# Carbon Footprint of Hydrothermal Liquefaction of Microalgae Biomass Cultivated in Availability and Limitation of Nutrients

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**This work aimed to assess the carbon footprint of microalgae biomass processing in hydrothermal liquefaction (HTL) to produce biopetroleum and co-products. The foreground inventory covered the cultivation in open ponds with availability (C1) and limitation (C2) of nutrients, followed by harvesting and processing in HTL for 1 kg of microalgae biomass in total solids. The ecoinvent™ 3.6 databases and IPCC- 2021 GWP 100 years method were used for background inventory and impact indicator in openLCA® 1.11.0. The carbon footprint of C1 (1.1 kg $CO_{2eq}$) was more significant than that of C2 (0.7 kg $CO_{2eq}$). The most considerable carbon footprint contribution per stage was the Production stage (cultivation and harvesting), with 64%-88%, in the evaluated scenarios. In comparison, this per process was the fertilizer (71%) in C1 and the heat (32%) in C2.**

**Keywords: Biotechnology. Environmental Performance. Life Cycle Assessment (LCA). Greenhouse Gases (GHG). Microalgae Bioproducts.**

## Introduction

Society industrialization contributed to the expansion of fossil energy consumption, which increased greenhouse gas (GHG) emissions. Therefore, several countries worldwide are committed to adopting measures to mitigate GHG emissions, such as replacing fossil resources with renewable resources [1-3]. In this context, fuels from renewable and carbon-neutral sources promise to replace the fossil fuel. However, substitutes, as first and second-generation biofuel production, demand fertile soils, which is associated with rising food costs. In this way, microalgae-based biofuels have advantages compared to first and second-generation biofuels due to their ability to grow in unsuitable land for agriculture, more significant photosynthetic activity compared to terrestrial plants, and potential to use inputs from residual sources such as gaseous and aqueous effluents [4,5].

Microalgae biomass can be converted into bioproducts using varied processes such as the thermochemical routes. Hydrothermal liquefaction (HTL) is a promising technology for converting wet biomass into biopetroleum [6]. Thus, HTL reduces energy consumption, environmental burdens, and financial costs associated with biomass drying [6,7]. In this regard, Life Cycle Assessment (LCA) is used to quantify the carbon footprint of a product system and support decision-making for GHG emission reduction. Thus, the carbon footprint is widely used in energy policy and practices such as the Brazilian Biofuel Policy (RenovaBio). Therefore, this study aims to quantify the carbon footprint of biomass processing in HTL from microalgae cultivation in availability (C1) and limitation (C2) of nutrients.

## Materials and Methods

The attributional LCA method based on ISO-14044 [8] was used in this study to quantify the carbon footprint in the evaluated scenarios. The reference flow and functional unit combined in this study was 1 kg microalgae biomass processing in total solids (TS). The product system covered the operation phase of the following processes in the foreground inventory: cultivation in open raceway ponds with availability (C1) and limitation (C2)

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of nutrients, followed by harvesting within the Production stage and conversion of microalgal biomass into biopetroleum and co-products in HTL in the Processing stage (Figure 1). In this regard, the evaluated scenarios consist of a product system of microalgae biomass processing in C1, a high-protein content in C1 and a high-carbohydrate content in C2.

The production stage consists of the cultivation in open raceway ponds with annual average productivity of 18 g $(m^2\ day)^{-1}$ in TS. It is supplied by nitrogen and phosphorus nutrients from synthetic fertilizers, saline water from a local source, and high-purity carbon dioxide from a residual source, followed by harvesting with settling, filtration, and centrifugation processes to achieve a 20% concentration in TS [9]. The Processing in HTL lasts 30 min at 350 ºC and 20 MPa. The operation phase of the Production and Processing stages of microalgae-based biopetroleum and co-products were assessed in this study. In contrast, the construction, decommissioning, and downstream stages, such as refining, delivery, use, and post-use, were disregarded. The foreground inventory of the Production stage was obtained from estimations, laboratory analysis, and field experiments in Medeiros and Moreira [10]. In contrast, Jones and colleagues obtained that of the Processing stage was obtained from estimations, laboratory analysis and field experiments [11] (Table 1).

The openLCA® software version 1.11.0 with the background inventory from the ecoinvent™ database version 3.6 for an allocation procedure of process subdivision (cutoff criteria) was used in this study. The assessed category for environmental performance was the carbon footprint from the IPCC-2021 method with the global warming potential indicator (GWP) for 100 years in a kilogram of carbon dioxide equivalent (kg $CO_{2eq}$).

## Results and Discussion

The carbon footprint of microalgae biomass processing in HTL was more prominent in the scenario with nutrient availability (1.1 kg $CO_{2eq}$ in C1) compared to that with nutrient limitation (0.7 kg $CO_{2eq}$ in C2). The most significant carbon footprint contribution per stage was the Production stage (cultivation and harvesting), with 88 % in C1 and 64% in C2 (Figure 2).

Table 2 presents the carbon footprint contribution per process for C1 and Table 3 shows it for C2. The most considerable carbon footprint contribution per process was the fertilizer (71%) in the Production stage of C1 and the heat (32%) in the Processing stage of C2. Even though C2 had a greater electricity demand, its smaller nutrient demand

**Figure 1.** Product system of microalgae biomass processing in hydrothermal liquefaction.

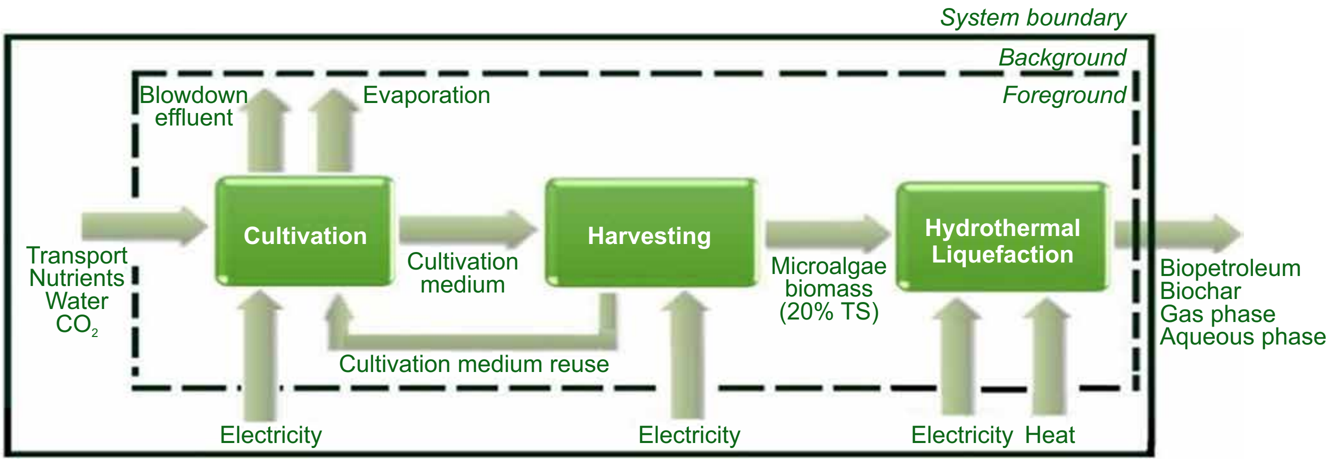


**Table 1.** Foreground inventory of the Production and Processing stages of 1 kg microalgal biomass processing in total solids.

| **Parameters** | **Unit** | **C1** | **C2** |
|---|---|---|---|
| Cultivation and Harvesting | | | |
| Occupied area | $m^2$ year | 0.15 | 0.16 |
| Water, saline | L | 32 | 34 |
| Carbon dioxide, $CO_2$ | kg | 1.9 | 2.1 |
| Ammonia, liquid | kg | 0.10 | 0.019 |
| Nitrogen, N | kg | 0.085 | 0.016 |
| Diammonium phosphate | kg | 0.046 | 0.009 |
| Nitrogen, N | kg | 0.010 | 0.002 |
| Phosphorus, $P_2O_5$ | kg | 0.025 | 0.005 |
| Transport of fertilizer, truck | t km | 0.30 | 0.056 |
| Electricity | kWh | 0.48 | 0.52 |
| Water, air | L | 22 | 24 |
| $CO_2$, loss, air | kg | 0.19 | 0.21 |
| Water, blowdown effluent | L | 5.9 | 6.7 |
| Biomass, loss | kg | $3x10^{-4}$ | $3x10^{-4}$ |
| Hydrothermal Liquefaction | | | |
| Electricity | kWh | 0.36 | 0.36 |
| Heat | MJ | 5.9 | 5.9 |

**Figure 2.** The carbon footprint of 1 kg microalgae biomass processing in the evaluated scenarios.

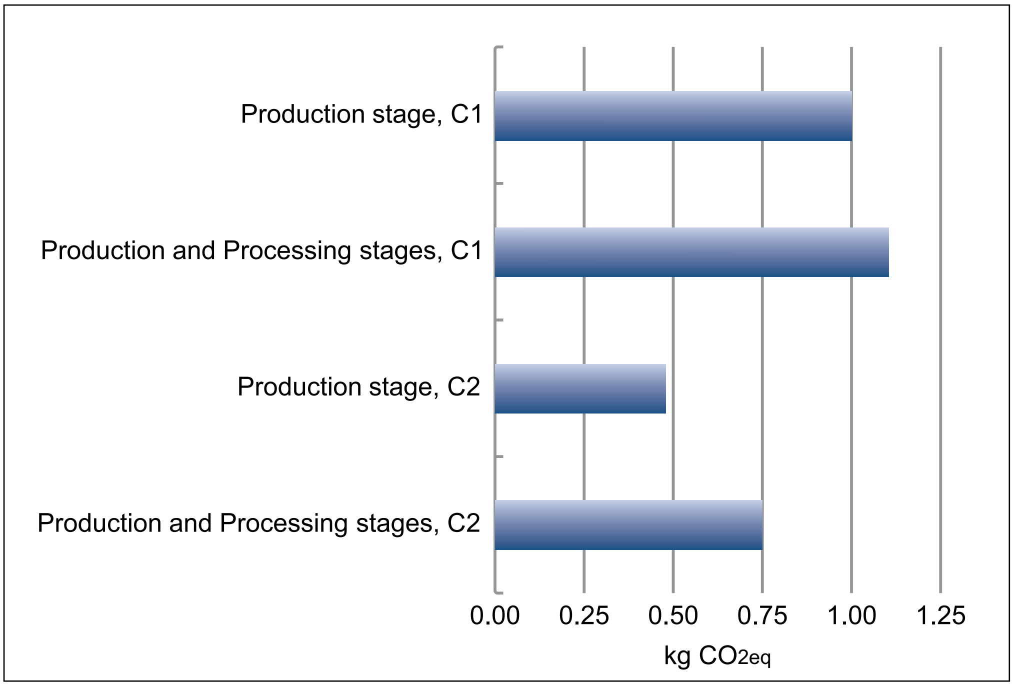
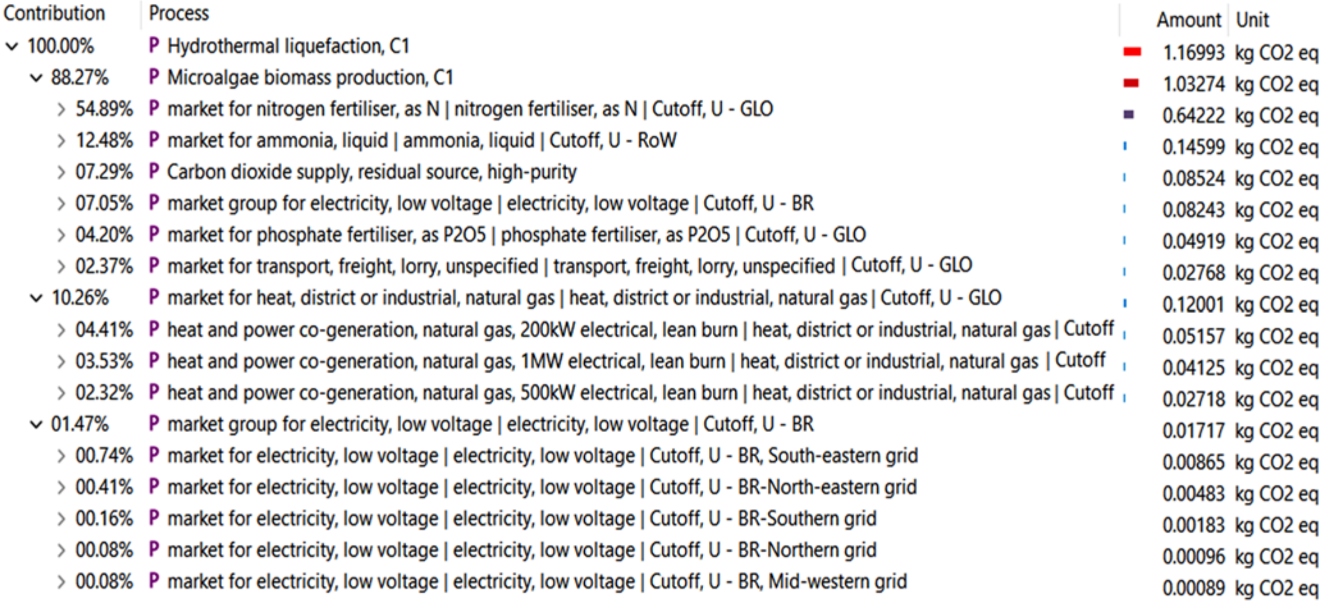
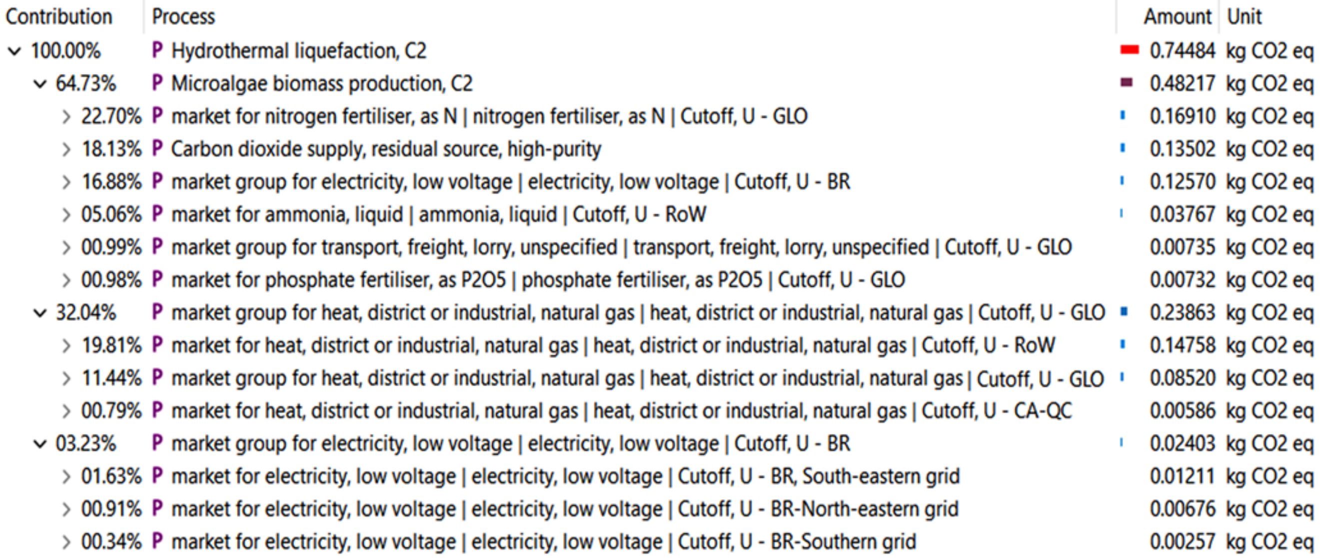


**Table 2.** Carbon footprint contribution per process of 1 kg microalgae biomass processing in C1.



| Contribution | Process | Amount | Unit |
|---|---|---|---|
| 100.00% | P Hydrothermal liquefaction, C1 | 1.16993 | kg CO2 eq |
| 88.27% | P Microalgae biomass production, C1 | 1.03274 | kg CO2 eq |
| 54.89% | P market for nitrogen fertiliser, as N \| nitrogen fertiliser, as N \| Cutoff, U - GLO | 0.64222 | kg CO2 eq |
| 12.48% | P market for ammonia, liquid \| ammonia, liquid \| Cutoff, U - RoW | 0.14599 | kg CO2 eq |
| 07.29% | P Carbon dioxide supply, residual source, high-purity | 0.08524 | kg CO2 eq |
| 07.05% | P market group for electricity, low voltage \| electricity, low voltage \| Cutoff, U - BR | 0.08243 | kg CO2 eq |
| 04.20% | P market for phosphate fertiliser, as P2O5 \| phosphate fertiliser, as P2O5 \| Cutoff, U - GLO | 0.04919 | kg CO2 eq |
| 02.37% | P market for transport, freight, lorry, unspecified \| transport, freight, lorry, unspecified \| Cutoff, U - GLO | 0.02768 | kg CO2 eq |
| 10.26% | P market for heat, district or industrial, natural gas \| heat, district or industrial, natural gas \| Cutoff, U - GLO | 0.12001 | kg CO2 eq |
| 04.41% | P heat and power co-generation, natural gas, 200kW electrical, lean burn \| heat, district or industrial, natural gas \| Cutoff | 0.05157 | kg CO2 eq |
| 03.53% | P heat and power co-generation, natural gas, 1MW electrical, lean burn \| heat, district or industrial, natural gas \| Cutoff | 0.04125 | kg CO2 eq |
| 02.32% | P heat and power co-generation, natural gas, 500kW electrical, lean burn \| heat, district or industrial, natural gas \| Cutoff | 0.02718 | kg CO2 eq |
| 01.47% | P market group for electricity, low voltage \| electricity, low voltage \| Cutoff, U - BR | 0.01717 | kg CO2 eq |
| 00.74% | P market for electricity, low voltage \| electricity, low voltage \| Cutoff, U - BR, South-eastern grid | 0.00865 | kg CO2 eq |
| 00.41% | P market for electricity, low voltage \| electricity, low voltage \| Cutoff, U - BR-North-eastern grid | 0.00483 | kg CO2 eq |
| 00.16% | P market for electricity, low voltage \| electricity, low voltage \| Cutoff, U - BR-Southern grid | 0.00183 | kg CO2 eq |
| 00.08% | P market for electricity, low voltage \| electricity, low voltage \| Cutoff, U - BR-Northern grid | 0.00096 | kg CO2 eq |
| 00.08% | P market for electricity, low voltage \| electricity, low voltage \| Cutoff, U - BR, Mid-western grid | 0.00089 | kg CO2 eq |

**Table 3.** Carbon footprint contribution per process of 1 kg microalgae biomass processing in C2.



| Contribution | Process | Amount | Unit |
|---|---|---|---|
| 100.00% | P Hydrothermal liquefaction, C2 | 0.74484 | kg CO2 eq |
| 64.73% | P Microalgae biomass production, C2 | 0.48217 | kg CO2 eq |
| 22.70% | P market for nitrogen fertiliser, as N \| nitrogen fertiliser, as N \| Cutoff, U - GLO | 0.16910 | kg CO2 eq |
| 18.13% | P Carbon dioxide supply, residual source, high-purity | 0.13502 | kg CO2 eq |
| 16.88% | P market group for electricity, low voltage \| electricity, low voltage \| Cutoff, U - BR | 0.12570 | kg CO2 eq |
| 05.06% | P market for ammonia, liquid \| ammonia, liquid \| Cutoff, U - RoW | 0.03767 | kg CO2 eq |
| 00.99% | P market group for transport, freight, lorry, unspecified \| transport, freight, lorry, unspecified \| Cutoff, U - GLO | 0.00735 | kg CO2 eq |
| 00.98% | P market for phosphate fertiliser, as P2O5 \| phosphate fertiliser, as P2O5 \| Cutoff, U - GLO | 0.00732 | kg CO2 eq |
| 32.04% | P market group for heat, district or industrial, natural gas \| heat, district or industrial, natural gas \| Cutoff, U - GLO | 0.23863 | kg CO2 eq |
| 19.81% | P market for heat, district or industrial, natural gas \| heat, district or industrial, natural gas \| Cutoff, U - RoW | 0.14758 | kg CO2 eq |
| 11.44% | P market group for heat, district or industrial, natural gas \| heat, district or industrial, natural gas \| Cutoff, U - GLO | 0.08520 | kg CO2 eq |
| 00.79% | P market for heat, district or industrial, natural gas \| heat, district or industrial, natural gas \| Cutoff, U - CA-QC | 0.00586 | kg CO2 eq |
| 03.23% | P market group for electricity, low voltage \| electricity, low voltage \| Cutoff, U - BR | 0.02403 | kg CO2 eq |
| 01.63% | P market for electricity, low voltage \| electricity, low voltage \| Cutoff, U - BR, South-eastern grid | 0.01211 | kg CO2 eq |
| 00.91% | P market for electricity, low voltage \| electricity, low voltage \| Cutoff, U - BR-North-eastern grid | 0.00676 | kg CO2 eq |
| 00.34% | P market for electricity, low voltage \| electricity, low voltage \| Cutoff, U - BR-Southern grid | 0.00257 | kg CO2 eq |

reduced the total carbon footprint compared to C1. The fertilizer supply from residual sources such as wastewater should be prioritized in microalgae cultivation to minimize the use of synthetic fertilizers. In addition, catalysts can be applied in HTL to reduce the reaction time and energy demand. Therefore, different optimization strategies are required to improve microalgae bioproducts' technical, environmental, and economic performance.

## Conclusion

Life cycle assessment (LCA) was used to quantify the carbon footprint of microalgae biomass production from cultivation in availability (C1) and limitation (C2) of nutrients and their processing in hydrothermal liquefaction (HTL). Even though C2 had a greater electricity demand compared to that C1, the carbon footprint of C1 was larger than C2 due to its greater synthetic fertilizer demand. Therefore, this work supports decision-making to reduce greenhouse gas (GHG) emissions in producing microalgae bioproducts such as biopetroleum and biochar.

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