# The water footprint of biofuels from microalgae

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**Abstract**

Microalgae are receiving much interest as a possible biofuels feedstock, resulting in increasing research and development efforts. Biofuels from microalgae are potentially important sources of liquid renewable energy carriers, replacing petrol. Algae are not produced on a large-scale yet, but research shows promising results. Biofuel production needs water, an increasingly scarce resource. The interest in biofuels, in combination with an increasing global water scarcity, causes a need for knowledge of the water footprint (WF) of this new energy resource. This chapter gives an indication of the water footprint (WF) of algae-based biofuels. It uses the WF method as an indicator of water use. We aim to give an overview of the methods used for the cultivation, harvesting and conversion to biofuels of microalgae and the related WF. The results from our case study for microalgal biodiesel produced in California, USA, show a blue WF between 16 and 172 $m^3$/GJ and a grey WF of 0. The results, however, show large variation and depend on the water recycling during the harvest and dewatering process. Compared to biofuels from crops, the green and grey WFs of biofuels of microalgae are favorable, but blue WFs might be larger in some cases. There is a need to assess the impact of the microalgae biofuels production on fresh water resources, because fresh water of adequate quality is an important criterion for assessing the physical, economic and environmental viability of energy systems.

## 1. Introduction

At present, microalgae receive much interest as a possible feedstock for biofuels. Possibly, biofuels will supply large amounts of liquid fuels for transportation in 2030 (European Commission, 2011). In the European Union in 2000, around 27 percent of the total energy demand was attributed to transportation, which is expected to increase to about 33 percent by 2030 (European Commission, 2010). The majority of liquid biofuels today, the so termed first generation biofuels (Nigam & Singh, 2011), is produced from food crops such as sugar cane, maize, soybean, rapeseed or jatropha (Gerbens-Leenes et al., 2009). Drawbacks of using food crops as fuel feedstock include a great water use, a high arable land usage and the competition with food (Nigam & Singh, 2011). Microalgae as an alternative feedstock for biofuels is attracting more attention lately because of the advantages compared to terrestrial crops with respect to:

- a relatively high production (tons per hectare per year);
- the high oil content (30-70 percent of the dry mass);
- and the opportunity to develop a completely closed $CO_2$ and mineral cycle.

Early work on microalgae focused on strains selection, open-pond cultivation (Sheehan et al., 1998), extraction and lipid esterification. More recently, new developments on the complete chain from microalgae cultivation to biofuel production have been carried out. Examples include new photobioreactor designs (Zijffers et al., 2008), efficient harvesting technologies, effective cell disruption techniques, as well as new conversion routes. In the past, most microalgae biorefinery systems aimed at producing biodiesel via an esterification process. Lately, other technologies such as hydrothermal liquefaction, supercritical water gasification (Chakinala et al., 2010) and catalytic hydrogenation have been applied to microalgae for producing other types of biofuels such as green diesel, ethanol, hydrogen or biogas (Xu et al., 2011).

Microalgae grow in water, in open ponds or in photobioreactors, and need water for growth. The rising interest in microalgal biofuels generates the need for knowledge of the environmental impacts, for example the water requirements, of this energy source. Because water scarcity is a growing problem, efficient use of this limited source is an important characteristic for biofuel crops. Recently, several life cycle analyses (LCAs) of microalgal biofuels have been accomplished (Clarens et al., 2011; Brentner et al., 2011). However, these provide limited information on the water use of microalgal biofuels. We estimate that the water footprint is one of the aspects which might restrict the scaling up of the production of biofuels from microalgae, because freshwater is scarce in many parts of the world. Therefore, the objective of this chapter is to give an overview of the current state of the art of technologies for making biofuels from microalgae, with a specific focus on the water footprint (WF) of microalgal biofuels. Gerbens-Leenes et al. (2009) and Mekonnen and Hoekstra (2010) applied the WF concept for bio-energy and reported WFs for bio-ethanol and biodiesel crops. Those studies excluded microalgae, meaning there are no data on the WF of microalgae available at present. To determine the water footprint of microalgal biofuels, we use the WF concept as proposed by Hoekstra et al. (2011).

This paper gives an overview of the current state of technology in microalgal biofuel production. Next, it gives a literature overview of water use in microalgae production. Finally, it applies the WF concept for the calculation of the WF of microalgal biodiesel for one specific case. The result can be compared with the WFs of other biofuels as presented in chapter xx. This gives an indication of the possible advantages of biofuels from microalgae from a water perspective.

## 2. Microalgae: the third generation biomass

The development of biofuels is classified into three generations according to their feedstock. The first generation biofuels uses the carbohydrate or oil fraction of food crops as a feedstock. In this way, the first generation biofuels compete with food. The second generation biofuels is produced from lingo-cellulosic biomass, either the non-edible residues of food crops or from the non-edible whole plant biomass, for example, switchgrass. In the case of the application of residues, there is no competition with food supply, and the land use efficiency is improved. Presently, ongoing research of the second generation biofuels focusses on the improvement of the process efficiency and the fuel quality. Biofuels from microscopic organisms, such as microalgae, are classified as the third generation biofuels. In general, this type of biofuel is expected to be a more sustainable energy resource.

Microalgae are unicellular photosynthetic micro-organisms, living in aquatic environments that convert sunlight, oxygen ($O_2$) and carbondioxide ($CO_2$) to algal biomass (Demirbas, 2010). Microalgae include a large diversity of different strains. They contain lipids, proteins, carbohydrates and nucleic acids (Lee, 1989). Despite the huge potential as an energy crop, at present the worldwide production of microalgae is still limited. The global microalgae production is approximately 5000 tons of dry algal biomass, with a price of 250 euro/kg (Pulz

& Gross 2004). For comparison, the world production of palm oil is around 40 million tons, with a market value of 0.50 euro/kg (Wijffels & Barbosa, 2010).

## 3. Biofuel production from microalgae

The entire chain of biofuel production from microalgae includes five major steps: cultivation, harvesting, dewatering, oil extraction and oil upgrading.

### 3.1 Microalgae cultivation

There are two types of microalgae, the autotrophic and the heterotrophic microalgae. The autotrophic algae use $CO_2$ as the main carbon source for the algae cell growth in the photosynthesis process. Heterotrophic algae do not apply the photosynthesis process, but use a carbon source like glucose instead. At present, microalgae cultivation takes place in two types of autotrophic cultivation systems: open-pond systems and closed photobioreactors. Table 1 gives a comparison between open ponds and photobioreactors for the cultivation of microalgae.

| **Variable** | **Open ponds** | **Photobioreactors** | **Reference** |
|---|---|---|---|
| Costs | Cheap | Expensive | Brennan & Owende, 2010 |
| Maintenance and cleaning | Easy | Difficult | Ugwu et al., 2008 |
| Land use | High | Low | - |
| Growing environment | Well controlled | Poorly controlled | - |
| Productivity | Low | High | Chisti, 2007 |
| Oil yield | 35-45 $m^3$ $ha^{-1}$ $yr^{-1}$ | 50-60 $m^3$ $ha^{-1}$ $yr^{-1}$ | |
| Biomass concentration | 0.14 kg $m^{-3}$ | 4.00 kg $m^{-3}$ | |
| Water evaporation | High | Low | Brennan & Owende, 2010 |

**Table 1: A comparison between open ponds and photobioreactors for the cultivation of microalgae.**

### 3.2 Harvesting and dewatering

Microalgae slurry contains much water, about 99.9 percent of the fresh weight in open ponds. Before being used for biofuel production, the microalgae need to be condensed and dried to a certain dryness. This process generally requires one or more solid-liquid separation steps. Bulk harvesting techniques, such as flocculation, ultrasonic aggregation, flotation and gravity sedimentation, reach a total solid matter concentration of two to seven percent (Brennan & Owende, 2010). After that, the dewatering process requires a number of mechanical thickening methods, such as centrifugation and filtration to reach a total solid matter concentration of about 15 percent (US-DOE, 2010). Finally, thermal techniques dry the algae slurry to a higher solid matter concentration of at least 85 percent. Traditional thermal drying techniques, such as shelf spray or drum drying, are energy intensive, however, and may result in a negative energy balance (Xu et al., 2011). Despite efforts on efficiency improvement and heat recovery, thermal drying consumes significantly more energy than mechanical solid-liquid separation. An energy efficient and reasonably cheap drying method needs to be developed to make microalgae production attractive.

### 3.3 Technical routes for biofuel production

There are several technical routes to convert microalgae into biofuels. Thermochemical processes produce oil and gas; biochemical processes make bio-ethanol and biodiesel, while combustion generates heat and electricity (Amin, 2009). Due to the specific focus on water use of microalgal biofuels, we distinguish the wet and dry route technologies. The wet route technologies keep the entire microalgal biofuel chain in the wet phase, while the dry route technologies minimize the energy consumption in the dewatering process.

- Wet route technologies

Fermentation. Algae biomass is converted to ethanol by yeasts.

Anaerobic digestion. In the absence of oxygen, organic material is digested to produce biogas consisting of methane ($CH_4$) and $CO_2$. The biogas can be directly used for combustion.

Hydrothermal liquefaction. This technology converts wet algal biomass to bio-oil with an energy content comparable to that of biodiesel. The bio-oil can be upgraded to a liquid fuel like biodiesel (US-DOE, 2010).

Gasification. This technology partially oxidizes biomass into synthesis gas (a mixture of CO, $CO_2$, N, $CH_4$ and $H_2$) at high temperatures (800-1000 °C) (Brennan & Owende, 2010).

Supercritical Water Gasification (SWG). SWG gasifies wet biomass at a pressure and temperature above the supercritical point of water, producing hydrogen or synthesis gas.

- Dry route technologies

Direct combustion. Power plants can use algal biomass with a moisture content below 50 percent dry weight for co-firing and produce electricity and heat (Brennan & Owende, 2010). The high pretreatment costs before combustion, combined with relatively low value end products, makes the technique unattractive for microalgae.

Pyrolysis. This technology thermally cracks the biomass in the absence of oxygen and produces charcoal, condensable vapors and pyrolysis gasses. The condensable vapors can be condensed to pyrolysis oil, while the pyrolysis gasses and charcoal can be used as fuels.

## 4. The water footprint of microalgae

The water footprint (WF) is a multi-dimensional indicator, giving water consumption volumes by source and polluted volumes by type of pollution. The WF of a product is defined as the volume of freshwater used for its production at the place where it was actually produced (Hoekstra et al., 2011). Water footprints include three components—green, blue and grey water—and distinguish between direct and indirect water use. More information on the concept is provided in another part of the present publication. This paper contains a case study for a microalgal biodiesel production system in California using an open pond for cultivation.

### 4.1 Water footprint of microalgal biodiesel in an open pond in California

#### 4.1.1 Cultivation characteristics

This case study calculates the WF of biodiesel from a specific microalgae strain, Chlorella Vulgaris, cultivated in an open pond in California. Chlorella Vulgaris is an autotrophic, freshwater microalgae that grows in open pond production systems. Yang et al. (2010) described the cultivation method of Chlorella Vulgaris in an open pond in California. For the calculation of the WF, we use information from Yang et al. (2010). Table 2 gives the characteristics for the cultivation of this microalgae strain.

| **Characteristic** | **Values** |
|---|---|
| Growth rate | 17 $g/m^2/day$ |
| Pond evaporation rate | 3,4 mm/day |
| Growth period | 10 days |
| Lipid content | 40% (dry weight) |
| Pond depth | 0,20 m |
| Pond area | 10.000 $m^2$ |

**Table 2: Cultivation characteristics of Chlorella Vulgaris in California (Source: Yang et al. 2010).**

### 4.1.2 Water footprint calculation

The WF of biofuels from microalgae has two components: grey water and blue water. When all nutrients are recycled, the grey water component is zero. In a case that all the best practices are applied, we assume that there is no water pollution and that the grey WF is zero. The blue WF calculation consists of four steps:
- calculation of the blue WF of the microalgal biomass production;
- assessment of the blue WF of harvesting and dewatering;
- assessment of the biodiesel energy yield;
- calculation of the blue WF of microalgal biodiesel.

Step 1: the calculation of the blue WF of biomass production
The water footprint of the production process WFpro,blue is given by:

$$WF_{pro,blue} = \frac{CWU_{blue}}{Y} \qquad [m^3/ton]$$

where Y is the crop yield (ton/ha) calculated as:

$$Y = growth\,rate * \lg P * \frac{1}{100} \qquad [ton/ha/day]$$

where the growth rate is in $g/m^2/day$, lgP is the growth period in days and the factor 1/100 is applied to convert $g/m^2/day$ to ton/ha/day.
CWUblue is the blue crop water use ($m^3/ha$) calculated as (Hoekstra et al., 2011):

$$CWU_{blue} = 10 \times \sum_{d=1}^{\lg p} LER \qquad [m^3/ha]$$

where LER is the pond evaporation rate (mm/day). The factor 10 is used to convert millimeters to $m^3/ha$.

Step 2 : the assessment of the blue WF of harvesting and dewatering
Harvesting and dewatering is performed in four steps (Xu et al. 2011). The blue WF of this process, WFharvest, is calculated by:

$$WF_{harvest} = \left(\frac{1}{BC,i} - 1\right) - \left(\frac{1}{BC,e} - 1\right) \qquad [m^3/ton]$$

where BC,i is the biomass concentration before harvest in percentage and BC,e is the biomass concentration after drying in percentage.

Step 3: the assessment of the biodiesel energy yield
The assessment of the biodiesel energy yield, Ebiodiesel is calculated using the method of Gerbens-Leenes et al. (2009):

$$E_{biodiesel} = DMF * f_{fat} * f_{diesel} * HHV_{biodiesel} \quad \text{[GJ/ton]}$$

where DMF is the dry-mass fraction of the crop yield (g/g), ffat is the fraction of fats in the dry mass, fdiesel is the amount of biodiesel obtained per unit of fat (g/g), and HHVbiodiesel the higher heating value of biodiesel (kJ/g). Table 3 gives the input data.

| | |
|---|---|
| Dry mass fraction (DMF) | 0,85 g/g |
| Fraction of fats dry mass (ffat) | 0,4 |
| biodiesel per unit of fat (fdiesel) | 1,0 |
| Higher heating value biodiesel (HHVdiesel) | 37,7 kJ/g |

**Table 3: Input data for the energy yield calculation (Source: Gerbens-Leenes et al., 2009)**

Step 4: the calculation of the blue WF of microalgal biodiesel
Finally, the WF of microalgal biodiesel, WFbiodiesel, is calculated by:

$$WF_{biodiesel} = \frac{WF_{tot}}{E_{biodiesel}} = \frac{WF_{proc} + WF_{harvest}}{E_{biodiesel}} \quad \text{[m}^3\text{/GJ]}$$

### 4.1.3 Results

We give two values for the blue WF of microalgal biodiesel. The first value includes the full recycling of the blue water from the harvest and dewatering steps, while the second value excludes the recycling. Table 4 presents the results for the blue WFs of microalgal biodiesel produced in an open pond in California with and without the recycling of the blue water. The blue WFs are expressed as blue WFs for the production process, for harvesting and dewatering, and for the biodiesel per unit of energy. The table also includes the biodiesel energy yield.

| **Recycling** | **WFproc, blue ($m^3$/ton)** | **WFharvest ($m^3$/ton)** | **Ebiodiesel (GJ/ton)** | **WFbiodiesel ($m^3$/GJ)** |
|---|---|---|---|---|
| No water recycling | 205 | 2000 | 12,8 | 172 |
| Full water recycling | 205 | 0 | 12,8 | 16 |

**Table 4: Blue water footprints of microalgal biodiesel expressed as blue WFs for the production process, for harvesting and dehydration, and blue WF for biodiesel per unit of energy. The table includes the biodiesel energy yield.**

The results indicate that the water recycling in the harvest and dewatering process has a large impact on the final result. The blue WF for microalgal biodiesel is 172 $m^3$/GJ for the process without recycling and 16 $m^3$/GJ for the process with full water recycling. The difference between these two values is more than a factor ten.

### 4.1.4 Discussion

In the calculation of WFs, we made four assumptions:

- (1) the calculation is based on one growth period, assuming a year-round operation. This might underestimate WFs, however;
- (2) we assumed that the evapotranspiration rate is equal to the pond evaporation rate;
- (3) the water recycling can interfere with the nutrient balance. We assumed that all the water from harvesting and dewatering can be recycled. However, additional efforts may be needed to ensure the water quality;
- and (4) we assumed the full conversion of lipids to biodiesel.

### 4.1.5 Comparison with WFs of biodiesel from crops

Other contributions from the present publication present the findings of the WFs of first generation biofuels, bio-ethanol and biodiesel. Table 5 gives the global average WFs for the main crops for first generation bio-ethanol and biodiesel, as well as the blue WFs for third generation microalgal biodiesel.

| | **Green WF** | **Blue WF** | **Grey WF** |
|---|---|---|---|
| | $m^3$/GJ ethanol | $m^3$/GJ ethanol | $m^3$/GJ ethanol |
| Sugar beet | 31 | 10 | 10 |
| Sugar cane | 60 | 25 | 6 |
| Maize | 94 | 8 | 19 |
| | $m^3$/GJ biodiesel | $m^3$/GJ biodiesel | $m^3$/GJ biodiesel |
| Rapeseed oil | 145 | 20 | 29 |
| Palm oil | 150 | 0 | 6 |
| Jatropha oil | 239 | 335 | - |
| Soybean oil | 326 | 11 | 6 |
| Microalgal biofuels | 0 | 16-172 | 0 |

**Table 5: Weighted global average green, blue and grey WFs for the main crops for first generation bio-ethanol and biodiesel (Source: Mekonnen and Hoekstra, 2010) and for microalgal biodiesel (Source: this article, Table 4)**

Table 5 shows that biofuels from microalgae are favorable in terms of green and grey WFs. With the exception of the blue WF of jatropha oil, the blue WF of algae oil can be larger than the blue WFs of the other crops, however.

### 4.1.6 Further research

This paper presents the findings of the WF of biofuels from microalgae based on one specific case. Further research should:

- Take different latitudes into account to study the effect of climate on productivity and the WF.
- Consider co-production systems that produce biofuels and other high value products.
- Model different algae species with their respective productivities, lipid contents etc.
- Compare PBR and open-pond cultivation.

### 4.2 Water footprints from earlier studies

Through literature review, we found three studies reporting the blue WFs of microalgae biodiesel production. Table 6 gives their main results in cubic meters of water per unit of energy.

| Blue WF of microalgal biodiesel ($m^3$/GJ) | Source |
|---|---|
| 16 - 97 | Yang et al., 2010 |
| 1555 | Murphy & Allen, 2011 |
| 570 - 760 | Clarens et al., 2010 |
| 16 - 172 | This chapter |

**Table 6: The blue water footprints of microalgae biodiesel production.**

Yang et al. (2010) have studied biodiesel production from microalgae. They have used common growth rates and lipid contents with cultivation in open ponds in California. Results from their analysis show that the WF of biodiesel varies between 591 and 3650 $m^3$/ton. The difference is caused by the water recycling ratio. The best case recycles the water from a settling pond, and the worst case discharges all harvest water. Assuming the biodiesel energy density of 37.8 GJ/ton, we estimate a blue WF between 15.6 and 96.6 $m^3$/GJ biodiesel.
Murphy and Allen (2011) have investigated the energy inputs for upstream operations like pumping water for cultivation in open ponds. They reported an US average water use of 11 m3/kg of algal biomass. We calculated the blue WFs based on their data. That study has reported an US average net yield of algae cultivation systems of 35.000 kg/ha per year. For water use, they have reported the US average annual water input of 39 $m^3/m^2$/year. This means 11 $m^3$/kg of algal biomass. Considering an average algal biomass energy content of 18 MJ/kg (Murphy & Allen, 2011), this gives a blue WF of 619 $m^3$/GJ. That study, however, excluded the downstream conversion process which makes the chain incomplete. We assumed that 40% of the primary energy in the algal biomass is converted to biodiesel. This gives a blue WF of 1555 $m^3$/GJ (assuming a biodiesel energy content of 38 MJ/kg).
Clarens et al. (2010) have compared the environmental impacts of microalgae and conventional crops. They also have excluded the conversion process. Based on the data from their study, we estimate the blue WF of microalgae cultivation to be 378.5 $m^3$/GJ for a case in an open pond in Virginia. With the consideration of the conversion of microalgae biomass into biodiesel, the blue WF value would increase by about 50-100%.
When comparing the results from this chapter with the earlier reported results, one may notice that our WFs for microalgal biodiesel are within a similar range as the results from Yang et al. (2010), while the other two studies reported in Table 6 give much higher WFs. All these results, however, show large variation and depend on the recycling of the water during the harvest and dewatering process. Future efforts need to analyze the water recycling process in detail in order to achieve more reliable blue WF results.

### 5. Conclusions

Microalgae are a versatile feedstock and the field is rapidly developing. At present, the majority of microalgae is grown for human and animal food, or for extraction of high value products. However, microalgae as an alternative feedstock for biofuels is attracting more attention because of their high yield and low land use. Most ongoing research is carried out at lab-scale, with a few pilot plants being developed presently. Results from small-scale cultivation indicate a microalgal oil yield of three to four times that of other oil crops such as palm oil. Researchers expect that the yields and energy contents can be greatly improved in the near future. With current oil prices, a co-production system of microalgal biodiesel and high value products is estimated to be economically viable. With rising oil prices and improvements in the production, extraction and conversion techniques, it is expected that algae will become an interesting alternative biofuel resource in the future.

The rising interest in biofuels, in combination with an increasing global water scarcity, causes a need for knowledge of the water footprint of this new energy resource. The results from our case study for microalgal biodiesel produced in California, USA, show a blue WF between 16 and 172 $m^3$/GJ. The results, however, show large variation and depend on the recycling of the water during the harvest and dewatering process.

This paper also indicated that there is a large amount of work being done on the microalgae cultivation and downstream conversion processes. However, less attention has been paid to the water footprint of microalgal biofuels. To be able to evaluate this new technology in the light of increasing water scarcity, it is suggested to take the water footprint into account.

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## Abbreviations

| | |
|---|---|
| $CH_4$ | methane |
| CO | carbon mono-oxide |
| $CO_2$ | carbon dioxide |
| $H_2$ | hydrogen |
| HHV | higher heating value |
| N | nitrogen |
| $O_2$ | oxygen |
| PBR | photobioreactor |
| US-DOE | US Department of Energy |
| WF | water footprint |