Can biofuels from microalgae become a sustainable alternative for the heavy-duty transport sector?

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Abstract

In this contribution, we explore how eight different scenarios involving microalgae biofuels could contribute to bringing the heavy-duty transport sector within the boundaries of sustainable operation. These scenarios comprise a variety of configurations, including two different fuel production methods (hydrodeoxygenation and hydrothermal liquefaction), two carbon sources (i.e., carbon dioxide captured from natural gas power plants or directly from the air) and two electricity mixes (i.e., the current mix and a future sustainable mix). The eight scenarios considered are analysed combining Life Cycle Assessment principles with an Absolute Environmental Sustainability Assessment method based on the Planetary Boundaries, adopting a cradle-to-wheel perspective. The selected approach goes beyond greenhouse gas emissions, embracing other impacts on key Earth-system processes and covering the carbon footprint, too. Our findings highlight that microalgae biofuels have significant potential in mitigating environmental impacts compared to the traditional fossil-based heavy-duty transport sector. Notably, pathways utilizing hydrodeoxygenation of microalgae oil and direct air capture with carbon storage demonstrate the potential to decrease the global climate change impact caused by heavy transport by 77%. Additionally, in contrast to standard biofuels, which often require extensive land use, microalgae biofuels also substantially reduce their impact on biosphere integrity.

**Keywords**: Microalgae biofuels, LCA, planetary boundaries, biosphere integrity

* 1. Introduction

Currently, the world production of biofuels is mostly based on agricultural crop biomass, causing competition for the available land between fuel and food production (Calvo-Serrano et al., 2019).

This study focuses on the Absolute Environmental Sustainability Assessment (AESA) of various biofuel production scenarios from microalgae, and their use in heavy-duty transport, adopting a cradle-to-wheel perspective (Cabrera-Jiménez et al., 2023). Integrating the principles of Life Cycle Assessment (LCA) and an AESA based on Planetary Boundaries (PBs) (Rockström et al., 2009), we can assert whether technological options are truly sustainable or not, and analysis out of reach of conventional LCA, which can only perform relative assessments. In addition, our analysis extends beyond greenhouse gas emissions to encompass broader impacts on key Earth-system processes related with the PBs.

* 1. Methodology

The study explores eight transformation scenarios for microalgae-to-biofuels, considering two distinct fuel production methods (hydrodeoxygenation (HDO) and hydrothermal liquefaction (HTL)) and utilizing two carbon sources (natural gas power plants (BLUE) and direct air capture (GREEN)). Additionally, two different electricity mixes are considered, the current one (labeled M2020) and a future sustainable mix (M2040). The integration of byproducts is included across all scenarios. In addition, we also assess the performance of conventional biofuels (i.e., from soybean), and the business-as-usual (BAU) scenario, where diesel is used as fuels for the trucks. In order to quantify the impacts of all these options on the environment, we will use the following methodology.

* + 1. Life Cycle Assessment combined with the Planetary Boundaries framework

LCA quantifies the environmental impacts of products, processes, and services over their entire life cycle, covering a wide range of potential damages. This is performed based on four steps for identifying environmental hotspots. In the initial phase, the goal and scope of the study are defined. In this context, we defined the annual world ton-km (tkm/yr) demand for road freight activities as the functional unit to quantify the absolute environmental sustainability of various scenarios for microalgae-based biofuel routes.

The second LCA phase focuses on quantifying the main inputs and outputs (e.g., energy, raw materials, byproducts, and emissions). We exploited mass and energy balance information from prior studies for foreground system activities, such as carbon sequestration, microalgae cultivation, drying, byproduct recovery, fuel production, and combustion. This data was combined with corresponding background activities data to compute life cycle inventories (LCIs) for the modeled scenarios.

Moving to the third phase, the LCA assesses the damage caused by LCIs across various environmental categories. In this case, nine control variables related to seven Earth-system processes were considered as impact categories. Hence, characterization factors developed by Ryberg et al. (Ryberg et al., 2018) were employed to express LCIs in terms of the control variables of the PBs.

When results are interpreted PBs framework, provides absolute thresholds against which to compare environmental impacts. Specifically, limits on control variables are used to define a safe operating space (SOS), i.e., an environmental budget for all anthropogenic activities. To avoid using downscaling methods for the SOS., we simulate the global anthropogenic impact of the whole economy that would result from replacing the BAU heavy-duty transport sector by an alternative scenario based on biofuels.

* 1. Results and discussion

The following section summarizes the results obtained for the different scenarios, outlining the environmental impacts associated with distinct pathways of microalgae-based biofuels across different categories. Findings reveal that the current heavy-duty transport sector (i.e., BAU) transgresses the SOS for CO2 concentration by a factor of 1.11. Similarly, conventional soybean-based biofuels exhibit a considerable transgression of the same boundary, with a factor of 1.41. This is primarily attributed to the substantial climate change impact during soybean oil production. Additionally, soybean farming contributes to change in biosphere integrity, reaching 35% of the whole SOS.

HTL scenarios achieve between 1 and 37% lower carbon footprint than HDO scenarios when M2020 is considered. This superiority stems from the more efficient use of energy and resources in the HTL process, eliminating the need for an oil extraction stage in contrast to HDO. The performance of microalgae-based fuels varies across scenarios, with the most favourable climate change category observed in HDO-GREEN-M2040. This scenario occupies only 25% of the SOS for the climate change PBs (i.e., atmospheric CO2 concentration and energy imbalance control variables), marking a 77% reduction compared to the BAU scenario.

Notably, biofuels derived from microalgae stand out in terms of high yield per hectare, resulting in minimal impact on land-system change and contributing to lower impacts on biosphere integrity. For instance, when compared to soybean scenarios, the impact is up to 4.1 times lower in the current electricity mix scenario (HDO-GREEN-M2020 vs HDO soybean) and 6.5 times lower considering the 2040 sustainable electricity mix scenario.

* 1. Conclusions

This study compared eight biofuel production pathways from microalgae for freight road transport, considering various scenarios from a cradle-to-wheel perspective. We assessed the impact of these scenarios on seven Earth-system processes through nine control variables. Our findings reveal that conventional fossil fuels, such as diesel, used in freight road transport are environmentally unsustainable, exceeding the climate change PB by 11%. The alternative of microalgae-based fuels shows promise in mitigating the adverse effects of conventional biofuels, potentially reducing the impact on biosphere integrity by up to six times. However, a carbon-intensive electricity mix combined with carbon sourced from fossil fuels could undermine the potential benefits of microalgae, making it a less favourable option than diesel in terms of climate change (up to two times higher impacts).

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