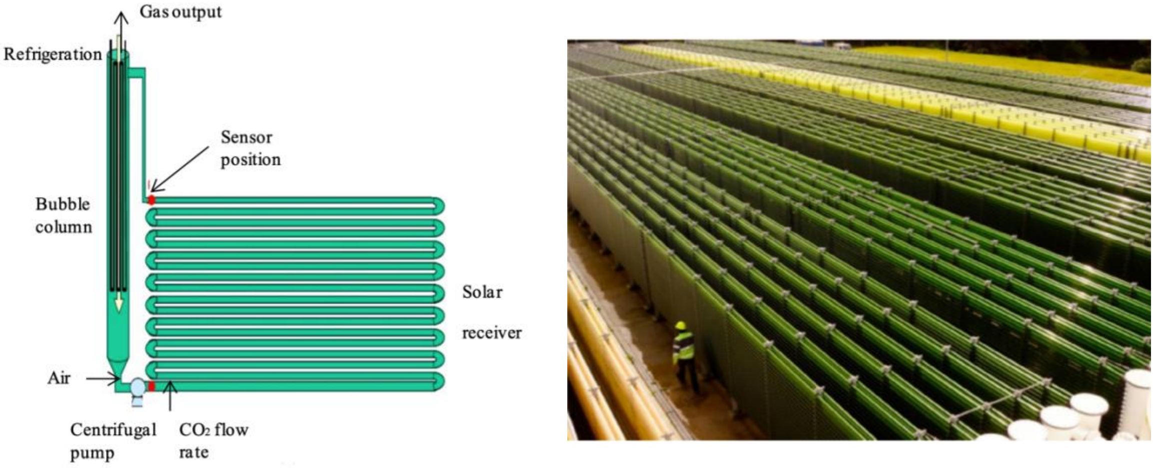


Figure 5. Photobioreactors : classical tubular system scheme (left) (Dormido et al., 2014) and representative picture (right) of commercial plant with vertical reactors in Portugal (Acién et al., 2017)

3.2 Biomass harvesting

Biomass harvesting represents an important share of the costs generated during the overall production, between 25% to 50% depending on the sources (Raheem et al., 2018, Bhagea et al., 2019), due to difficulty of the task caused by microalgae cell size, energy input and costly chemicals (Bhagea et al., 2019). Besides, the selected techniques of biomass collection (i.e., dewatering) strongly depend on the desired output. Choosing the right one early on is thus essential. Among the harvesting methods used to dehydrate the slurries, gravity sedimentation, filtration, centrifugation and (bio-)flocculation are the main options (**Figure 6**). The physical method of sedimentation is based on the gravitational force and may offer a recovery rate between 55% and 80% (depending on the species). The process is however very slow due the limited difference in density between cultured microalgae and water. A more rapid but costly technique is filtration that uses a porous membrane to retain cells from the culture flow with a very high recovery rate. Centrifugation (based on high-speed rotation of microalgae culture) is also expensive but benefits from a recovery rate that can reach 95%. Finally, flocculation operates with flocculants agents that promote the aggregation of microalgae cells. Bio-flocculation is another version of this technique where naturally flocculating microalgae or microorganisms are used to coagulate non-aggregating microalgae cells.

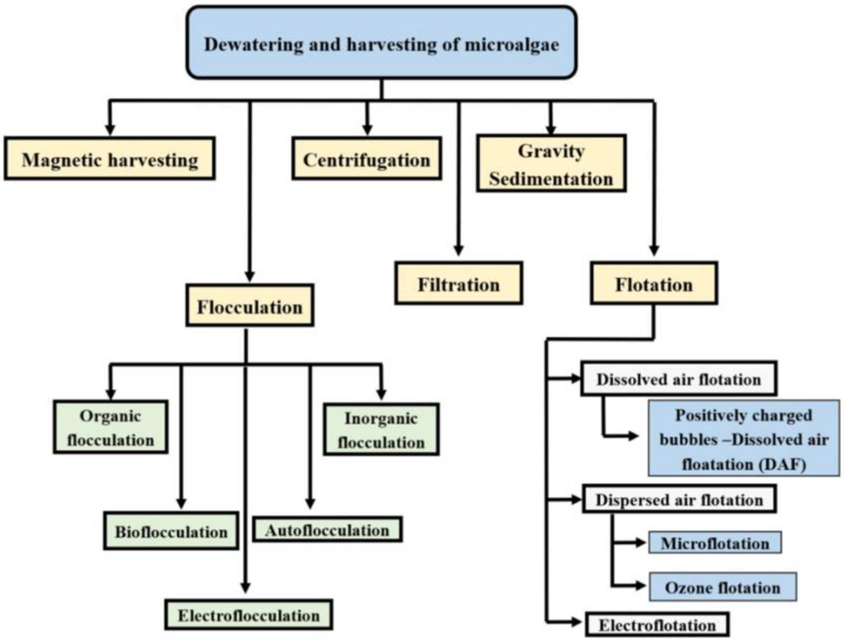


Figure 6. Conventional microalgae harvesting and dewatering methods (Jeevanandam et al., 2020).

3.3 Biomass conversion

After harvesting, the biomass undergoes a pre-treatment where the objective is to disrupt cells in order to release the components relevant for the production of biofuel, i.e. lipids and carbohydrates (Bhagea et al., 2019). Among these methods, chemical hydrolysis is generally preferred over methods such as sonication and freezing for large-scale cultivation. Following this first processing, microalgae biomass is then converted in biofuels. This post-treatment falls into 3 types: chemical, biochemical or thermochemical process (**Figure 7**) (McKendry, 2002b).

The chemical process is primarily used to produce *biodiesel* upon esterification of triglycerides (that are the type of lipids stored by microalgae into lipid droplets). The biochemical process refers to the fermentation (mostly using yeast) that generates *bioethanol* from microalgae biomass. Here, carbohydrates such as sucrose, and not lipids, are exploited (after hydrolysis in glucose or fructose) so that in theory a same microalga can generate both biodiesel and bioethanol. Most of the time however, the microalgae species are chosen for their capacity to generate high yields of one or the other.

More recently, processing of microalgae into dedicated thermochemical reactors has been proposed to extract oil at industrial scale. Thermochemical conversion actually includes dry-processes (namely torrefaction, pyrolysis and gasification) and wet-processes (hydrothermal liquefaction). Torrefaction, also called combustion, consists in degrading microalgae in an inert atmosphere using high temperatures for a specific period of time, ranging from a few minutes to a few hours. By reaching temperatures up to 200-300° C, this process leads to the production of bio-coal and charcoal. The concept is the same for pyrolysis, except those temperatures are yet higher, up to 400 to 600°C. Gasification of microalgae is used to convert biomass into combustible gases such as methane (CH_4) and hydrogen (H_2); the energy demand for gasification is however so high that the option is considered as uneconomical. Liquefaction converts liquid biomass into bio-oil (thus without the need of dewatering) at temperatures of 200-300°C but at high pressure.

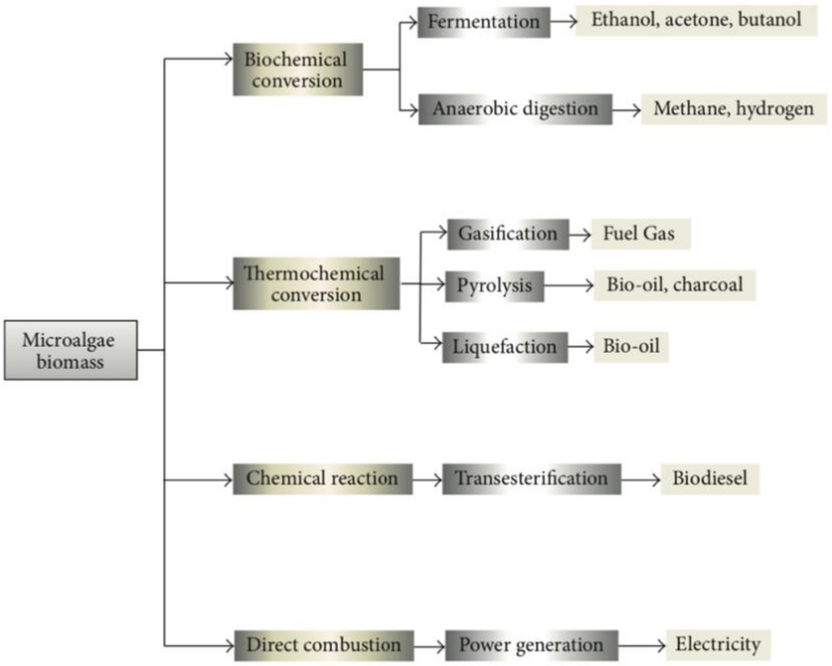


Figure 7. Microalgae biomass conversion processes (Medipally et al., 2015).

4. Microalgae: techno-economic analysis (TEA)

4.1 TEA methodology

Although initiatives from different organizations do exist to generate statistics on microalgae biomass production in Europe and all over the world, datasets are largely incomplete (Camia et al., 2018). Evidence on the growth potential of microalgae field in Europe are currently mostly limited to techno-economic analyses (TEA) largely published by academics. TEA is used for assessing economic viability for a process or a service, providing costs and setting guidelines to guide future commercial success.

As mentioned in the previous chapter, there are many steps in the cultivation of microalgae and many alternative approaches. Besides, the technical development of algae biofuel production is in constant evolution. The models studied, mostly over a short period of time and on a small laboratory scale, therefore vary greatly in their degree of detail and uncertainty.

However, although these models are preliminary, they are valuable for future research and development, and can be analysed through TEA to reach more cost-effective and climate-friendly biofuel production processes. TEA constantly assess the current needs, set research priorities and establish a direction for technical development, acting as a strategic planning and decision-making tool. More formally, the process of techno-economic modelling cycle consists of four iterative stages (Borowitzka, 2013).

Scoping the project is the first step. Applied to the case of marketable biofuels, a high level of details in each phase of the process is needed, including production size and location, species selected, production and harvesting processes, type of conversion, energy products desired and so on. At this point, a critical part is also to identify the required and available data to model this project.

Following the scope of the project, the next step is to build a model and define its complexity given the availability of data (Borowitzka, 2013). To facilitate the evaluation and comparison of models, the latter are based on several sub-models, which, in the case of microalgae, refer to the different alternative options existing at each stage of the culture (e.g., open ponds or closed PBRs in the production stage). In order to visualize the relationships and dependencies between each part of the process and develop an economic model, it is recommended to realize a flow diagram and determine the predicted flows and mass balances.

Third step of TEA consists in evaluating the results of the economic model, using sensitivity analysis, the simplest but still the most used method in this field (Borowitzka, 2013). Its purpose is to identify which inputs have the most influence on the project's outcomes. In the context of microalgae as the source of biomass, the key outcomes discussed for biofuel commercialization are two basic indicators of a project worth, the Net Present Value (NPV) and the Internal Rate of Return (IRR). The project viability is either determined by comparing its IRR to the economic cost of capital or judged worthwhile if the NPV is positive.

In order to achieve this purpose, the sensitivity analysis must be conducted in a systematic way and must follow a number of specific steps (Iloiu and Csiminga, 2009). Firstly, a set of key variables must be identified according to some criteria such as those being numerically large, essential to the start of the project or economically critical. Secondly, in order to study the implications of adverse or positive changes in these key variables, the indicators previously chosen for the base case need to be recalculated for several alternative growth scenarios. It is done by varying one input variable at a time and leaving the others unchanged. Sensitivity indicators (SI) are used to compare a change in percentage in the outcome and a change in percentage in a variable. This means the higher the SI is, the more sensitive the indicator is. They can then be calculated following these equations:

Towards the IRR: $\mathrm{SI} = \frac{(IRR_b - IRR_1)/(IRR_b - d)}{(X_b - X_1)/X_b}$

Where $X_b = value\ of\ the\ variable\ in\ the\ base\ case$
$X_1 = value\ of\ the\ variable\ in\ the\ sensitivity\ test$
$IRR_b = value\ of\ IRR\ in\ the\ base\ case$
$IRR_1 = value\ of\ IRR\ in\ the\ sensitivity\ test$
$d = discount\ rate$

Towards the NPV: $\mathrm{SI} = \frac{(NPV_b - NPV_1)/NPV_b}{(X_b - X_1)/X_b}$

Where $X_b = value\ of\ the\ variable\ in\ the\ base\ case$
$X_1 = value\ of\ the\ variable\ in\ the\ sensitivity\ test$
$NPV_b = value\ of\ NPV\ in\ the\ base\ case$
$NPV_1 = value\ of\ NPV\ in\ the\ sensitivity\ test$

Another manner to investigate the effects of changing variables is by calculating switching values (SV). It is the percentage change in key variable necessary to cause NPV to become zero or IRR to equal the discount rate, meaning the lower the SV is, the more sensitive the indicator is. When sensitivity indicators (and switching values) have been calculated for all the key variables, sensitivity analysis consists of comparing them to determine to which key variables the indicators are the most sensitive (and to which extent of variation key variables will not affect the viability of the project). To help with such comparison, tornado plots are usually presented.

Of note, the theoretical fourth and last step of TEA aims at refining the model to continue improving it. In the field of microalgae, such update is sometimes described in follow-up papers from investigators working in a same laboratory or organization. But the diversity of alternatives in the processes of generating biofuels from microalgae is such that new models are most often preferred to iterative improvement of a single original model.

4.2 Meta-study – sensitivities

The conclusions of multiple studies can be combined in a statistical analysis. To apply this meta-analysis approach to sensitivity data resulting from microalgae TEA is however not possible since this is only relevant if the studies address the same question. In the growing field of microalgae, TEA explore a large variety of issues either in open ponds or PBR, with or without outputs, taking into account sustainability or not. A quantitative comparison between the different studies appears therefore inappropriate.

Still, a meta-study reviewing related research publications may offer tools to evaluate the economic viability of modalities of microalgae-derived biofuel production and to identify future development axes. A systematic search on *Google Scholar* (early 2021) using the following key words: microalgae, techno-economic analysis and sensitivity identified more than 7000 references. When “tornado plots” was added, >160 references were identified. A first evaluation of the abstracts of these publications led us to identify TEA that were either strictly focused on the biofuel production from microalgae while others either described various outputs that could be associated with biofuel production or instead described how wastewater input could be integrated in the designed models. We will discuss here below the results of representative TEA studies with the emphasis on the sensitivity analysis to identify the most relevant variables.

In 2011, Davis and colleagues were among the first to report a comprehensive sensitivity analysis using a set of assumptions for what can plausibly be achieved with autotrophic production of biofuel from microalgae via both open pond and photobioreactor (PBR) systems (Davis et al., 2011). In this study, the cost of lipid production to achieve a 10% return was determined to be \$8.52/gal for open ponds and \$18.10/gal for PBRs. Changes to these production costs according to different parameters are presented in sensitivity tornado diagrams (**Figures 8 and 9**).

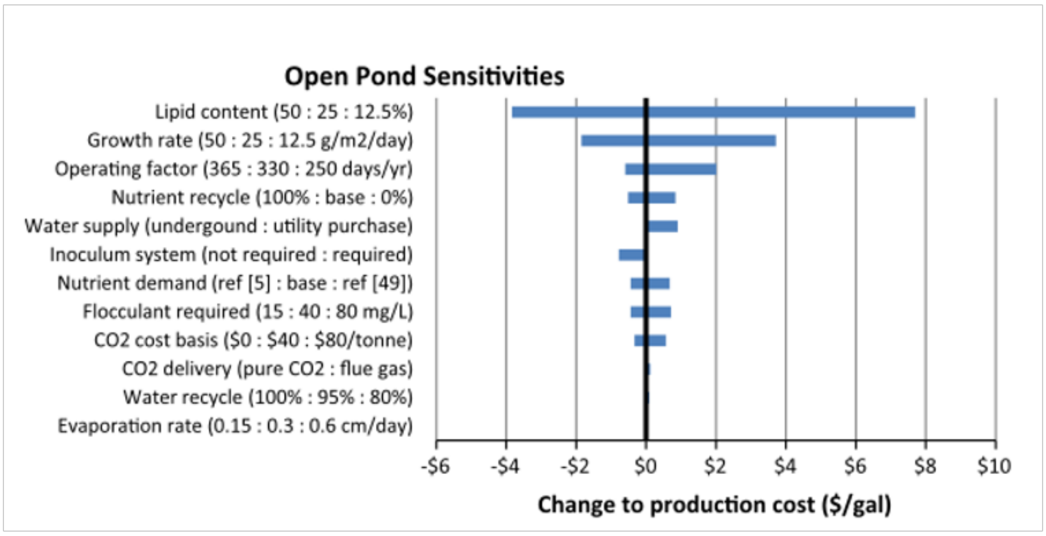


Figure 8. Open pond sensitivity analysis (Davis et al., 2011).

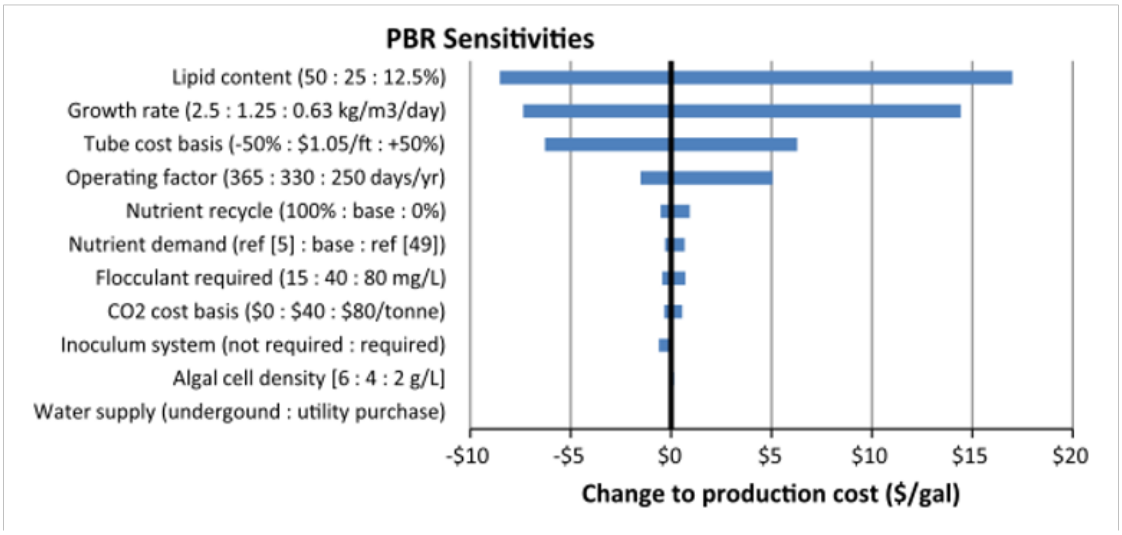


Figure 9. PBR sensitivity analysis (Davis et al., 2011).

Figures 8 and 9 indicate that growth rate and lipid content are by far the most sensitive parameters that influence the economics. In particular, the lipid content (50:25:12.5%) greatly influences the cost impact in the open pond case, twice as much as the growth rate (50:25:12.5 g/m2/day). Indeed, an increase in the oil content decreases the amount of biomass that must be produced while the increase in growth rate limitedly influences the cost of the pond system. By contrast, the contribution of the PBR system to the overall cost is quite high (70% of the base case production cost according to the authors) so that cost reduction due to increased oil content is less pronounced.

Besides the lipid content and growth rate parameters, the other critical parameters largely refer to operating factors (e.g., operating days per year), then to a lesser extent, the degree of nutrient recycle. It is worth to note that sustainability is not discussed in this sensitivity study even though some parameters are clearly related to environmental questions. For instance, for the open ponds, the authors consider that water was pumped from an underground aquifer so that only pumping expenses were considered. Therefore, as shown in Figure 8, water only impacts the costs if being purchased ($1 per gallon). At the time of this study, microalgal biofuel was very far to compete with traditional fossil fuels (petroleum diesel production being around $2.60/gal). Still, the above sensitivity study allowed to conclude that significant cost reduction is possible, in particular in the optimization of lipid content for open ponds. As for PBRs, cost improvements are more likely to arise from capital cost reductions (i.e., cheaper equipment) than from operating cost reduction.

Other authors have pointed the influence of microalgal species on the processing efficiencies (Kang et al., 2018). To evaluate the effect of cell characteristics on microalgae-based lipid production system, these authors focused on the different processing stages including cultivation, harvesting, dewatering, cell disruption and lipid extraction (**Figure 10**).

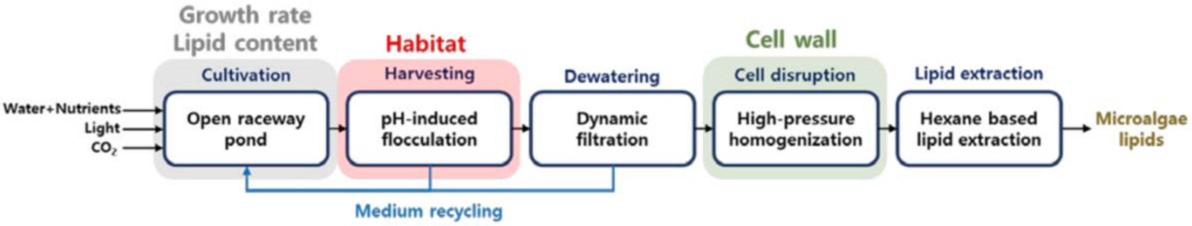


Figure 10. Stages of microalgae-based lipid production (Kang et al., 2018).

They reported different total production costs according to the microalgae species ($6.4/kg lipid, $7.0/kg lipid, and $8.3/kg lipid for *Chlorella vulgaris, Tetraselmis suecica, and Nannochloropsis sp.,* respectively). Interestingly, the impact of each processing stage contributing to this cost was quite different depending on the species. Still, to identify the most influential characteristics on the production costs of microalgae-based lipids, they carried out a sensitivity analysis. For this purpose, they changed the parameter values one by one by ± 50% of the baseline value (**Figure 11**).

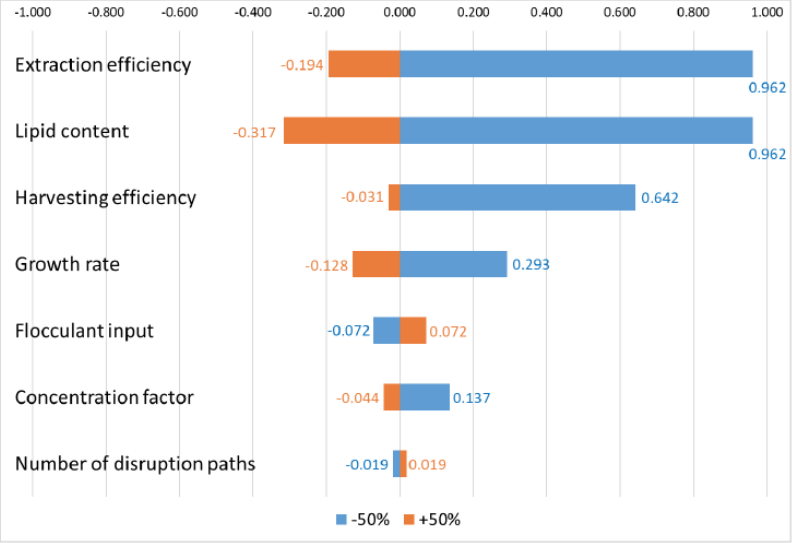


Figure 11. Sensitivity analysis results for Chlorella vulgaris, the analysis is performed by changing the parameter values one by one by ± 50% of the baseline value to observe the change in the total production cost (Kang et al., 2018).

As shown in Figure 11, while lipid content and growth rate were among the most sensitive parameters, extraction and harvesting efficiencies were identified as critical. Optimizing process efficiencies are thus expected to improve the economics at least to the same extent as microalgae lipid productivity. In particular, it is the recovery rate of hexane in the extraction process that appears as a key parameter; a recovery rate of 90% instead of 99% leading to a >70% increase in total production costs.

Several authors postulated that the co-production of high-value **outputs** from biomass residues may allow for microalgae-derived biofuels to be competitive. For instance, besides biodiesel, Doshi and colleagues identified fertilizer and feed as attractive output products from the harvested microalgae biomass (Doshi et al., 2017).

In their model, the baseline output allocation of the microalgae biomass was set at 40% for biodiesel and 30% each for fertilizer and feed. It is worth to note that above this threshold of 40% for biodiesel, NPV was found to be negative (mostly because of the costs for lipid extraction) and that only 2% of the revenues were related to the biodiesel production. Feed and fertilizers thus represented the greater sources of revenues and an attractive combination to sell microalgae-derived biodiesel at a competitive price (1.50$/L rather than 24$/L according to the author's calculation). The authors further conducted a sensitivity analysis across various parameters (**Figure 12**).

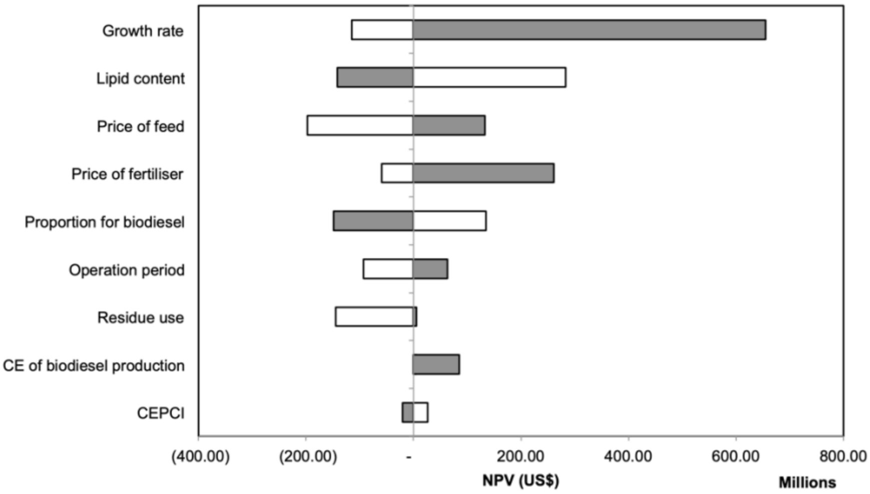


Figure 12. Sensitivity analysis (grey bars represent increases and white bars represent decreases in parameter from baseline; baseline NPV at 5,000,000$) (Doshi et al., 2017).

As in other sensitivity studies related to microalgae production (Davis et al., 2011, Kang et al., 2018), they found that growth rate and lipid content had the largest impact on the NPV. Because the feed and fertilizer sales were dependent on the amount of biomass produced, the growth rate however exhibited a higher potential than the lipid content (that is more directly related to the biodiesel production). It should be noted however that the authors considered very broad ranges of growth rate between 10 and 60 g/m^2/day and of lipid content between 10 and 60%. The price for feed and fertilizers were the next key parameters in terms of potential impact on NPV. Here also, the ranges were quite broadly fluctuating between 2.5 and 18 $/kg and between 9 and 24 $/kg, respectively. These large ranges may explain the potential huge changes in NPV presented in Figure 12. More generally, these numbers also support the interest for multiple outputs that give a producer entry into a wider market that can reduce risks associated with price volatility.

Batan and colleagues reported another study focusing on the technical and economic feasibility of PBR system integrating different outputs (Batan et al., 2016). For these authors, biodiesel co-products were naphtha (that can be sold as a blending component in gasoline) and a product called lipid-extracted algae (LEA) that has different applications including food, cosmetics, energy and pharmaceutical input. Among those, the authors considered fish feed for aquaculture as a major output. They analyzed the financial success for the microalgal production system through the concept of minimal fuel selling price (MFSP) which is the price the fuel must be sold to make the net present value (NPV) of the algae production facility equal to zero (**Figure 13**).

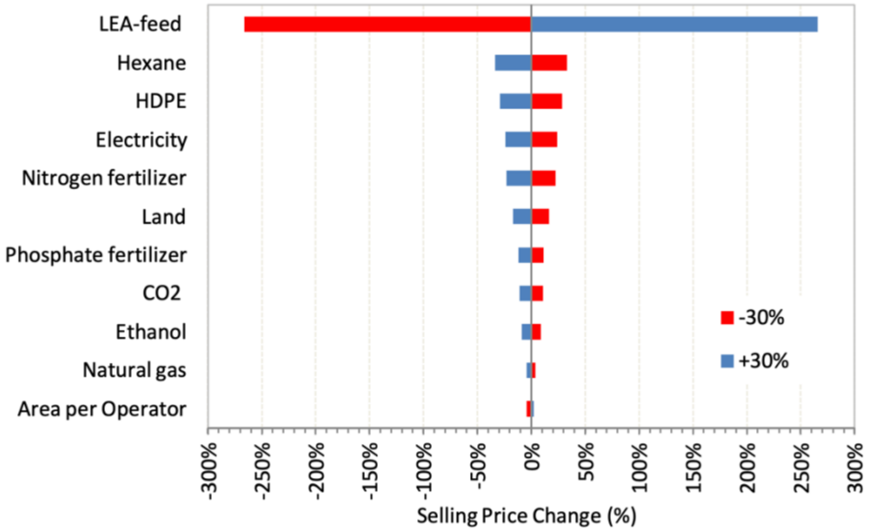


Figure 13. MFSP sensitivity analysis. Tornado plot demonstrated the extent to which algal MFSP changes with ±30% of input parameters. The center line represents the baseline case. The blue and red shading bar represents the direct and reverse relationships. (Batan et al., 2016).

For this MFSP analysis, every input factor was independently modified by ±30%. The change in the selling prices of the co-product LEA as fish feed had the greatest influence leading to a potential 270% change in MFSP. The other parameters (mostly operating cost-related) were in the range below 30% (i.e., the extent of the incremental change used in the sensitivity study). This study reinforces the conclusions of the above study by Doshi et al. (Doshi et al., 2017) supporting the concept that economic performance of microalgae-derived biofuel production is dependent on access to co-product markets. This is actually illustrated in the sensitivity study: a MFSP with a negative value means that the product can be sold even with loss, while supplementary revenues can make the project profitable.

Besides those integrating various outputs, there are also TEA studies that refer to the economical complementarity between biofuel production from microalgae and **wastewater** treatment (Ranganathan and Savithri, 2019). The so-called wastewater-based algal systems are designed to simultaneously treat wastewater and provide the required nutrients for microalgae including carbon, nitrogen, and phosphorus. Although the concept seems attractive, its economic performance is tempered by the cost of wastewater treatment.

Ranganathan and Savithri describe such a model integrating wastewater treatment, microalgae culture and hydrothermal liquefaction (HTL) process (Ranganathan and Savithri, 2019). The latter uses water as a solvent at high temperature and pressure to convert microalgae biomass in different products including biocrude that can be used for heating, gas such as CH4 (after further processing) and fertilizer. The proposed process design is summarized in the diagram presented in **Figure 14**.

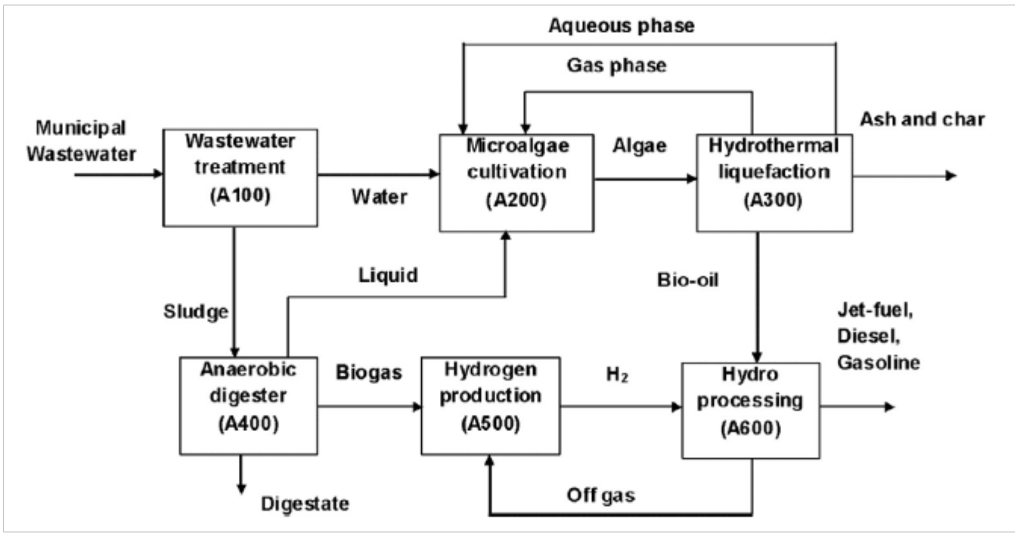


Figure 14. Process block diagram of microalgae-based renewable liquid fuels (Ranganathan and Savithri, 2019).

The connections between the different subprocesses as shown in **Figure 15** are well thought but represent a huge challenge when practical issues are considered. The first subprocess in particular, the wastewater treatment, requires several interventions including grit subtraction and several steps of sludge sedimentation. Sludge needs actually to be activated using aeration, exposure to microorganisms (to break down organic components of the sewage) and settled in dedicated tanks to allow the biological flocs to be separated from clear treated water.

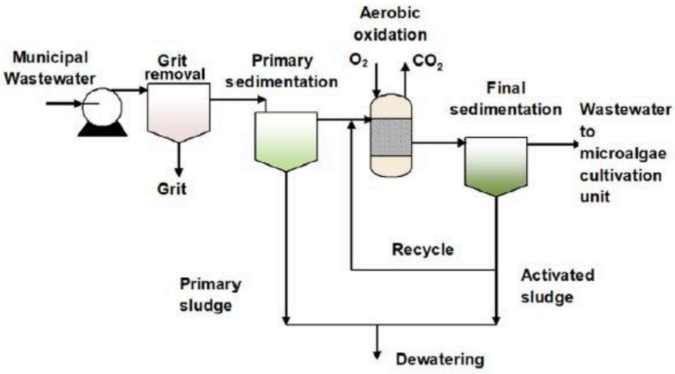


Figure 15. Subprocessing of wastewater treatment before contact with microalgae (Ranganathan and Savithri, 2019).

In this study, the authors further explored the hydrothermal liquefaction strategy to produce microalgae-derived biofuel. This allowed them to perform a sensitivity analysis of different parameters (varying each of them by 10%) influencing the minimal selling price of biofuel (MSP), calculated based on a 10% rate of return with the period of 20 years. This analysis revealed a quite well-balanced influence of a 10%-increase or -decrease in parameters such as yield of digestate, income tax rate and annual rate of return. The most impactful parameters were biooil yield and nitrogen concentration. While increase in both parameters barely reduce fuel MSP, 10%-reduction led to very significant increase in MFSP (**Figure 16**).

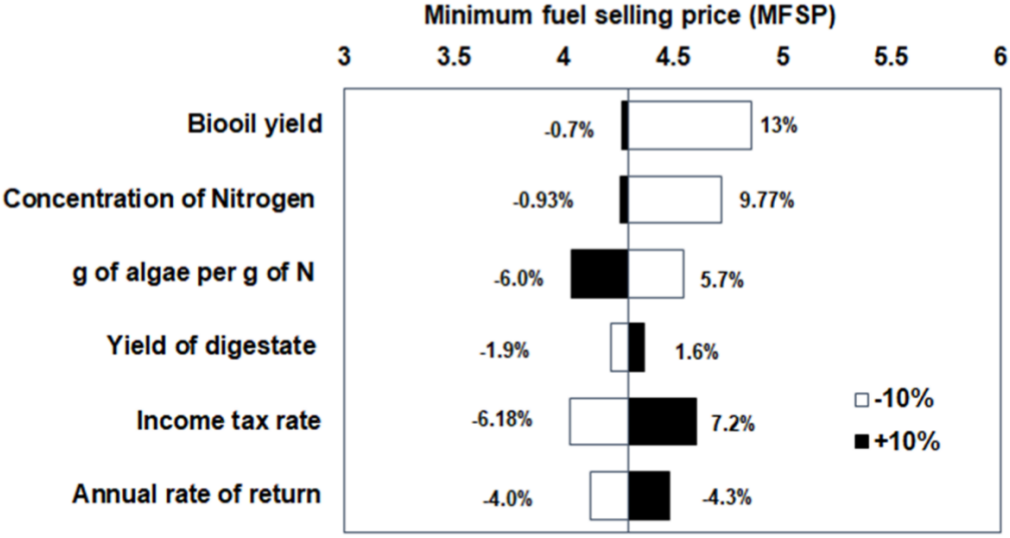


Figure 16. Sensitivity analysis on the MSP of microalgae-derived biofuel, calculated at 4.3 US $/G (base case) (Ranganathan and Savithri, 2019).

The conclusions of this study integrating water waste treatment are somehow quite similar to those not considering water as a limiting resource. The main reason according to the authors' analysis is that the whole installation for wastewater treatment is estimated to represent 75% of capital cost and if treated wastewater provides all the nutrition for microalgae cultivation, the need of electrical supply is enormous to power aerators and transfer heavy mass to the tanks.

In another study investigating the economic performance of wastewater-based microalgae cultivation system to generate biofuel, Xin and colleagues ended up with the critical determinants of success being related to the outputs (Xin et al., 2016). Among them, they identified the sale of nitrogen and phosphorus in regional or national trading market, and the sale of syngas (as heating gas) and ash (as fertilizer).

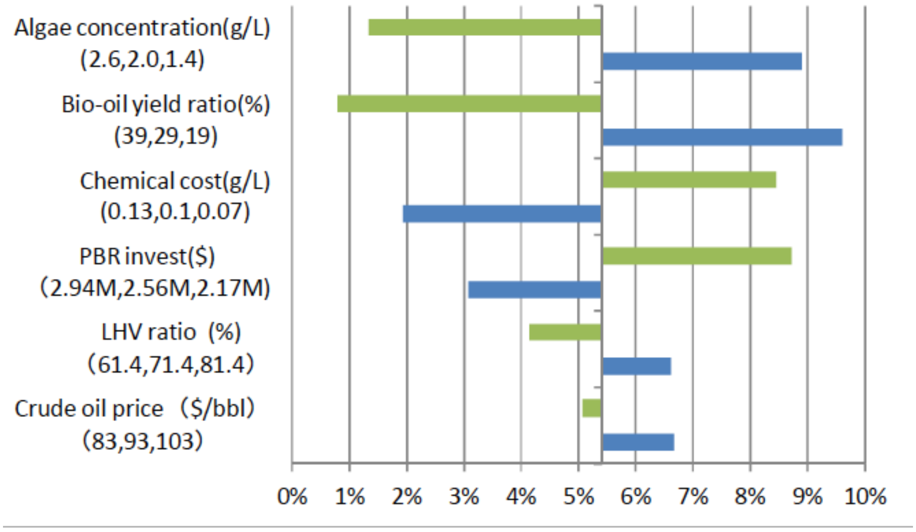


Figure 17. Sensitivity analysis of wastewater-based algal biofuel production system (Xin et al., 2016).

Their uncertainty analysis found that besides algae concentrations and bio-oil yield, internal rate of return (IRR) was also largely influenced by chemical and PBR costs (**Figure 17**). They further evaluate which technology upgrade was the most likely to impact on IRR and found that harvesting through electro-coagulation instead of the chemical approach could lead to more significant changes than upgrading PBR. This study stresses that if combining wastewater treatment and microalgae cultivation represents an obvious theoretical synergy, economic feasibility should not underestimate the need to optimize downstream steps leading to biofuel production (e.g., algae harvesting).

4.3 TEA-derived recommendations for microalgae-based biofuel production

The examples of TEA studies presented here above illustrate the variety of contexts wherein microalgae-derived biodiesel production is evaluated and the difficulty to compare studies in a single meta-analysis. It appears however from the different reviewed sensitivity evaluations that some critical parameters, in particular biological parameters such as lipid content and growth rate, are commonly identified whereas others are more specific. Among the latter, productivity parameters are often identified as critical whatever the pond or PBR modes of production.

An obvious "biological" recommendation based on the sensitivity analysis would be to select microalgae able to produce as much as lipids as possible since the lipid content determines the amount of biofuel that may be generated from algae culture. Biologists however point out that (i) not all the lipids are triacylglycerides suited to biodiesel production (Davis et al., 2011) and more importantly, (ii) an increase in lipids in microalgae cells necessarily results in a reduced fraction of other cell components (i.e., proteins, carbohydrates and nucleic acids) and thus leads to reduced growth rates (Williams and Laurens, 2010). It is actually estimated that an increase in lipid content from 15 to 30% will reduce growth rate by >50% (Griffiths and Harrison, 2009). Models that predict high lipid content together with elevated growth rate are thus unrealistic and compromises are unavoidable. The other way to see this issue is that these two parameters somehow neutralize each other and may thus not be considered as stringent as emphasized in many published studies. It should however be mentioned that efforts are currently made to genetically develop microalgae strains where lipid content (in particular the relevant triacylglycerides) and growth rate are optimized (Chisti, 2013).

Other consensus from TEA studies are the synergism with wastewater treatment and the need to produce a range of co-products besides microalgae-derived biofuels (**Figure 18**).

About wastewater, it is worth to note that if increase in urban effluent production may benefit from microalgae-based removal of nitrates and phosphates (Molazadeh et al., 2019), there is also a real potential for microalgae to be used to reduce organic loads and minerals from aquaculture wastewaters (Aggelis et al., 2020).

At the other side of the supply chain, various outputs may have a remarkably higher market value than that of microalgae themselves. The most straightforward co-product derived from microalgae is derived from the biomass remaining after oil extraction. Animal feed, fertilizers and methane are described in many studies. They usually require extra-steps such as drying for animal feed and fermentation for methane that represent additional costs. The market for these co-products however is larger than for other co-products generated from microalgae, such as carotenoids and long chain polyunsaturated fatty acids. It is worth to note that even if such products have a higher value, they are intrinsically linked to lipids, and may therefore impact the production of biodiesel that is also derived from the lipid droplets present in microalgae. It is actually often suggested that the high cost of production of biofuel from microalgae could be subsidized by high value co-products as long as the costs for production and marketing to sell the latter remain low. This quite unusual business model could however make sense if the sustainability issue is part of the reasoning (see next chapter).

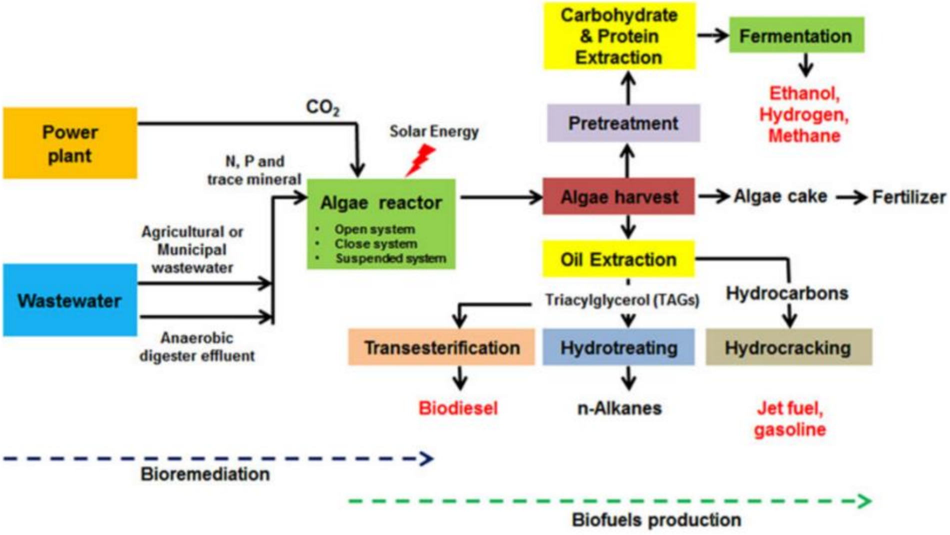


Figure 18. Example of an integrated algal culture system for the production of biofuels and co-products (Hwang et al., 2016).

5. Microalgae: the sustainability issue

In the TEA studies detailed above, the environmental and societal impacts of microalgae-based biofuel production are often underestimated. The main objectives of TEA studies are indeed to determine how economic feasibility, if any, may be reached but the interrelationship with the two other dimensions of sustainability (i.e., environment and society issues) (**Figure 19**) make somehow these analyses outdated.

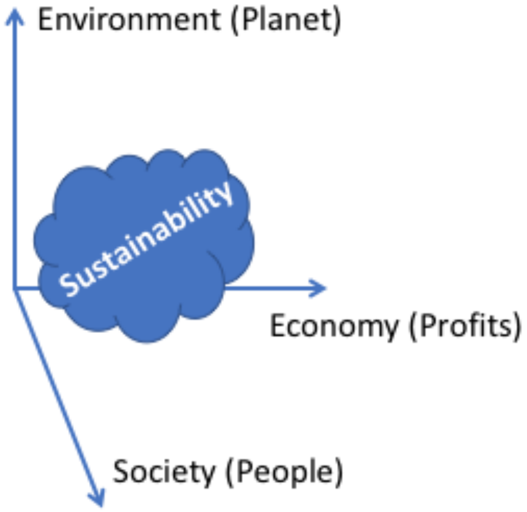


Figure 19. Three-dimension model for sustainability. The axes represent the three pillars of sustainability, namely economic efficiency, social solidarity and environmental responsibility.

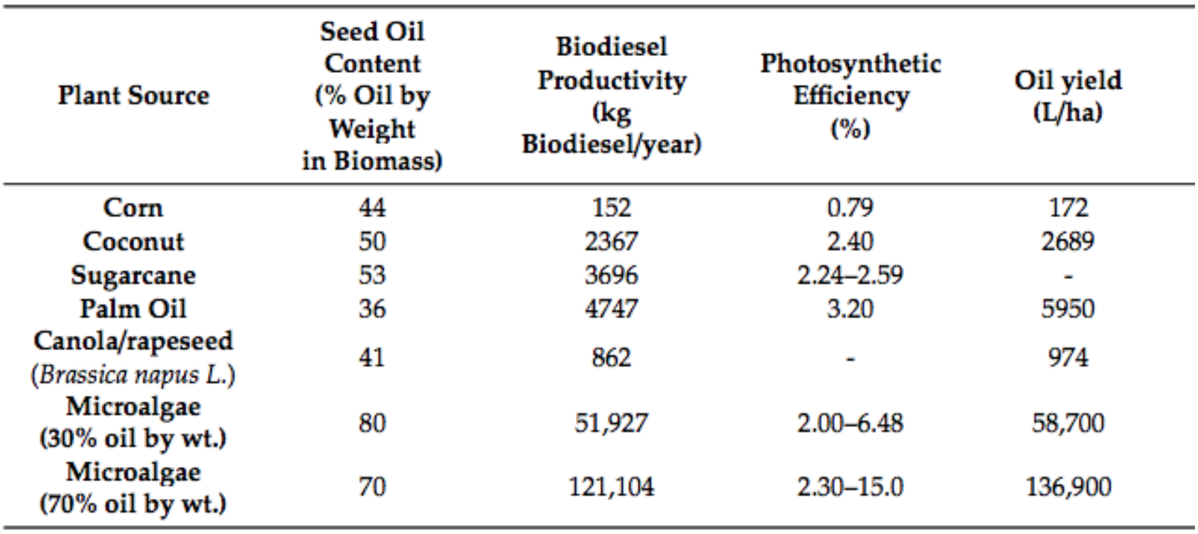
"Meeting the needs of the present without compromising the ability of future generations to meet their own needs" is indeed increasingly considered as a must. In the energy areas, the push for sustainability is even become part of the corporate ethics and used as a marketing strategy. There is a cost for such transition but the commitment to reduce overall emissions via for instance contribution of energy generation from solar, wind, hydropower and biomass is encouraged by governments.

One may reasonably hypothesize that the limited input of sustainability criteria in TEA studies may arise from the self-evident perception that biofuel production from microalgae will always be environmentally friendly compared to first- or second-generation biomass. The gradual rise of greenhouse gas (GHG) in the atmosphere is indeed intimately coupled to our dependence on fossil fuels and the competition for arable land is a major drawback of biofuel production from biomass of previous generations. On the contrary, the use of microalgae is proposed to be a more sustainable solution capable of minimizing these disadvantages and even making them disappear.

First, like any biofuels, microalgae are generated in shorter cycles, as compared to the geological processes required to generate fossil fuels. Also, contrary to other renewable energy such as sunlight and wind that are subject to variability, the production of biofuels can be controlled and tuned according to the needed volume of energy.

Second, when compared with other sources of biofuels, microalgae have a production rate higher than land crops, thanks to their short doubling time, with in addition a higher lipid/oil production content (**Table 1**). As a direct consequence, they require smaller land space and are thus not dependent on large refineries located in remote areas (thereby limiting distribution costs).

Table 1. Comparison of productivity metrics of microalgae and other energy crops (Culaba et al., 2020).



Plant Source	Seed Oil Content (% Oil by Weight in Biomass)	Biodiesel Productivity (kg Biodiesel/year)	Photosynthetic Efficiency (%)	Oil yield (L/ha)
Corn	44	152	0.79	172
Coconut	50	2367	2.40	2689
Sugarcane	53	3696	2.24–2.59	-
Palm Oil	36	4747	3.20	5950
Canola/rapeseed (*Brassica napus L.*)	41	862	-	974
Microalgae (30% oil by wt.)	80	51,927	2.00–6.48	58,700
Microalgae (70% oil by wt.)	70	121,104	2.30–15.0	136,900

Despite the above theoretical advantages, the *adoption* of microalgae-based biofuels still represents a challenge. Demand and supply are thus critical for the diffusion of microalgal biofuels. Capacity expansion is needed to meet increase demand and avoid gaps in supply. To reach this goal, initiatives are in the hands of governments but also industrial investors. Governments can contribute to enhance production capacity either through direct funding of facilities or via incentives (or penalties). While emission reduction may represent a short-term stimulus for investors, the demonstration of economic feasibility is required to promote external investment for longer term growth of production (while respecting the balance of supply chains for resources).

To address this question, authors refer to Life Cycle Assessment (LCA) as an internationally standardized tool dedicated to the evaluation of the environmental performance of a given product. As a first step, the cradle-to-grave method is often used to establish the system boundary from microalgae cultivation (raw material extraction) to biodiesel production (**Figure 20**). The second stage of LCA consists in the life cycle inventory that gathers all inputs to and outputs from the process within the system boundary (Figure 20); those have been discussed when reviewing representative TEA. The respective impact of inputs/outputs on sustainability is then calculated in a third step to identify specific indicators that take into account one, two or three dimensions (i.e., environment, society and economy) (see Figure 19).

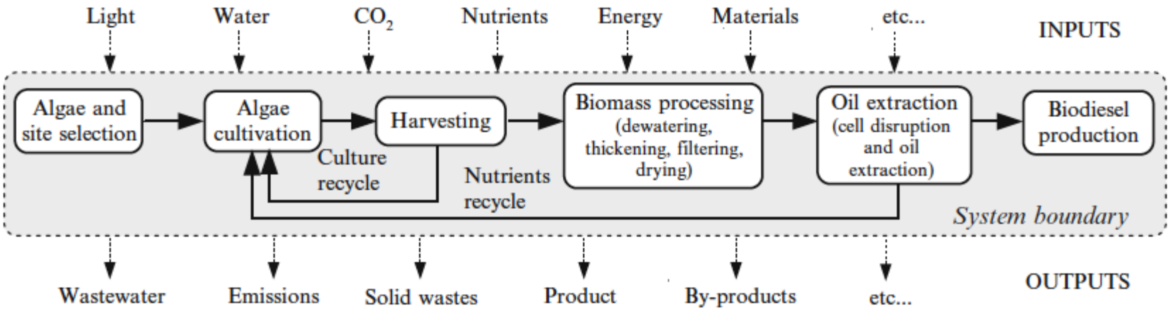


Figure 20. System boundary for microalgae biodiesel: focus on supply chain stages (Mata et al., 2013)

From the LCA studies applied to microalgae (Sander and Murthy, 2010, Jegathese and Farid, 2014, Stephenson et al., 2010, Rafiqul et al., 2005, Subhadra and Edwards, 2011, Liu et al., 2012, Louw et al., 2016, Collet et al., 2014, Dutta et al., 2016, Vuppaladadiyam et al., 2018, IEA Bioenergy, 2010, IEA Bioenergy, 2017), the most frequently identified sustainability indicators are (in order of importance):

- net energy ratio
- water footprint (WF), i.e., consumption of water (including wastewater)
- GHG emission
- nutrients
- land use

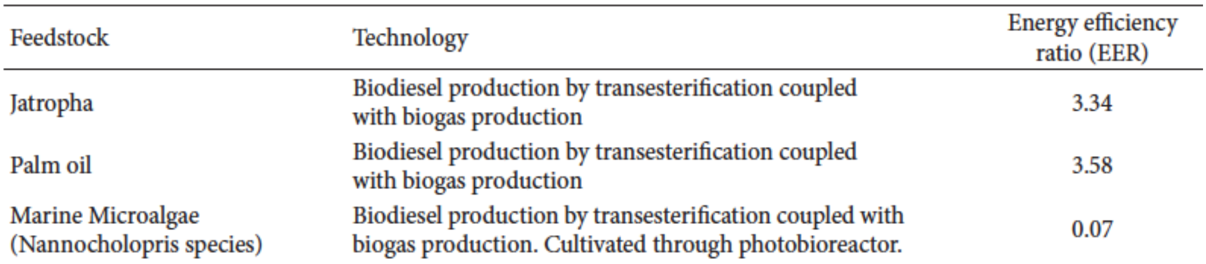
- toxicity risk incl. chemicals used for extraction and management of residual biomass
- employment

Using these indicators, the fourth and last step of LCA consists in the identification of the environmental/societal bottlenecks and the recommendations to address identified concerns. Here below, we will discuss the main conclusions of different microalgae LCA regarding the three major indicators, namely energy balance, GHG and water-related issues.

5.1 Energy balance

The Energy Efficiency Ratio (EER) is defined as the ratio of energy output to energy input so that a ratio higher than 1 corresponds to net positive energy generated and inversely. As shown in Table 1, EER values for biodiesel derived from oil bearing crops are more than 3 while EER for microalgae is well below 1 (**Table 2**).

Table 2. EER for biodiesel produced from different feedstocks (adapted from (Jegathese and Farid, 2014)).



Feedstock	Technology	Energy efficiency ratio (EER)
Jatropha	Biodiesel production by transesterification coupled with biogas production	3.34
Palm oil	Biodiesel production by transesterification coupled with biogas production	3.58
Marine Microalgae (Nannocholopris species)	Biodiesel production by transesterification coupled with biogas production. Cultivated through photobioreactor.	0.07

Main energy hotspots are harvesting/dewatering of microalgae biomass (Sander and Murthy, 2010) but also operation and maintenance of photobioreactor (Jegathese and Farid, 2014). Tubular PBRs may consume up to 350% more energy than raceway ponds, mainly due to the large amount of electricity needed to achieve the right mixing effect (Stephenson et al., 2010).

However, energy use is also hidden in the production of inorganic (chemical) source of nitrogen (or N-fertilizer) (Jegathese and Farid, 2014). Production of ammonia as N source for microalgae may actually represent up to 50% of overall energy consumed in the process of biofuel production (Rafiqul et al., 2005). Together with the intrinsic higher consumption of inorganic substrates by microalgae than by other oil-bearing crops, this issue makes the use of inorganic substrates not sustainable and supports the use of wastewater that contain significant amounts of nitrates (as long as they are not removed during primary treatment).

5.2 Water footprint

Numerous studies have shown that large-scale cultivation of algae would require massive amounts of water. The water footprint indicator represents the sum of all freshwaters engaged in the process and is particularly important to consider in areas with water shortage or arid regions. If one considers that photosynthesis consumes one mole of water per mole of CO_2, this means that 5–10 kg of water is consumed per kg dry biomass (Jegathese and Farid, 2014). Regardless technological innovations aiming to spare water, commercial biomass generation from microalgae will consume billions of liters of water that may thus lead to irreversible consequences in water resources. The huge extent of water loss in a pond (in particular in sunny regions) actually explains the trend to favor closed systems that are more efficient in recycling water and that generate a lower water footprint (Subhadra and Edwards, 2011).

Water supply is therefore one of the biggest challenges surrounding the cultivation and processing stages. However, one of the major advantages of using algae is the possibility of using water not intended for human consumption without competitive usage, such as wastewater, seawater, reutilization of harvest water, brackish water…

5.3 Greenhouse gas emissions

Greenhouse gas (GHG) emissions are part of the main environmental concerns. In theory, the production process of algal biofuel is said to have a carbon-neutral cycle, meaning the system has no impact on atmospheric emissions. However, fossil fuels are currently used along the process of microalgae-derived production of biodiesel. CO_2 emissions might actually be even greater than the amount of CO_2 absorbed and stored over the algae growth period (Louw et al., 2016). Some studies have further documented that, depending on the scenarios, the GHG emissions related to microalgal biodiesel is comparable to terrestrial biofuels (Liu et al., 2012).

Interestingly, GHG emissions are also directly influenced by the energy balance since a large fraction of them stem from the production of the electricity required for producing, harvesting, and transforming microalgae. For instance, Dutta et al. reported that the lipid extraction process contributes significantly to GHG emissions and fossil energy consumption because of the use of heavy chemical solvent usage (hexane) (Dutta et al., 2016). Collet and colleagues recently compared scenarios where up to 45% of electricity was produced by a local renewable source with technological improvements of the process to increase microalgal productivity (Collet et al., 2014). They showed that the impact of a renewable source of electricity on the climate change criterion had the same effect than increasing by threefold productivity.

As supplying CO_2 for algae cultivation is one of the most expensive and energy intensive task (IEA Bioenergy, 2017), an option would be to associate the production of biofuels with power plant flue gases. The potential of microalgae has indeed the capacity to absorb concentrated forms of CO_2-rich flue gases from coal burning plants for instance and could help to eliminate carbon in the power utility sector. In this case, if the power plant emits 24 hours a day while the algae production would only capture emissions during the daylight, then gas storage would be necessary. This system where the power plant would donate its CO_2 emissions to the algae cultivation facility would therefore serve as an alternative for plants to carbon capture and storage (CCS) (IEA Bioenergy, 2010), whose main cost is the physical capture of emissions and gas separation at the source. As the latter is not necessary for algae production, only the capture and transport would be included in the technology price. The location of algae facilities should then be close to these gas sources, which could, however, distance them from other critical resources.

From this system, carbon credits could then be used to reduce costs of algae production that could *in fine* lead to important reductions of GHG (Vuppaladadiyam et al., 2018). While this sounds promising, there is still a serious lack of data regarding logistical and practicality constraints of the use of flue gases and therefore an urgent need of studies integrating the costs related to the supply of CO_2 from power station and this carbon credits system.

6. Towards a future EU algae strategy

What is poorly addressed in TEA and LCA studies are the roles of European institutions and/or national governments in the development of a future sustainable European Union algae sector along the whole value chain. Although the number of European companies active in this sector has increased in recent years, in 2015, the production of algae biomass in the EU accounted for less than 1% (0.23 Mt) of world production (30.4 Mt) mainly supplied by Asian producers (Ullmann and Grimm, 2021).

An essential step for the growth of the European sector would therefore be the implementation of an EU algae strategy. The European Commission recently published in December 2020 an Inception Impact Assessment called "*Blue bioeconomy - towards a strong and sustainable EU algae sector*" (European Commission, 2020) in an effort to communicate the initiatives designed to address the obstacles identified by stakeholders in the growth of the sector. While the potential of algae has been recognized on multiple occasions in official papers, notably in the European Green Deal (European Commission, 2019) in 2019 and in the Renewable Energy Directive (European Parliament and Council of the European Union, 2009), stakeholders have called for a strong European algae Strategy for setting clear targets and implementing appropriate policies capable of assisting the algae sector in Europe.

The European Regions Research and Innovation Network (ERRIN), which includes more than 120 regional and local actors, shared in November 2020 an input paper on a potential future EU algae strategy where they pointed out all the opportunities but also barriers present in the sector (ERRIN, 2020). Many constraints actually prevent the development of the algae sector and lead to an under-exploitation of expertise in Europe as well as a distortion of competition with non-European countries. We will briefly discuss here below these challenges and proposed solutions.

6.1 Regulatory and governance framework

The first issues limiting the growth of the sector are related to EU/national legal and policies framework (ERRIN, 2020). To ensure the competitiveness and sustainability of algae biomass, a change in the European regulations, which are for the moment not consistent with the current growing methods, is necessary. One example of these unsuitable policies concerns the insufficient rate of nutrients allowed for organic algae cultivation, generating an increase in water use and waste production and thus making them unfit for production. The fact that the regulations intended for animal aquaculture is used for algae aquaculture is another drawback for the sector. Finally, it was also identified that a valorization of side streams products through a legal alignment was required in order to enhance the circular economy of the sector.

New EU regulations are thus expected to minimize the associated discrepancies between the European countries and to simplify the access of new algae products within the European market. The aim is to accelerate the development of the sector and to provide better access to international markets. In answer to this, the European Commission has recognized regulatory and market gaps and wishes to improve its regulations and governance context, as well as to help the market operate better. Today concrete initiatives consist in standardization of specifications for algae-based products, harmonized labelling and licensing for the latter, and improvement in existing regulations (European Commission, 2020).

6.2 Business development and funding

As supported by the previous chapters of this dissertation, the feasibility of the business model is the main challenge in the algae industry. Since clear competitive advantages in the algae production are hard to identify and recent advances in research are not easy to find, it made the business development difficult for the compagnies engaged in the sector. The European Commission acknowledged a lack of access to research infrastructures and wants to take action to create a better business environment (European Commission, 2020).

In order to address these concerns, the idea is to create an online one stop source for European algae stakeholders where they will be able to find in a single location all kind of resources such as recent research results, detailed information on funding projects, problem- and knowledge-sharing. These data-sharing platforms will help with the dissemination of the results and filling the gap between sciences, the public sector and consumers (ERRIN, 2020).

6.3 Social awareness and consumer acceptance

Another difficulty noted by stakeholders is the lack of visibility and consumer awareness about products with algae. Their perception might be still biased by old clichés and could prevent them from understanding the true potential of algae. To counter this and for a wider consumer acceptance of algal products, ERRIN network suggests that Research & Innovation teams start working on consumer understanding in addition to the more technical aspects and initiate a dialogue with the public in the beginning of the development phase (ERRIN, 2020).

For its part, the European Commission would like to launch a wide campaign across Europe promoting the scientifically proven benefits of algae for the health, environment, society, and economy. It also acknowledges the need for labelling of “sustainable/safe/organic” algae products (European Commission, 2020).

6.4 Technology & Innovation

Another point that ERRIN’s group wanted to emphasize for the future growth of the industry is obviously the need to improve the production chain by developing new technologies capable of minimizing production costs and enhancing the sustainability of the process, in terms of energy, water consumption and so on. Investing in opportunities for upscaling capacity is also critical for the European algae market to develop. Another strategic focus point should thus be the creation of basic and applied research centers with an emphasis on applicative research, project development, publications and commercialization of patents (Ullmann and Grimm, 2021).

A goal of the European Commission is therefore to fill these innovative, knowledge and research gaps by developing better products, technology, cultivation, and processing methods. One concrete idea is notably the development of a biorefinery concept transforming algal biomass into multiple products and for multiple applications (see below), using flue CO_2 gas as well as wastewater (Dębowski et al., 2020).

6.5 Economic, social, environmental impacts

From an economic point of view, a European algae strategy would increase the market with a greater diversity in the species of algae and improve the competitiveness compared to actors from outside of Europe. This would also accelerate the development of new technologies and reduce the costs of large-scale algae cultivation investment and licensing (European Commission, 2020).

Socially speaking, possible impacts would be an increase in the number of skilled workers and graduates in bioeconomy with an augmentation in local employment (European Commission, 2020).

The most likely environmental impacts are better energy security and circularity through the substitution of fossil fuels by biofuels, consequently a reduction of emissions from transport, biodiversity growth, decrease of pressure on the land use and fish stocks, better quality in local water, enhanced carbon sequestration and nutrient uptake (European Commission, 2020). While these issues represent huge opportunities, business models that include carbon offsets for instance are not yet in place.

To conclude this section about EU algae strategy, making the algal industry sustainable would enable it to become part of a future bio-economy where biofuels, food and other end-products would be resource efficient and for which jobs and new businesses would be created (Ullmann and Grimm, 2021). Regarding biofuels in particular, two (complementary) strategies could be implemented by institutions such as the European Commission to increase their competitiveness. The first one would be to develop technologies with upscaling capacity to support a biorefinery concept where algae are processed into multiple products and for multiple uses (all issued from the same biomass). The second strategy would be to monetize ecosystems services and to combine this with legal adjustments (Ullmann and Grimm, 2021).

More generally, for biofuels to become competitive, the European Commission has to harmonize the legislative landscape in all the European countries. Differences in the adoption rate for renewable energies and the applicable credits are currently too big and prevent the creation of incentives to promote sustainably. With clearer system boundaries, it would also be easier to incorporate credits or other policies into techno-economic studies. Therefore, the combination of supportive measures from governments and introduction of policy mechanisms will give incentives to investors and boost the commercialization of algae biofuels (Avinash et al., 2020).

6.6 Norwegian case

An example that could inspire the European Union to develop its competences and cooperation is Norway. Indeed, through several projects, Norway has shown leadership in the algae sector.

We can notably mention, Algenettverk Nord AS (ALGENETT), a coalition that brings together 21 Norwegian actors engaged in the algae sector in the areas of primary production, harvesting, processing, marketing, as well as project financing, development and management. Their goal is to use the huge production capacity in the coastal areas of the Nordland Sea and the rest of the country, and to develop a strong and sustainable industry through this collaboration.

Other inspiring projects funded by the Research Council of Norway include a national research consortium between universities, SMEs, and commercial partners with the aim of developing a biotechnological toolbox for microalgae R&D in Norway by 2021 (The Research Council of Norway, 2013), as well as the project named ALGECO (The Research Council of Norway, 2021) which was initiated this year. ALGECO is a collaborative project launched by the Norwegian Institute for Water Research (NIVA) composed of highly experienced national and international research groups as well as two industrial partners. Their goal is to enhance circular economy of Norwegian wastewater treatment plants by developing cost-effective algae technologies. With these innovations, they plan to implement a green “3R” concept, which consists of reducing wastes, reusing wastes, and regenerating values.

7. Conclusions

Today a large part of the world is moving towards a transition to a sustainable and circular economy balancing the growth of economic activities, the needs of an increasing world population and the protection of natural resources. One of the goals of the EU is in particular to become climate neutral by 2050 and according to the European Commission's Green Deal, the use of biofuels instead of fossil fuels has a high potential to contribute to this objective (Araújo et al., 2021).

Biofuels began to gain prominence after controversies over the role of fossil fuels in the climate change and the fact that this energy source is no longer considered infinite and sufficient to meet society's needs (Bhagea et al., 2019). Biofuels are a form of renewable energy by the fact that they are generated in shorter cycles, as compared to the geological processes required to generate fossil fuels. First- and second-generation biofuels then appeared to be the solution to decarbonize the transport sector by replacing diesel and gasoline. While they addressed the pollution problems, the production of these biofuels competed for land use and led to the debate between fuel and food production. The increasing awareness for sustainability led to the identification of algae as an alternative much less dependent on arable land (see **Figure 21**). Because of their very high photosynthetic efficiency, microalgae can generate biomass with a high lipid content that represents an attractive feedstock for production of biofuel, in particular biodiesel. Among their other advantages, microalgae contribute to carbon sequestration, are easy to culture and can adapt to various climate conditions (Dębowski et al., 2020).

Algae are therefore recognized as a promising technology for enhancing the sustainability of the bioenergy production thereby contributing to EU goals such as carbon neutrality, biodiversity protection and even food supply security (Araújo et al., 2021). However, the economic feasibility of microalgae as a biodiesel source and consequently its full-scale implementation are not yet demonstrated (Dębowski et al., 2020).

PBR and open ponds are the two major systems used for microalgae production. Our work led us to unravel that both systems have their advantages and drawbacks. PBR that are the most common system used for microalgae cultivation, offer a stricter control of biomass production but require high investment and operating cost. Open ponds require more water and are more exposed to risk of microbial contamination but consume less energy and can produce higher biomass volumes. Other challenges whatever the origin of microalgal biomass is the need for nutrients to culture microalgae and high-energy and capital-intensive harvesting/dewatering processes to extract lipids.

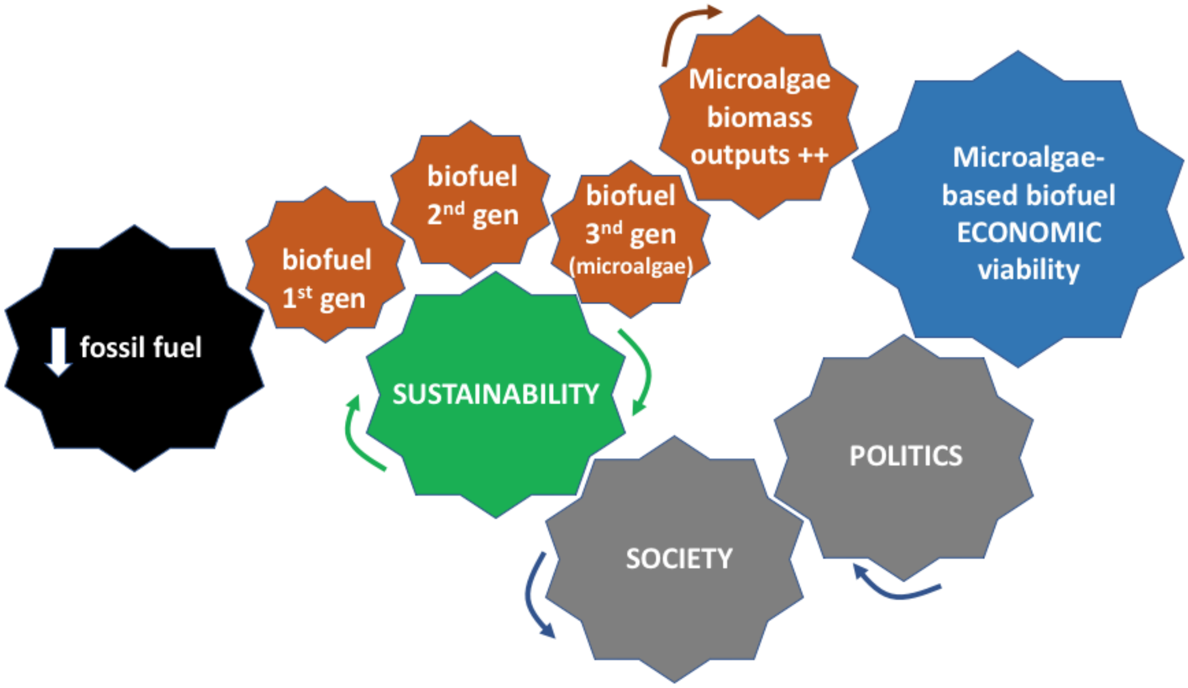


Figure 21. Gear representation depicting the central role of sustainability in stimulating the search for new generations of biofuels to replace the announced lack of fossil fuels (1st, 2nd and 3rd generations consisting in feedstock intended for human consumption, lignocellulosic feedstocks and microalgae, respectively) but also an engine for driving societal lobbying on politicians to set up supportive strategies (funding, incentives, penalties, …). This model should complement the ongoing efforts of innovation in the field, in particular through the identification of the most adequate outputs to combine with biofuel generation from microalgae.

The environmental benefits of microalgae are therefore a more complicated issue than thought at a first glance. Our survey of representative TEA and LCA led us to document that many studies aimed to propose technological innovations and/or to increase economic viability to address these issues. Biological solutions mainly involve the selection of the most adequate microalgae strains to maximize yield and the use of wastewater as an inexpensive nutrients source (Ranganathan and Savithri, 2019). Economically, the diversity of outputs including animal feed and crop fertilizers is proposed to reduce the production costs of biodiesel from microalgal biomass (Doshi et al., 2017) and thereby to maximize return on investment. LCA studies recommend the combination with wastewater as a source of nutrients (Jegathese and

Farid, 2014) and the utilization of CO_2 from power plant (Vuppaladadiyam et al., 2018) to reduce environmental impact. Also, LCA studies document that the largest influencer on ecological footprint is the energy recovered in the production process (Dickinson et al., 2016). In conclusion, the current perception from TEA and LCA is that while large production is technical feasible, economic viability of large-scale biofuel production from algae biomass remains challenging.

From an econometric point of view, while examining the different publications available to write this dissertation, we identified a huge diversity of models analyzed through TEA and LCA studies (IEA Bioenergy, 2017). The TEA and LCA examples presented in previous chapters actually illustrate the variety of scenarios wherein microalgae-derived biodiesel production can be evaluated. An obvious challenge for the economic feasibility is the scale up limitations of TEA studies and their poor reliability due to the difficulty to transfer technology from lab-scale microalgae systems to commercial operations. Our study indeed revealed a lack of technological advancement and innovation in the cultivation and harvesting steps, that could help replicating the productivity potential of algae on a large scale and create better chances for commercial success (Dickinson et al., 2016). All the different contexts leading to large differences in the estimated results, complicates the task of drawing meaningful conclusions. There is thus a clear need of harmonization and standardization of analytical approaches to ease the comparison between studies and identification of obstacles to economic viability and environmental sustainability of microalgae biodiesel (IEA Bioenergy, 2017).

Another limitation of TEA and LCA studies that goes hand in hand with the difficulty to compare each of them is the need to include in these analyses, integrated systems of algae cultures within industrial processes (such as using flue gas from surrounding power plants, performing wastewater treatment, producing other valuable products) and the resulting cost reductions. Since the approach “biofuel only” cannot work due to huge initial capital costs and significant production costs (Mu et al., 2020), research and development work must rapidly select which integrated and innovative models are the most prone to lead to economic viability. This is actually currently explored with the development of an integrated biorefinery concept (algae biofactory), where algal biomass would be transformed, besides biodiesel, into multiple products and for multiple application (Dębowski et al., 2020).

The question today is not whether biofuels can replace fossil fuels but how? How can biofuels be adopted? How to convince economical actors that biofuels of third generation, in particular those derived from microalgae, can contribute to a profitable model shift?

Sustainability could be the response.

Sustainability acted as a trigger to identify better biofuels than those initially generated through the use of agricultural land normally dedicated to human food (see Figure 21). Our work suggests that the awareness of sustainability by the society also represents a unique opportunity to put pressure on politicians to help making microalgae-derived biofuel economically viable and support the development of a circular bioeconomy (Araújo et al., 2021). As mentioned above, technological innovations are certainly required to reduce economic costs, in particular through the diversification of outputs from microalgae-derived and the search for less energy intensive systems. Today these technological developments however do not allow to address all the issues to make this strategy economically viable. Governmental and supra-national initiatives including changes in the legislative landscape to support the algae sector with funding and/or incentives is therefore needed. It is clear that today there is a lack of consistent policy framework and funding environment throughout the European Union in particular, such as subsidies and carbon pricing (Dębowski et al., 2020). To make the algae industry successful, the sector urgently needs policy support to attract investors and more coordination to facilitate technology transfers.

My optimistic view is that the desire of sustainability in our societies, in particular among the young generations, represents a unique opportunity not only to stimulate the innovation but also to maintain the lobbying in matter of climate, the time for strategies such as microalgae-based production of biofuels to become economically viable and … even profitable.

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