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Revisiting competitiveness of hydrogen and algae biodiesel

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ABSTRACT

There is a shared belief across latest literature that hydrogen and algae biodiesel are promising substitutes for fossil fuels. However, hydrogen infrastructure for everyday mobility is still in its early stage from a global perspective and there is no algae biodiesel refinery in operation. Despite all this, recent geopolitical developments have caused a tipping point to be reached in the EU and hydrogen mobility has become cheaper (7 €/100 km) than conventional fossil fuels (15.6 €/100 km) for the first time. In many other countries the breaking point is also approaching and recent methods in waste refining could make hydrogen production even cheaper (5.4 €/100 km). Switching to algae biodiesel is less technically challenging for the industry. Nevertheless, technological barriers in scaling up commercial-scale algae production make the hypothetical price of algae biodiesel far from price-competitive (292 €/100 km). At the present state of knowledge it is recommended to refine algae for non-energy purposes.

Keywords: Circular economy Production cost Hydrogen Algae biodiesel Bioeconomy

1. Introduction

Although the ongoing pandemic has deviated global fuel consumption from predicted trends, it has already quickly returned to pre-crisis levels and continues to rise, pulled primarily by China and India **[1]**. There is a widespread belief that the main motive for investments in biofuel research is the evident signs of climate change **[2]**. Moreover, countries dependent on energy imports are motivated by security concerns **[3]**. Hydrogen (H_2) is one of the most common elements in the universe, so it is not surprising that it can be produced in many ways. However, it is widely agreed that among the most economically and environmentally interesting technologies are low-cost ways of producing H_2 from waste. Very promising wastes are, for example, liquid packaging boards (dominated by the TetraPak brand). Processing of these wastes releases large amounts of H_2 at 0.7 € kg^{-1}. Nevertheless, the development of algae biodiesel is subject to a higher level of support. In chemical terms, biodiesel refers to monoalkyl esters of long-chain fatty acids resulting from lipids produced via transesterification of triglycerides using methanol and catalysts **[4]**. Today, there are numerous modern technologies that (see **Fig. 1**), through the use of catalysts, high temperatures, and other improvements, make it possible to produce a wide range of biofuels, also known in technical terms as biodiesel **[5]**.

Although there is no longer a consensus on whether transesterification is the best cost-efficient method, oil remains the key feedstock for all these production processes **[6]**. Since biodiesel can be blended with fossil fuels it takes advantage of existing distribution chains and plays a unique role among other biofuels **[7]**. In addition, it was repeatedly and independently demonstrated **[8,9]** that biodiesel shows lower emissions of particulate matter (PM_x), carbon oxides (CO_x), unburned hydrocarbons (UHCs) and improves some engine performance indicators like brake-power (BP), brake torque (BT), brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC). From an environmental point of view, waste or rancid oils are among the most recommended feedstock **[10]**. Nevertheless, following the boom of population, industrialization, and economic growth **[11]**, the quantity of such waste resources is far from sufficient to meet the global demand **[12]**. Algae already have gained interest as a source of valuable lipids such as arachidonic, eicosa-pentaenoic, and docosahexaenoic acids, which are predicted to positively impact human health **[13]**. However, most research has focused on growing algae to convert the oil into biodiesel **[14]**. Many authors believe that, based on immense growth potential, algae cultivation is automatically destined for economic success **[15]**. These beliefs are developed on the exceptional photosynthetic efficiency of algae which is capable to generate over 50 g m^{-2} day^{-1} **[16]**, which is approximately double the amount compared to oilseed crops **[17]**. Such a fast growth is made possible for the reason that the captured light is being synthesized into less stable and easily degradable organic matter (starch, oligosaccharides, sucrose, water-soluble polysacharides etc.) rather than energydemanding highly crystalline and long-chain molecules (such as cellulose or lignin) as is the case with terrestrial plants **[18]**. From an environmental point of view, it is worth noting that 1.83 kg of CO_2 is fixed into each kg of algae dry weight (DW) on average **[19]**. Better yet, macronutrients necessary for algae growth can be obtained from wastewaters **[20]**.

Consequently, over 120 k research papers can be found in Web of Science and SCOPUS regarding algae, though some 98 % were published over the last decade (compare to only some 70 papers dealing with H_2 production from waste). The most cited reviews and meta-analyses agree that biodiesel production from algae is considered more or less technically mastered **[21]**. However, obtaining algae biodiesel at a price competitive to fossil diesel remains an unsurpassed challenge **[22]**. Despite numerous publications on algae biodiesel published on daily basis, there is growing scepticism about whether some of the investors are misled by overestimated interpretations of results obtained under unrealistic laboratory conditions **[23]**. In contrast, research and development of H_2 production from waste is marginal and the financial assessment of these technologies is hardly traceable. The main requirement of any industrial optimization is always some financial analysis (net present value, internal rate of return, payback period etc.) **[24]**. However, a deeper look into the literature on algae processing reveals that, in contrast to other technical disciplines, the vast majority of authors tend to ignore established procedures of process optimization according to the financial indicators **[25]** and leans more towards optimization according to some of the biological aspects, such as maximizing carbohydrate or protein content **[26]**. Billions of USD generously funded in algae research has yielded many exciting insights into algae evolution **[27]**, reproduction **[28]**, and metabolism **[29]**. However, there is no algae biofuel on the market yet, and no commercial project is known to be under construction or planned **[30]**. Following the above, the urgent hypothesis is: What are the main reasons that hydrogen from waste and algae biodiesel are still far from commercial deployment?

2. Methods

Only the literature indexed in Web of Science and SCOPUS was reviewed to ensure quality standards. Both databases were searched for combination of the following keywords: hydrogen; hydrogen production; hydrogen fuel; waste; algae; microalgae; cultivation; production; reactor; bioreactor; photobioreactor; raceway; process parameters; optimization; oil; yield; cost; biodiesel. Of the top 100 most cited and 50 most recent publications in each database, the Abstracts were screened, and relevant papers were identified. Data on production dynamics and product characteristics were extracted and subjected to technoeconomical calculations. The average consumption of fossil fuels (2.02 €/L) and algae biodiesel is calculated to be 7.7 L/100 km and the average consumption of H2 is calculated to be 0.5 kg/100 km.

3. Discussion and techno-economic considerations

The common understanding throughout forthcoming legislation across EU, USA, China and India is that H2 production should be divided into "green", "grey" and "black". According to current policy concepts the "green" H_2 is to be preferred since prevealing definitions states that "green" H_2 will be produced exclusively by electrolysis driven by renewable energy. There is less consensus on establishing a clear definition of what so-called "blue" and "grey" H_2 are and what their application and possible support will be. Both the "blue" and "grey" H_2 are defined as produced from fossil fuels, natural gas or CH_4.

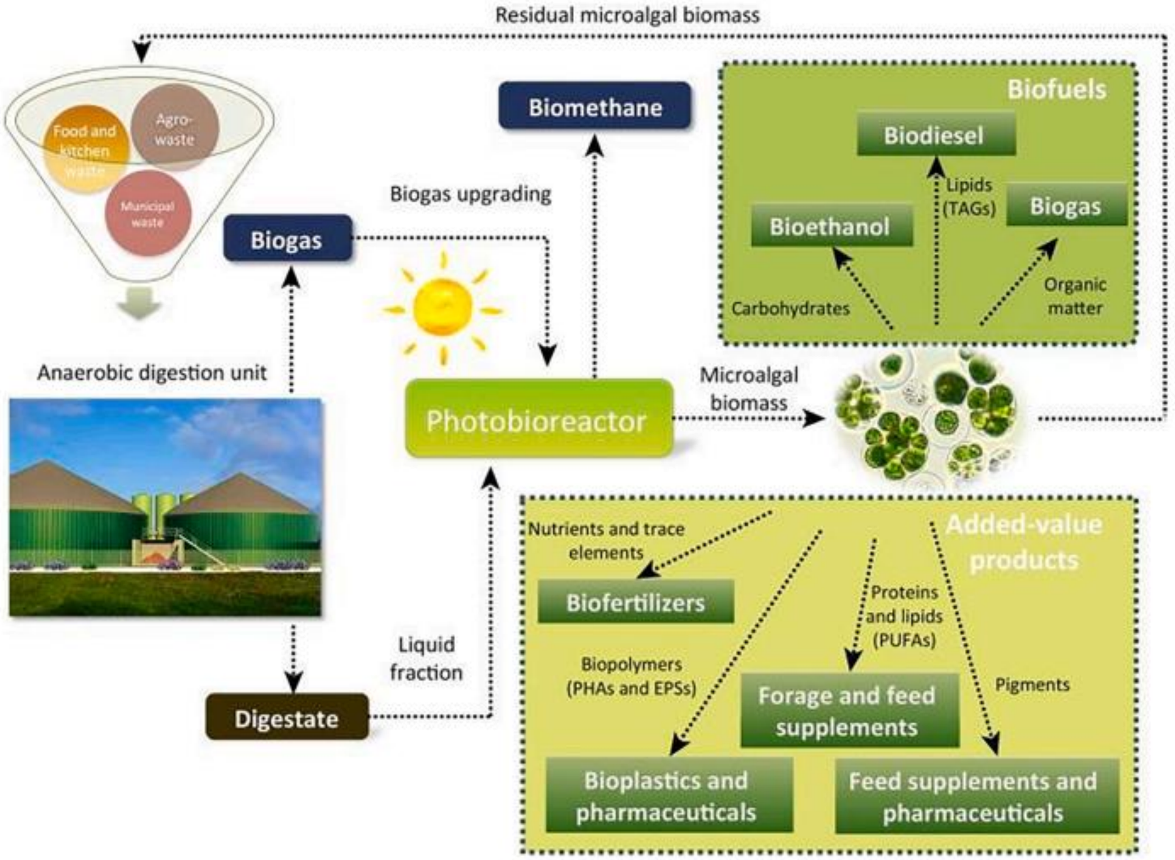

Fig. 1. Trends in algae production and processing **[12,137]**.

The difference is that in the case of “blue” H_2, the CO_2 release is captured by CCS (carbon capture and storage), while in the case of “grey” H_2, the CO_2 released is emitted into the atmosphere. It is clear from the above that no definition foresees any support for any really environmentally friendly H_2 such as H_2 obtained from waste (released during its treatment) or biowaste (via micro-organisms). Nevertheless, the production cost shows signs of cost competitiveness with established fosil fuels (see **Table 1**).

Table 1 Breakdown of production cost indicates that (1) H_2 production from waste refining might outperform established H_2 production methods and (2) algae production is far from mastered.

	$H_{2\ \text{electrolysis}}$ (€ kg^{-1})	$H_{2\ \text{waste refining}}$ (€ kg^{-1})	Algae biodiesel (€ L^{-1})
Feedstock	0.1	0.2	34.5
Equipment depreciation	0.2	0.1	0.1
Reactants and energies	5.5	4.2	3.1
Wages	0.1	0.1	0.1
Other costs	0.2	0.2	0.2
Revenues from other material flows	0.0	-0.2	-0.1
Revenues from gate fees	0.0	-0.3	0.0
Total production cost	6.1	4.3	37.9

In contrast, with regard to algae biodiesel, only some countries admit to a small degree of support after commercialization. Two main technologies (see **Fig. 2**) established themselves on the algae cultivation market: (A) photobioreactors) and (B) open ponds (also referred as raceways) **[31]**. Photobioreactor (A) can be defined as an apparatus made of transparent plastic or glass tubing, which allows complete control and management of all the production parameters **[32]**. The highest algae yields ever recorded were achieved with this type of technology **[33]**. These sophisticated reactors are suitable for growing genetically modified varieties, as they allow it separation from the outside environment. The disadvantage is limited scalability, as the production cost rises sharply at higher volumes **[34]**. Open ponds (B) refer to shallow (1 up to 30 cm) basins similar to a racetrack where some sort of mechanism (pumps; paddlewheels etc.) continuously spins the water oneway movement to prevent algae clumping **[32]**. The latter technology is cheaper **[35]**, but notwithstanding the advances of recent years, it still suffers from numerous shortcomings that significantly limit the algae yields **[36]**. The main problem is the sharply increasing demand on area as production increases **[37]**. Some authors point out questionable light management in lower levels of the pool; contamination from the air (birds, insects, dirt, etc.), and evaporation of the processing liquid (increased demands on workforce, or an increased degree of automation with high demands on reliability) which further raises the cost of production **[38]**. Recent literature suggests that only monocultures such as Spirulina (Arthrospira); Chlorella and perhaps even Dunaliella may be industrially suitable **[39]**. These assumptions are based on the intended processing on feed, colorants, bioactive additives in food or cosmetics, and as far as algae biodiesel production is concerned, it can only be applied to a limited extent **[40]**. To make matters worse, any monoculture increases the system’s instability **[41]**. Spirulina and Dunaliella belong to the algae species frequently applied as fish feed **[42]**. They are widely claimed as a sustainable and cost efficient feedstock **[43]**, which is added directly to the feed mix to feed the larvae and juveniles of various crustacean and fish species **[44]**. Because the composition of algae is similar to soya, they can also serve as a source of protein for food and feed **[45]**. In addition, algae contain omega-3 fatty acids and can thus serve as a sustainable source of these compared to overfishing in the oceans **[46]**. As far as oil production is concerned, reviewed literature still recommends paying attention to Spirulina and Chlorella, but Dunaliella is surpassed by Nanochloropsis **[47]**. However, these recommendations are difficult to review because they tend to focus on assessing oil levels but do not consider the financial point of view **[48]**. However, many of the results achieved have never been constantly reproduced. To make matters even worse, the authors themselves admit that some of these numbers were accomplished only during the short phases of algae logarithmic growth. These "abstract" experiments were not connected to large scale production and took place under conditions that are optimal from a biological point of view (optimization on: density; temperature; light intensity; nutrients and CO_2), which is usually quite far from financial point of view **[12]**.

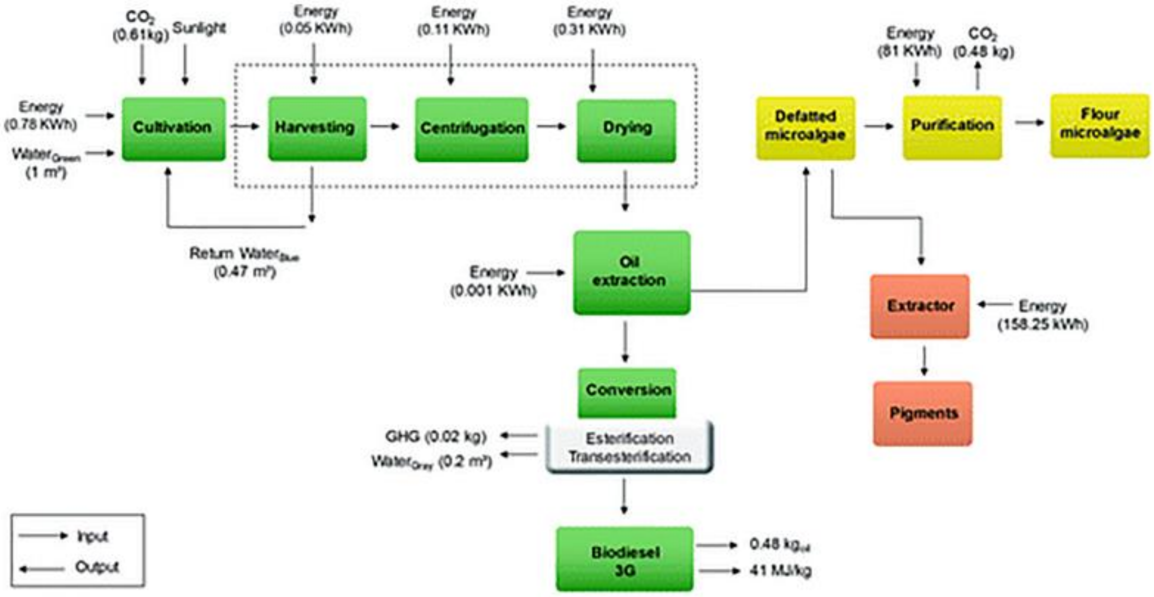

Fig. 2. Simplified energy balance of algae production **[12]**.

Despite lower growth rates (Tab. 1), Nanochloropsis and Spirulina belong to the most intensively researched algae in terms of algae biodiesel since the available literature estimates that they are predicted to have the lowest oil production costs **[49-65]**. This is probably conected to a widespread misconception when Kebede and Ahlgren back in 1996 stated that they observed an extremely high growth rate of 1.8 day^{-1} **[66]**. This report, is endlessly repeated thorough the reviewed literature without being put in relation to the fact that it was achieved in a very small reactor under conditions that are not feasible in operational dimensions **[15,67,68]**. As for cultivating algae in larger dimensions, the concentration of algae phytomass reaches a wide range of values (0.3 up to 5.2 g DW L^{-1}) **[49-65]**. Dos Santos et al. **[69]** reportedly achieved record breaking algea concentration of 6 g DW L^{-1}, but these values have not been reproduced.. To make matters worse, it can be inferred from the context that the cultivation parameters were optimized to maximize growth, and not any of the established financial criteria **[70,71]**. Nevertheless, these yields appear insignificant compared to Hu et al. who produced over 50 g of Spirulina m^{-2} day^{-1} (over 4.4 g L^{-1} day^{-1}) in a raceways that was only 1.2 cm deep **[72]**. Commercialisation of such technological approach is therefore difficult to implement due to the high space requirements **[73]**. It should also be noted that the lipid content in Nanochloropsis and Spirulina rarely exceeds 11 % **[74]**. From the technical as well as economical point of view, it is problematic that cultivation of both species requires monocultures with high demands on water purity;

and salinity levels **[75]**. High temperature optimum is also a critical parameter, which makes the cultivation of Nanochloropsis and Spirulina unsuitable on raceways under temperate and cold climates **[76]**. Cultivation of Spirulina in open ponds never surpassed 19 t ha^{-1} per vegetation season **[78]**. Thorough literature there is a broad consensus that production of Chlorella is more versatile than cultivation of Nanochloropsis and Spirulina due to the smaller cultivation requirements and fast growth **[49-65]**. Masojidek et al. documented that Chlorella might produce over 55 g DW L-1 in autotrophic conditions **[16]**. On the other hand, grown phototrophically with inorganic medium Chlorella typically reaches only some 3 g DW g L^{-1} **[78]**. An alternativesolution for Chlorella seems to be organic substrate (over 75 g glucose L^{-1}) that allows reaching some 100 g DW L^{-1} **[79]**. The cheapest production is made possible by raceways that produce over 10 g Chlorella DW m^{-2} d^{-1} **[80]**. However, this says nothing about the cost of producing algae oil **[81]**. Most authors in Chlorella research, however, do not seem to be looking for optimal economic process conditions, but trying to break the record in production intensity by elevating reaction temperature; adding CO2; or increasing light intensity **[82]**. As a result, numerous authors reported that Chlorella is capable of the highest grow rate of all the algae [83], which is completely irrelevant from an economic point of view **[84]**.

Due to its high lipid content, the marine microalga Nannochloropsis seems to many at the best option in terms of biodiesel production **[85]**. The lipid content in Nannochloropsis is most often in the vicinity of 14 % and can increase three times after one week of restricted access to nitrogen **[86]**. Better yet, the maximum growth rate reported for Nannochloropsis varies from 0.2 up to 0.5 day^{-1} and average phytomass productivity is in the vicinity of 0.6 g DW L^{-1} day^{-1}.However, these values are far from the results usually obtained in larger dimensions **[87]**, which makes them difficult to grasp from a financial point of view **[88]**. It showed out that the production dynamics can be accelerated by improved nutrient management **[89]**; increase in cultivation temperature, and continuous removal of inhibiting residues originating from damaged algae [90]. Rodríguez-López et al. reached some 10 g DW L^{-1} day^{-1} after 7 months of cultivation using the outdoor flat panels **[91]**. Nevertheless all of the measures necessary to achieve such a record seems to be problematic from the financial point of view **[92]**. Achieving economic sustainability of such production would require a breakthrough in nutrient regeneration **[93,94]**. This is perhaps one of the reasons why no mention of large scale cultivation of Nannochloropsis can be found since then. All literary sources are in agreement that sufficient concentration of inorganic carbon as well as easily hydrolysable sources of carbon and other easily bioavailable nutrients and should be managed to accelerate algae metabolism **[95]**. However, vast majority of the literature on algae ignores the fact that buying all these additives (of analytical grade) can hardly be realized in commercial operation **[96]**. Large-scale cultivation of algae requires the use of cheaper nutrient salts (nutrients: N, P, K, Mg, S and micronutrients: Cu, Co, Mn, Mo, Zn, V) that are less acceptable to algae metabolism and are often burdened with unknown impurities resulting from mass production. Aditionally, cheap nutrient regeneration techniques pose a risk of contamination by pathogens **[97]**. According to Delrue et al. algae are capable of metabolizing elevated nitrogen levels (above 2.4 g L^{-1} in the form of urea or ammonium salts) and nearly extreme levels of phosphorus (above 200 mg L^{-1} of phosphate) **[50]**. However, there is much controversy about algae nutrition in large dimensions and no wide consensus can be found in the literature. It was demonstrated that if the recommended nutrient levels are diluted to one-fourth, there can be an increase in yields **[98]**. Of economic significance are the findings of Ruiz et al., who observed a decrease in algae production of only a few small units of percent when the "optimal nutrient solution" was diluted to one-fifth of the required values **[99]**.

Given the importance of photosynthesis, it's no surprise that the intensity of (sun)light **[100]** as well as length of the day **[101]** results in higher algae production at equatorial and tropical areas (over 1800 irmol m^{-2} s^{-1}) over subtropical, mild and cold areas (lower than 900 irmol m^{-2} s^{-1}). The same understandings are independently obtained from industrial algae cultivation, where any barrier to the passing of light (coatings of impurities, increased algal concentration, bubbles, deeper water levels, etc.) leads to a significant reduction in algae growth. The finding of Liang et al., who observed that Chlorella growth decreased by half and then by up to nine-tenths when increased the depth of the rearing layer from 3 to 5 and then to 11 cm, also appears to be economically significant **[102,103]**. Similar effects have been demonstrated for elevated algal concentrations. In contrast, the light intensity in the 1 cm deep Chlorella runway decreased by approximately-one third when algal concentration increased from 1 g DW L^{-1} to a fivefold value, leading to a two-thirds reduction in algae yield **[104]**. Many independent studies confirm that Spirulina is even more sensitive to sufficient light. There is a broad consensus among runway manufacturers that a depth of 20 cm may be close to both the biological and economic optimum for most of commonly cultivated algae **[105]**. As far as bioreactors are concerned, most manufacturers tend to agree on a 5 cm pipe diameter **[106]**. What all these findings have in common is that they increase the cost of producing cultivation technologies. Deviations from the recommended values are financially sensitive; for raceways deeper than 20 cm, reductions in yields of more than nine-tenths have been observed in large sizes, and for pipes wider than 5 cm, yields are sharply reduced by two thirds.

It turns out that it is rational to minimize sharp temperature fluctuations and keep them close to 25-28 °C **[107]**. While lower-temperatures tend to slow down metabolic processes, exceeding the recommended temperature range can more easily lead to the destruction of the cultivated algae **[108]**. There are ways how to to cool bioreactors, for example by spraying **[109]**. However, such methods are difficult to transform into the commercial scale and act only as an additional factor in increasing production costs **[110]**. It can be stated with a reasonable degree of uncertainty that deviations of up to 10 °C from the recommended biological optimum reduce the algal yield by approximately half **[111]**.

In most experiments, $NaHCO_3$ (sodium bicarbonate, also known as baking soda) or Na_2CO_3 (sodium carbonate, also known as washing soda) is added to the algae culture or CO2 is aditionally supplemented **[104]**. Total dissolved carbon levels below 8 mM significantly reduce algal metabolism and population dynamics **[112]**. This aspect is solved in most experiments by a slight bubbling of CO_2, which is also able to stabilize the pH. However, even these technically managed minor complications increase the operating costs **[113]**.

Another key factor is maintaining the O_2 concentration in the area of 3 mg O_2 g^{-1} DW min^{-1} thorough the entire cultivation technology. O_2 supersaturation is considered a serious problem, especially in closed photoreactors. Kazbar et al. **[114]** reported that without effective degassing, the O_2 concentration quickly reached over 25 mg O_2 L^{-1}, which reduced Chlorella cultivation productivity by nearly-one third. It is possible to achieve these O_2 values with a simple spinning wheel. However, from the industrial point of view the spinning wheel does not only increases the purchase and running costs, it is also risky mechanical element that is susceptible to failure and can threaten the entire production process **[115]**. Fully automatic apparatuses are also available that continuously control the levels of all gases present and are also capable of degassing the culture liquid **[116]**. However, the cost of these apparatuses makes them more suitable rather for experimental use **[117,118]**.

One of many problems that is inadequately addressed in the vast majority of the reviewed literature on algae production is the overnight respiration of algae. It’s worth reminding that one of the main reasons why industrially promising algae synthesize energy-rich oil is to create a supply to overcome the darkness. In other words, during the night, Chlorella and Nannochloropsis tend to lose about a third of their energy reserves, and the loss can further increase if there is a sharp drop in temperature at the same time **[119]**. Spirulina also copes poorly with lower darkness temperatures and the night weight losses were up to a third at 24 °C and almost a quarter at 34 °C. Tanaka et al. **[120]** were able to reduce the energy loss to less than 2 %, but this achieved only by artificially extending the light period or increasing the operating temperature above 30 ° C during the night, both of which are costly to realize on a commercial scale **[121,122]**. It is generally agreed that nocturnal respiratory losses range from one tenth to one third.

Autoinhibition of microalgal growth was identified more than eight decades ago **[123]** and was originally attributed to a mystical substance referred to as chlorellin **[124]**. It was only with the improvement of analytical techniques that it was found to be a mix of fatty acids. However, this mixture has been shown to inhibit the growth rate of Chlorella by more than one-fifth by limiting the replication processes in the cells. Though, this effect is not observed at high cell densities that were provided with increased levels of nutrients or CO_2 and most researchers are inclined to believe that it is negligible. Robust cultivation of Nannochloropsis also led to increased levels of autoinhibitory substances. Efforts to continuously remove dead cell walls were intensively investigated but did not solve the problem **[125]**, although it was demonstrated that light intensity is more critical for phytomass yield **[126]**. From an industrial point of view, however, assumptions of unlimited availability of nutrients or CO_2 sounds speculative, so the importance of self-regulatory mechanisms is a debatable risk **[127]**. As already indicated, many algae experts do not include any comments on the economic aspects of their revelations in their papers, and those who do are often confused by the financial terms or by the results itself. Many calculations are so misguided that they do not include the cost of designing or building infrastructure or the operational costs of maintenance and management **[128]**. It is not uncommon to find absurd economic reasoning on algae production in even the most prestigious journals. The common misconceptions are based on assuming that the highest theoretical yields observed in small laboratory production units (knowing that the algae have been cultivated in conditions close to the biological optimum) can be extrapolated to dozens or hundreds of hectares **[106]**. The most credible reports mention the 0.1 km^2 system of raceways built in the USA for nearly 125 M USD **[129]**. Running cost are estimated for 75 k USD ha^{-1} $year^{-1}$ **[130]**. The reported cost of producing 1 kg of DW from algae ranges between 0.5 and 60 USD, with the cheapest costs being achieved in territories that are closer to the equator, do not have safety problems and have cheap labor **[131]**. Based on a cost breakdown directly from production, the typical cost of producing 1 kg of DW algae using runway is in the neighborhood of 15 USD. When photobioreactors are used, the average cost is usually double that **[132]**. Most calculations obtained from larger apparatus, or at least semioperations, thus present results that are about five times lower than ambitious reports from laboratories. In other words, the cost of algae production needs to be reduced by more than a factor of ten to make them price-competitive to oil crops which are now traded at approximately USD 0.4 kg^{-1} **[133]**. In comparison, the market price of Chlorella is somewhere in the neighbourhood of 45 € DW kg -1and Spirulina is traded for some 65 € DW kg^{-1} **[39]**. However, these market figures are problematic because the market volume is small **[134].** Only about 3.5 k DW t of Sprirulina; 2.5 k DW t of Chlorella, 1.5 k DW t of Dunaliella, and less than 1 k DWt of other algae are produced annually worldwide, with the vast majority of production reportedly coming from China. Most technical algae have two-fifths of the oil in DW **[135]**. There are many technologies available to refine algae into biodiesel, with thermochemical liquefaction at temperatures in the vicinity of 340 ° C and pressures of approximately 18 MPa considered the most efficient. However, it has been repeatedly and independently confirmed that the role of the chosen technology is of little importance, with the main cost share of biodiesel production being the cost of oil **[136]**.

4. Conclusions

In most countries, there is still no political consensus on hydrogen production which hinders the development of hydrogen infrastructure. Existing concepts envisage “green”, “blue” or “grey” hydrogen obtained by processes conceptually close to power-to-gas technology. However, the production of hydrogen from waste or by biological methods does not fall into these categories and is thus only of marginal scientific research interest. Nevertheless, the findings indicate that these novel concepts has a high potential for competitiveness.

On contrary, vast majority of the research on algae biodiesel production receives generous support from public budgets and tends to be overly optimistic. Multiple techno-economical bottlenecks have been identified that block the transformation of algae biodiesel production to commercial scale. All of them are linked with algae production. To bring algae biodiesel closer to price competitiveness processing into biodiesel would have to be just a side branch of a complex biorefinery process.

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