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# LIFE-CYCLE ASSESSMENT OF MICROALGAE BIODIESEL: A REVIEW

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**Abstract** *Microalgae are an attractive way to produce biofuels due to the ability to accumulate lipids and very high photosynthetic yields. This article presents a review of life-cycle assessment studies of microalgae biodiesel production, including an analysis of modeling choices and assumptions. A high variation in GHG emissions (between -0.75 and 2.9 kg* $CO_2$*eq* $MJ^{-1}$*) was found and the main causes were investigated, namely modeling choices (e.g. the approach used to deal with multifunctionality), and a high parameter uncertainty in microalgae cultivation, harvesting and oil extraction processes.*

## 1. INTRODUCTION

Microalgae have been investigated as a feedstock for biofuels due to fast growth, relatively high lipid content, and their growth is season independent [1]. Moreover, microalgae do not have to compete with food crops for arable land or other agricultural inputs [2], conversely to first generation biofuels [3, 4]. In spite of these advantages, a life-cycle assessment (LCA) is required to ensure that biodiesel produced from algal feedstock does not result in higher life-cycle impacts than fossil diesel and first generation biofuels. The main objective of this article is to present a comprehensive review of LCA studies published in recent years of biodiesel produced from microalgae. An assessment of important aspects, including modeling choices, was conducted to identify the main causes for the high variability of greenhouse gas (GHG) intensity.

## 2. LIFE-CYCLE CHAIN OF MICROALGAE BIODIESEL

The life-cycle stages of microalgae biodiesel production are shown in Figure 1. Microalgae biodiesel production is not yet clearly established, because technology is in its infancy and there are few commercial scale installations. Figure 1 shows available technologies for each life-cycle stage, as identified in the literature review.

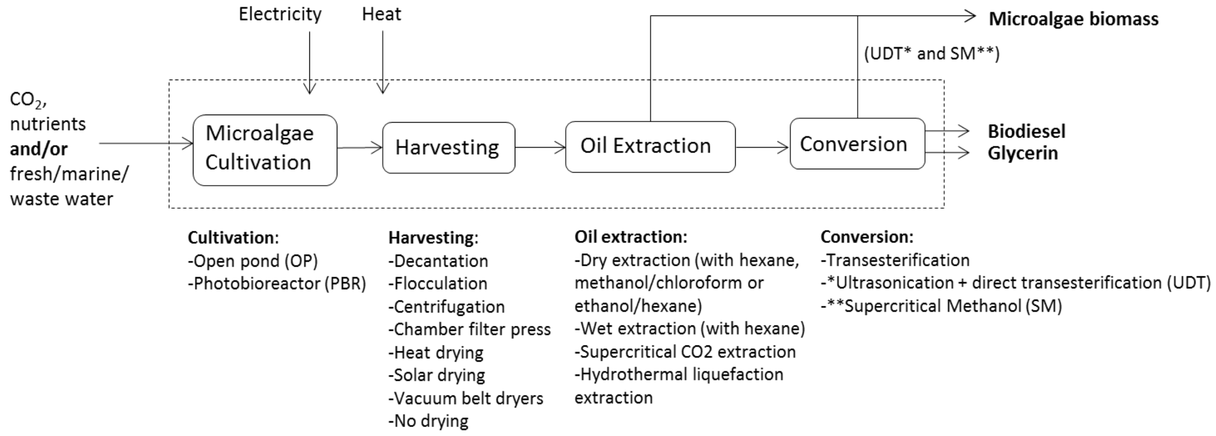

Figure 1. Life-cycle chain of microalgae biodiesel, including alternative technologies.

Cultivation of microalgae can be conducted in photobioreactors and/or open ponds. Possible growth media include: (i) fresh water with growth nutrients; (ii) marine water with growth nutrients; and (iii) wastewater. For harvesting, several technologies can be combined. Microalgae may be decanted and/or flocculated followed by a centrifugation or filtration step. Depending on the oil extraction technology, microalgae can also be dried. In the extraction step, oil can be extracted from the microalgae biomass with a solvent (through dry and wet extraction), with supercritical $CO_2$ (dry extraction) or with hydrothermal liquefaction (wet extraction). Conversion into biodiesel can be made with a traditional transesterification reaction (the most common technology in the reviewed studies), or using more recent technologies like ultrasonication with direct transesterification or supercritical methanol (less common).

## 3. REVIEW OF MICROALGAE BIODIESEL LCA

An online search of articles published (since 2009) with LCA studies of microalgae with detailed information on the methodology, assumptions and data used was conducted. A total of more than 30 studies were assessed, of which a selection of 14 is presented in Table 1. The remaining studies have been excluded due to: lack of transparency and insufficient quantitative information; assessment of only one life-cycle stage of biodiesel production; or the use of wastewater as culture medium (microalgae from wastewater medium have low productivity and lipid content compared with microalgae grown under nitrogen-limited growth conditions). Discussion of results was only detailed for GHG emissions, since this was the only impact category common to all analyzed studies.

### 3.1. Geographical scope, system boundaries and functional unit

The geographical scope of the majority of the reviewed studies was the USA (6 studies), 2 studies for the UK and 2 for China. Remaining studies were from Singapore, Israel, Colombia and Europe. Three alternative life-cycle approaches were adopted. Six out of 14 used a "well-to-gate" approach (ending at the gate of the biodiesel production plant). One study considered a "well-to-pump" approach, which is similar to the "well-to-gate" plus the biodiesel distribution step. Finally, seven studies considered a "well-to-wheels" boundary, also called in the literature "cradle-to-combustion" and "pond-to-wheels", which includes combustion in a specific vehicle. The definition of the functional unit (FU) in biodiesel LCA depends on the scope and system boundary of the study [18]. The reviewed studies employed functional units based on energy or mass. Ten out of 14 considered 1 MJ or 10 MJ of biodiesel (measured in terms of the lower heating value).

### 3.3. Multifunctionality

The reviewed studies used different approaches to deal with multifunctionality. Six out of 14 studies considered the system expansion method and expanded the system boundaries of microalgae biodiesel to include alternative functions for the co-products. The main alternative functions considered were the use of microalgae biomass for animal feed, fertilization, anaerobic digestion, and/or cogeneration (for electricity and heat production), and the use of glycerin by pharmaceutical industries, displacing fossil glycerin. Three of the revised studies considered different allocation methods: mass, energy and economic (market prices) allocation. Three studies considered a combination of the two described methods (system expansion and allocation) and one study performed a sensitivity analysis of different allocation methods. One study [8] attributed all impacts to the main product.

### 3.4. GHG emissions

Figure 2 presents the GHG emissions reported in the revised studies. Well-to-Gate and Well-to-Wheels GHG emissions of fossil diesel are also shown (red lines), as reference. The GHG emissions of reviewed studies varied from -0.75 to 2.9 kg $CO_2$eq $MJ^{-1}$. Main causes for this were related to modeling choices (e.g. multifunctionality approach), and the high uncertainty related to the microalgae cultivation, harvesting and the oil extraction processes. Three studies [2, 12, 16] reported negative GHG emissions due to the multifunctionality approach used (substitution approach) and the accounting of biogenic $CO_2$ absorbed during microalgae growth.

More than 50% of the GHG results reported in the microalgae biodiesel LCA studies (many studies included several scenarios) were higher than fossil diesel GHG emissions. Nevertheless, microalgae biodiesel production systems are very recent and technology developments are focused on finding higher production efficiencies. In this context, the reviewed studies present future scenarios with expected GHG emission reductions associated with microalgae biodiesel. The development of less energy-intensive technologies, e.g. for microalgae cultivation and harvesting steps, will provide a reduction of the associated fossil GHG emissions.

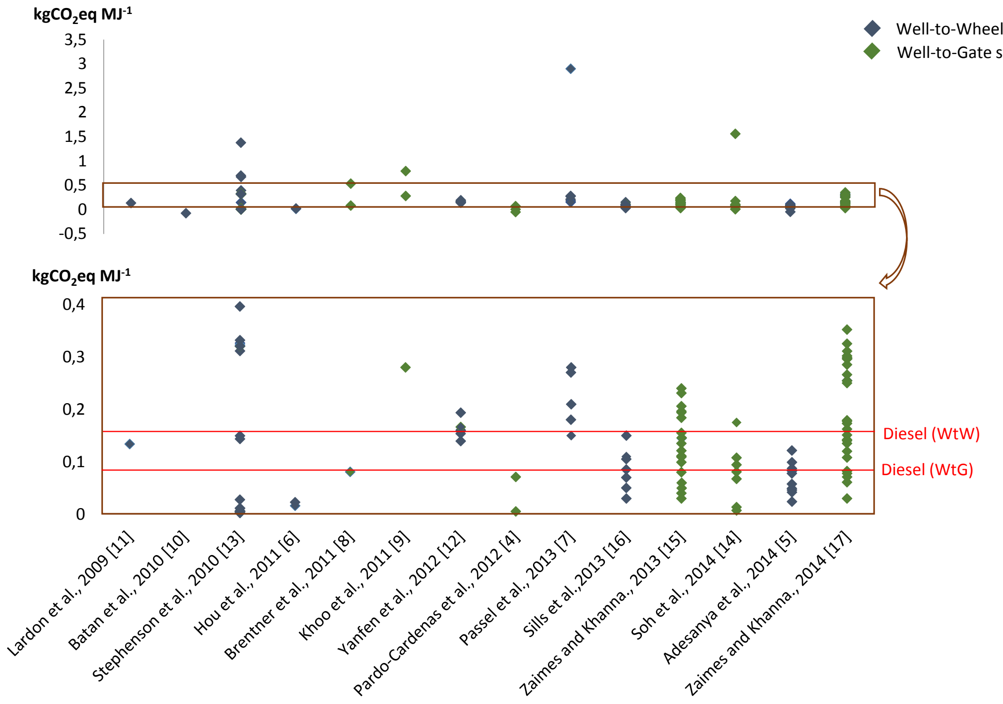

Figure 2. GHG intensity of microalgae biodiesel.

## 4. CONCLUSIONS

A review of recently published life-cycle assessment studies of microalgae biodiesel production was performed. A high variation in the GHG emissions was found among the various studiews (between -0.75 kg and 2.9 kg $CO_2$eq $MJ^{-1}$). Main causes for this variability were related to modeling choices and the high parameter uncertainty in microalgae cultivation, harvesting and oil extraction. Microalgae biodiesel production systems are very recent and the quest for the best production technologies is still undergoing. Future LCA studies should also be performed for commercial systems to better support the selection of the most environmentally benign production pathways.

Table 1. Review of life-cycle assessment studies of microalgae biodiesel production: relevant model choices and assumptions.

| **Relevant choices and assumptions** | **Hou et al. [5]** | **Passel et al. [6]** | **Brentner et al. [7]** | **Khoo et al. [8]** | **Batan et al. [9]** | **Lardon et al. [10]** | **Yanfen et al. [11]** |
|---|---|---|---|---|---|---|---|
| **Geographical scale** | China | Israel | USA | Singapore | USA | Europe | China |
| **System boundary** | Well-to-Wheels (WtW) | Well-to-Wheels (WtW) | Well-to-Gate (WtG) | Well-to-Gate (WtG) | Well-to-Pump (WtP) | Well-to-Wheels (WtW) | Well-to-Wheels (WtW) |
| **Microalgae species** | n.d. | *Nannochloris* and *nannochloropsis* | *Scenedesmus dimorphus* | *Nannochloropsis* | *Nannochloropsis* | *Chlorella vulgaris* | *Chlorella vulgaris* |
| **Microalgae cultivation type** | OP | OP | OP and PBR | PBR (inoculum) and OP | PBR | OP | OP and PBR |
| **Functional unit** | 1 MJ | 1 MJ | 10 GJ | 1 MJ | 1 MJ | 1MJ combusted | 1000 kg biodiesel |
| **Lipid content (%)** | 45 | 50 | 25 | 25 | 50 | 37.9 | 40 |
| **Multifunctionality** | Mass and energy allocation | Energy allocation and Substitution method | Market allocation with Substitution method | All impacts attributed to the main product | Substitution method | Energy allocation | Substitution method |
| **LCIA method** | CML 2001 | n.d. | CED, BEES | n.d. | IPCC | CML 2001 | n.d. |
| **IA categories** | ADP,GWP,OLD, POP, AP,EP,HTTP, FAETP, MAETP,TETP | GWP, POCP, PM, WD, NER, NOx, SOx | CED, GWP, WU, EP, LU | ER, GWP | NER, GWP | ADP,AP,EP,GWP,OLD,HTP,MTP, LU, Ra, POP; CED | GWP, AP, POF, NE, soot and ashes |
| **Extraction type** | Dry (hexane) | Wet (hexane) | Dry (hexane); Supercritical $CO_2$; ultrasonication and direct transesterification; supercritical methanol | Dry (hexane) | Dry (hexane) | Dry and Wet (hexane) | Dry (hexane) |
| **Harvesting type** | Flocculation | Auto-flocculation and centrifugation | Centrifugation/flocculation /chamber press filtration with drying or not | Flocculation and centrifugation | Flocculation, centrifugation, vacuum belt dryers or solar dryers | Flocculation and drying or only flocculation | Sedimentation, flocculation, centrifugation and heat drying |

Table 1. (Continued)

| **Relevant choices and assumptions** | **Stephenson et al. [12]** | **Soh et al. [13]** | **Adesanya et al. [2]** | **Zaimes and Khanna. [14]** | **Sills et al. [15]** | **Pardo-Cardenas et al. [16]** | **Zaimes and Khanna. [17]** |
|---|---|---|---|---|---|---|---|
| **Geographical scale** | UK | USA | UK | USA | USA | Colombia | USA |
| **System boundary** | Well-to-Wheels (WtW) | Well-to-Gate (WtG) | Well-to-wheels (WtW) | Well-to-Gate (WtG) | Well-to-Wheels (WtW) | Well-to-Gate (WtG) | Well-to-Gate (WtG) |
| **Microalgae species** | *Chlorella vulgaris* | *Neochloris oleoabundans*; *Chlorella sorokiniana*; *Nannochloropsis oculata*; *Tetraselmis suecica* | *Chlorella vulgaris* | n.d. | n.d. | *Chlorella vulgaris* | *Chlorella vulgaris* |
| **Microalgae cultivation type** | PBR and OP | Laboratorial scale (Erlenmeyer flasks) with | Hybrid (PBR+OP) | OP | Hybrid (PBR+OP) | OP | OP |
| **Functional unit** | 1 t biodiesel | 1 kg biodiesel | 1 t biodiesel | 1 MJ | 1 MJ | 1 MJ | 1 MJ |
| **Lipid content (%)** | 40 | 18, 22, 19, 26, 9, 35, 2, 13 | n.d. | 25 | n.d. | 30 | 20-25 |
| **Multifunctionality** | Substitution method and Market price allocation | Substitution method | Substitution method | Market and Energy allocation and system expansion | Substitution method | Energy allocation | Substitution method |
| **LCIA method** | EDIP 2003 | GREET[*] | CML 2001 | TRACI and CED | Eco-Indicator 2002 | EDP 2007 | n.d. |
| **IA categories** | GWP and ER | GWP, EP, CED | GWP, ER and WF | OLD, GWP, Smog, AP, EP, Carc. NCarc, Re, EcT, EU | ED, ED and GWP | GWP, AP, EP, POP, ODP, nRE-fossil | GWP and ED |
| **Extraction type** | Dry (hexane) | Dry (hexane) | Dry (hexane) with two cell disrupting processes (mechanical and enzymatic) | Dry and Wet (hexane) | Dry (hexane) and wet (Hydrothermal liquefaction) extraction | Dry (hexane, methanol/chloroform and ethanol/hexane) | Dry and wet (hexane) |
| **Harvesting type** | Flocculation and centrifugation | Flocculation, Centrifugation and decanted | Flocculation centrifugation | Flocculation and chamber filter press | Autoflocculation, centrifugation or filter press | Flocculation and thermal dryer | Flocculation, centrifugation or chamber filter press |

[*] GREET is a life-cycle model; ADP: abiotic depletion potential; GWP: global warming potential; OLD: ozone layer depletion; POP: photochemical oxidation potential; AP: acidification potential; EP: eutrophication potential; HTTP: Human toxicity potential; FAETP: fresh water aquatic ecotoxicity potential; MAETP: marine aquatic ecotoxicity potential; TETP: terrestrial ecotoxicity potential; POF: photochemical ozone formation; PM: particulate matter; WD: water depletion; NER: net energy ratio; CED: cumulative energy demand; WU: water use; LU: land use; ER: energy requirements; MTP: marine toxicity potential; Ra: radiation; NE: nutrient enrichment; WF: water footprint; Car: carcinogens; NCar: non carcinogens; Re: Respiratory effects; EcT: ecotoxicity; EU: energy use; ED: energy demand; nRe-fossil: non renewable fossil; PBR: photobioreactor; OP: open pond; n.d.: not defined.

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