Life cycle assessment of biofuels from an integrated Brazilian algae-sugarcane biorefinery

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Abstract

Sugarcane ethanol biorefineries in Brazil produce carbon dioxide, electricity and heat as byproducts. These are essential inputs for algae biodiesel production. In this paper, we assessed ethanol's life cycle greenhouse gas emissions and fossil energy use produced in an integrated sugarcane and algae biorefinery where biodiesel replaces petroleum diesel for all agricultural operations. Carbon dioxide from cane juice fermentation is used as the carbon source for algae cultivation, and sugarcane bagasse is the sole source of energy for the entire facility. Glycerin produced from the biodiesel plant is consumed by algae during the mixotrophic growth phase. We assessed the uncertainties through a detailed Monte-Carlo analysis. We found that this integrated system can improve both the life cycle greenhouse gas emissions and the fossil energy use of sugarcane ethanol by around 10% and 50%, respectively, compared to a traditional Brazilian sugarcane ethanol distillery.

KEYWORDS: ethanol; biodiesel; LCA; uncertainty analysis; sustainability.

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1. Introduction

Interest in algae derived bioenergy began more than 50 years ago [1]. The first oil crisis spurred the establishment of large research programs in Japan and in the United States on algae biofuel production [2]. In addition to the high productivity and oil content of microalgae [3], algae derived biodiesel has properties similar to petroleum diesel in viscosity, density, flash point, solidifying point, cold filter plugging point and H/C ratio [4].

More than 10^5 species of microalgae can be used as feedstock for biodiesel production [5]. Green algae, diatoms and cyanobacteria (blue-green algae) are the most promising biofuel feedstocks [1]. Microalgae are made up of long-chain fatty acids, proteins and carbohydrates in high concentration, making them a rich source of ingredients for pharmaceutical and nutraceutical products (e.g. antibiotics, algacides, vitamins, functional foods), as well as biodiesel [1,6].

Microalgae have lower harvesting and transportation costs than woody or herbaceous biomass. They do not need arable land, pesticides or herbicides for cultivation. They can also be produced in wide range of environmental conditions such as fresh, brackish or salt water, or effluent with high organic load concentration [6,7]. Finally, microalgae biodiesel production results in high value co-products [8]. However, algae production still has many challenges due to high technology barriers and costs. All the preferred microalgae characteristics like cells with high yield under high light intensity, thin membranes, easy flocculation, fast growth and high lipid content are not found concurrently in one ideal strain [2]. Hence, current applications of algae biodiesel production are restricted to special, niche cases of viability like we identify in this paper.

Light, water, nutrients and CO₂ are essential inputs for algae production. Due to a favorable climate, Brazil has the potential to become a major algae producer [9]. Further, the Brazilian sugarcane sector is an excellent source of pure CO₂, which is generated during sugarcane juice fermentation, along with substantial quantities from the combined heat and power system.

At the same time, onsite diesel consumption is responsible for 2/3 of the fossil energy consumption and 1/3 of the greenhouse gases (GHG) emissions in the sugarcane ethanol life cycle [10]. With an average consumption of 4 L/t sugarcane [10], it is estimated that the sugarcane sector alone was responsible for about 4% of all diesel consumption in Brazil in 2013 [11,12]. Given these reasons, we designed an integrated algae-sugarcane biorefinery to explore how it can affect the life cycle performance of the products from a traditional sugarcane ethanol factory.

We evaluated the life cycle fossil energy use and greenhouse gas (GHG) emissions of the biofuels produced in such integrated biorefinery using an attributional LCA method. The hypothesis is that replacing diesel by algae biodiesel can substantially improve the life cycle GHG profile of sugarcane ethanol. Such an integrated plant is novel and we could not find any study that performs an LCA of the same. We do recognize however, that such a factory is not yet commercial primarily due to technological and economic barriers for algae production. Nevertheless, algae have been identified as a promising feedstock for biodiesel production [7] and integrating its production with a sugarcane ethanol factory will help reduce costs by taking advantage of synergies that substantially improve overall system efficiency. For example, algae requires pure carbon dioxide for the photosynthesis process, heat and electricity all of which are produced in excess in the sugarcane ethanol process [13].

2. Microalgae as feedstock for biodiesel production

Microalgae are prokaryotic (cyanobacteria) or eukaryotic (green algae, red algae and diatoms) photosynthetic microorganisms that can be found in both marine and freshwater ecosystems [6,14,15]. When compared with land-based plants, their photosynthetic mechanism is generally more efficient in converting solar energy into biomass because they are submerged in an aqueous ecosystem that allows for efficient access to water, CO_2 and other nutrients [15]. They are easily cultured due to the unicellular or simple multi-cellular cell structure, able to grow rapidly and live in a wide range of environmental conditions [6,14]. However, land-based crops use the surface of their leaves to receive, reflect and dissipate the light, while algae are limited to using only the light at the water surface. Hence, algae need to receive stirring in order to ensure access to CO_2 [3].

Algae metabolism can be photoautotrophic, photoheterotrophic, heterotrophic or mixotrophic, and depending on the environmental conditions, the same species can shift from one process to another. Photoautotrophic metabolism utilizes sunlight as the energy source and CO_2 as the inorganic carbon source. Photoheterotrophic metabolism requires sunlight for energy but uses organic substrate as the carbon source. Heterotrophic metabolism does not depend on light and utilizes an organic substrate (e.g. glucose, acetate, and glycerol) as both the energy and carbon source. In the mixotrophic metabolic process microalgae are able to grow in both heterotrophic and photoautotrophic pathways depending on the concentration of organic carbon sources and light intensity [1,6,16].

There is a wide range of lipid content in microalgae species (1-70% of dry weight) and high oil content is frequently associated with low biomass yield. Thus, it is important to

select microalgae species that have high lipid content and high biomass productivity [6]. Other desired microalgae characteristics from a biodiesel perspective are cells with thin membranes, high yield under high light intensity, and that easily flocculate [2]. As we mention above, not all of these features are found in a single species so the choice of species involves tradeoffs between features.

Biodiesel production from microalgae consists of the growth of cells, followed by separation of the cells from the culture media and lipid extraction [17]. In the following sections, we discuss briefly the microalgae production process. A more detailed description of microalgae is presented in the literature [1,2,14,16,18,17,19–22].

2.1. Production system

Open ponds and photobioreactors (PBRs) are the two most common engineered systems used for microalgae cultivation. Both systems require light, nutrients and CO₂ [23], where the light and temperature are especially crucial factors for growing algae [6]. Currently, neither open ponds nor closed photobioreactors are mature technologies for biofuel production [8]. Open ponds can be designed as raceways, tanks or circular ponds, but raceways have become the most popular since motorized paddlewheels have been used for continuous circulation [8]. Mixing and circulation are required to prevent sedimentation and to stabilize algae growth and productivity [14]. CO₂ must be sparged into counter-current water flow [1]. Biomass productivity in open ponds is less efficient due to evaporation losses, temperature fluctuation, CO₂ deficiencies, inefficient mixing, and light limitation [14]. Besides, they are more susceptible to culture crashes once they are directly in contact with the environment and thus amenable to introduction of invasive algal species as well as predators and pathogens [24]. Hence, in this paper, we design algae growth using photobioreactors.

Photobioreactors are enclosed tanks with several geometries and designs, such as flat-plate, airlift tubular, vertical columns, hemispherical domes, among others [8,22]. Water, nutrients and CO₂ are supplied in a controlled way and O₂ has to be removed. Sunlight diffuses into the PBR through transparent walls or through light fiber or tubes [2,15]. Several methods can be used for biomass harvesting and drying. Microalgae species, properties such as cell size and density, culture conditions [15] and the desired co-products [25] will define the harvesting and drying technique.

Once the algae are harvested from the PBR, lipids are extracted. Conventional solvent extraction, supercritical fluid or heated oil extraction, mechanical extraction, biological extraction and fractionation can all be used for algal lipid recovery [26]. The choice depends

on the pre-treatment of algal biomass, which can provide a biomass concentrate or dried powder [27], and on the species and its cell wall physical properties, which also depends on the algal growth cycle [26]. Finally, algal oil is converted into biodiesel through a standard transesterification process [27,28].

3. Integrated algae-sugarcane biorefinery

In the proposed integrated biorefinery, sugarcane and algae are processed in a combined ethanol-biodiesel plant, which uses only bagasse as fuel for cogeneration. We assumed the algae production process developed by SEE ALGAE¹ Technology (SAT) company. We made some adjustments to their system to fit our design needs. Carbon dioxide is captured from the sugarcane juice fermentation process to feed the algae production in a photobioreactor, which also receives sunlight (solar prism). Algae flows to a mixotrophic reactor fed with organic carbon source and fertilizers. The mixotrophic process also receives a small quantity of carbon dioxide.

Flocculation and flotation are followed by a de-watering process employed by SAT. We are unable to disclose the full details of the de-watering method and chemicals used in this process due to our non-disclosure agreement with SAT. We modeled di-methyl ether (DME) lipid extraction and transesterification to convert algae oil into biodiesel.

We chose the microalgae species *N. salina* because of its high lipid content and high biomass productivity [29]. Glycerin is used as carbon source because it is available as a co-product of biodiesel production onsite and because *N. salina* has demonstrated a better carbon assimilation using this substrate [30].

It is important to highlight that we are only using CO₂ from the fermentation process because it is pure [13]. Additional CO₂ could be provided from biomass burning (bagasse-based cogeneration), but that is not a pure CO₂ source and, further, we find that the fermentation process provides enough carbon dioxide for the needs of the integrated biorefinery. However, the CO₂ flow needs to be diluted because the growth of microalgae can be inhibited at CO₂ concentration above 5% (pure CO₂-air), depending on the species [31,32].

¹ SEE ALGAE shared their system design and data with us under a non-disclosure agreement. Hence, all data that we publish in this paper abides by this agreement or is publicly available.

Figure 1 and our main assumptions are:

- We use the algae species *Nannochloropsis salina* in our biorefinery.
- Carbon dioxide from cane juice fermentation is used as one of the inorganic carbon sources for algae cultivation in photoautotrophic and heterotrophic processes.
- Biodiesel production is constrained by the CO₂ availability.
- All glycerin produced from the biodiesel plant is consumed as energy and carbon source in the mixotrophic process. However, the supply is not enough and additional glycerin is bought from the market.
- The alcohol source for transesterification is the ethanol produced onsite.
- Ethanol, electricity, biodiesel and algae meal are the output products of the system.
- The diesel used in the sugarcane cultivation is replaced entirely by biodiesel (B100) without engine modification [33,34].
- Stillage and filtercake are used for fertirrigation and organic fertilization. Filtercake is applied in 100% of the plant-cane area.
- Sugarcane bagasse is completely used for heat and power generation, supplying the energy demand of the combined plant (ethanol and biodiesel) and producing surplus electricity.
- Fifty percent of the sugarcane area is irrigated.

Considering that some producers are irrigating the sugarcane production, especially in Mato Grosso and Goiás states, we assumed salvage irrigation in 50% of the sugarcane area, based on our field data. However, the goal here is not to discuss irrigation and its effects on sugarcane growth, but identify the diesel consumption for this activity. Furthermore, the use of irrigation in sugarcane crops is still incipient in these states, and the procedures and irrigation rates vary within a wide range among the producers.

Figure 1. Integrated algae-sugarcane biorefinery.

Note: dark grey boxes: processes; white boxes: products consumed inside the system; green boxes: output products; orange boundary: energy flow, which supplies all the process; and black arrows: mass flow.

4. Methods

We applied an attributional life cycle assessment technique [35,36] and chose 1 MJ of hydrous ethanol as the functional unit (FU) for the sugarcane ethanol LCA and 1 MJ of ethyl biodiesel as FU for the algae biodiesel LCA. Note that the goal is to compare the ethanol production (1 MJ of hydrous ethanol) between the traditional and the biorefinery systems. The system boundary, in this cradle-to-gate LCA, includes sugarcane and algae cultivation and biofuel and co-products production. The environmental aspects considered were fossil energy use and GHG emissions. In order to compare the traditional sugarcane ethanol production with our integrated biorefinery, we assessed three product systems: 1) traditional

ethanol production, 2) algae biodiesel production, and 3) algae-sugarcane biorefinery system. We first present the results for the algae biodiesel life cycle for a better understanding of the impact caused by diesel replacement in the sugarcane cultivation activities. We then present the results for the integrated biorefinery. Using Monte-Carlo simulation we compared these results with the traditional sugarcane ethanol. Each of these systems is described below:

- **Traditional system (reference case):** A conventional sugarcane production and processing system that uses only diesel (B5) as fuel in the agricultural operations and transportation. Ethanol and electricity are the output products.
- **Algae biodiesel system:** An algae production system that has meal and biodiesel as products. Biodiesel is produced by transesterification using ethyl route. The electricity, heat and ethanol are provided by the sugarcane mill and by the cogeneration plant. Carbon dioxide is also provided by the sugarcane distillery, but we did not attribute any environmental burden to CO₂ as it was not considered as a product of the traditional sugarcane sector.
- **Integrated Biorefinery:** An integrated production of biodiesel, glycerin, algae meal, ethanol, and electricity. The biodiesel produced is used to replace 100% of the conventional diesel (B5) consumed in the agricultural operations and sugarcane transport. The system also provides surplus biodiesel. Glycerin is not an output product since algae consume it as a carbon and energy source.

The life cycle fossil energy use and GHG emissions of material and energy inputs were retrieved from Ecoinvent v.2.2. [37] and CTBE's database (Brazilian Bioethanol Science and Technology Laboratory) [38–40], which are specifically for Brazilian conditions (Table S1). All energy flows were calculated in terms of primary fossil energy.

For the integrated biorefinery, we used an energy basis allocation to split the fossil energy and the GHG emissions between ethanol and surplus electricity. For the algae biodiesel system, the products are meal and biodiesel, and we used an allocation based on mass.

4.1. Input data

The sugarcane life cycle inventory was based on data collected from sugarcane mills and sugarcane suppliers (Table S2). The data refer to the states of São Paulo, Mato Grosso and Goiás, and were collected employing direct field observation methods through

questionnaires. In a previous study, we assessed the LCA of a soybean-sugarcane biorefinery system in these regions [41]. Soybean is the main feedstock used for the biodiesel production in Brazil, and Mato Grosso state already has a soybean-sugarcane biorefinery factory in operation. These states have the greatest potential for integrated biorefineries of the type we propose in this paper. Hence, we selected the same regions for this paper.

The diesel consumption was validated through data from sugarcane mills covering all cultivation activities. The contribution of each source of nitrogen fertilizer was defined according to Seabra et al. [10]. To calculate the diesel consumption from irrigation, we assumed that pump and reel systems are used, with two water reels per pump, 400 meters hose, 60 m spacing between the reels, and 66 m/h reel speed.

Table 1. Agricultural and industrial inputs - sugarcane production

Agricultural parameters	
Number of cuts ^a	5
Sugarcane yield (t/ha.yr) ^a	85
Straw yield (kg/t cane; DW) ^d	140
Stillage application rate (m ³ /ha) ^a	140
Ash application rate (kg/ha.yr; DW) ^a	5,000
Filter cake application rate (t/ha; DW) ^a	5
Agricultural Inputs (kg/ha) ^a	
Nitrogen	84
Phosphorus	30
Potassium	79
Insecticide	0.2
Fungicide	0.01
Herbicide	4.1
Limestone	1000
Gypsum (CaSO ₄)	500
Diesel consumption (L/ha.yr)	262.5
Industrial Inputs	
CaO (g/t cane) ^a	530
Antifoam (g/L ethanol) ^a	0.3
Dispersant (g/L ethanol) ^a	0.3
Sulfuric acid (g/L ethanol) ^a	6.6
Lubricants (g/t cane) ^b	13
Cyclohexane (g/L ethanol) ^{a,c}	1.2
Sodium Hydroxide (g/L ethanol) ^a	0.4
Mill processing capacity (t cane/yr)	4,000,000

^a Data provided by visited sugarcane mills and farms. ^b[39]. ^c Used to produce anhydrous ethanol (input for the transesterification process). ^d [42].

Direct N₂O emissions from crop residues were estimated according to the IPCC tier 1 method [43]. We did not include the direct N₂O emissions from the biological nitrogen fixation due to lack of evidence indicating significant emissions arising from this process [4].

The biorefinery cogeneration system operate at 90 bar/520°C/120 t/h of steam [44] which is able to produce 135.5 kWh of electricity per metric ton of sugarcane. The heat

demand of the algae plant reduces this amount to 132 kWh, while 30 kWh/t is consumed in the distillery [44] and 21 kWh/t is used for algae biodiesel production (Table 2). The sugarcane crushers are driven by electric engines. The electricity consumption for algae biomass production, including photobioreactor, flocculation and de-watering, was provided by SAT and cannot be disclosed separately due to our NDA. Other input data for the algae life cycle inventory was based on literature.

Table 2. Demand and supply of steam and electricity of the biorefinery system.

Electricity consumption		
CO ₂ recovery from fermentation ^a	300	kWh/t biomass (DW)
Photobioreactor, flocculation and de-watering ^b	374	kWh/t biomass (DW)
Oil extraction (DME) ^c	1079	kWh/t extracted oil
Transesterification ^c	0.38	kWh/t biodiesel
Steam consumption		
Oil extraction (DME) ^d	5.49	MJ/kg biodiesel
Transesterification ^e	3.06	MJ/kg biodiesel
Supply and demand of electricity		
Electricity production ^f	132	kWh/t cane
Ethanol plant ^g	30	kWh/t cane
Biodiesel plant ^h	22.3	kWh/t cane
Surplus electricity	79.6	kWh/t cane
Production		
Ethanol	340,000	m ³ /yr
Electricity	527,500	MWh/yr
Biodiesel	34,850	t/yr
Consumed	13,380	t/yr
Surplus	21,470	t/yr

^a 219,900 [t CO₂/yr]/75,280 [t algae/yr] x 0.1026 [kwh/kg CO₂] [13]. ^b [45]. ^c 0.51 kWh/kg biomass [46]; Oil content = 50%, oil extraction efficiency = 94.5%. ^d DME, 500 kPa, 20 °C [46]. ^e 50 °C, 1 atm (process). ^f [44]. ^g Boiler = 90 bar, 520°C, 120t/h of steam; electric drivers for milling and cane preparation [44]. ^h Supplied by the cogeneration plant.

Carbon, nitrogen and phosphorus consumption for algae production are calculated assuming an algal composition of [C₁₀₆H₁₈₁O₄₅N₁₅P] based on the Redfield Ratio (Table 3). We considered ammonia, single superphosphate and potassium chloride as sources of nitrogen, phosphorous and potassium, respectively [47]. The lipid content was assumed as 50% by weight, which is conservative [48]. Under laboratory conditions, *Nannochloropsis salina* can achieve 60% of lipid content by weight [48]. For the uncertainty analysis, the minimum (33%) and maximum (61%) values were defined according to Fábregas et al. [49]. Carbon dioxide from fermentation was determined by the stoichiometric conversion of glucose into ethanol and CO₂ (90 g/mol = 46 g/mol ethanol + 44 g/mol CO₂), resulting in 0.76 g of CO₂ per liter of ethanol. We assumed the CO₂ recovery efficiency to be 90% [13] and the CO₂ utilization efficiency of algae to be 58% [50].

Table 3. Parameters of production and processing of algae and biodiesel

Biodiesel production (t/yr)	34,850
Chemicals input	kg/t algae (DW)
Nitrogen ^a	92.3
Phosphorus ^a	12.8
Potassium ^a	8.2
Salt ^b	80
Glycerol ^c	126.6
Transesterification	kg/t biodiesel
Chemicals input ^d	
Ethanol	154
Sodium methoxide	33.4
Citric acid	0,65
Hydrochloric acid	9.5
Sodium hydroxide	1.5
Sulphuric acid	0.2

^a According to Redfield relation [51]. ^b [45]. ^c Equivalent to the external demand for glycerol. ^d [52].

Algae production is limited by the amount of CO₂ available from cane juice fermentation. Thus, the algae production is function of CO₂ utilization efficiency, algae carbon content, ethanol yield, and substrate consumption (glycerol). We assumed a fixed value for glycerol consumption, according to Sforza et al. [53], of 152 g per kg of biomass (DW). The additional carbon required to satisfy the mass balance of the algae carbon content comes from CO₂, which justifies this input as a limiting factor for the algae supply.

Given that glycerol has a carbon content of 39%, the organic carbon consumption is 59.6 g/kg biomass. Thus, assuming a carbon content of 52.4% (w/w) for *N. salina* [54], the total carbon required from flue gas (CO₂) is 464.3 g/kg biomass, which corresponds to 1.7 t CO₂ per ton of algae (DW). However, an excess CO₂ is necessary and, according to Rubio et al. [50], up to 40% of the CO₂ may be lost during photoautotrophic growth, which corresponds to a real CO₂ consumption of 2.9 t CO₂ per ton of algae (Table 4). We did not include CO₂ recirculation, which means that the unused carbon dioxide is released to atmosphere.

Table 4. Carbon consumption in the mixotrophic reactor and photobioreactor

Mixotrophic reactor	
Glycerol concentration in basic medium (%; w/v) ^a	1
Algae glycerol consumption efficiency (%) ^a	3.2
Glycerol consumption (g glycerol/L solution)	0.32
Biomass concentration (g/L) ^a	2.1
Final consumption of glycerol (g glycerol/g biomass)	0.152
Glycerol C content (%)	39
Carbon provided by glycerol (g C/kg biomass) ^b	59.6
Elemental C content in <i>N. salina</i> (%) ^c	52.4
Photobioreactor	
Carbon provided by CO ₂ from fermentation (g C/kg biomass) ^d	464.3
CO ₂ recovery from fermentation (t CO ₂ /yr) ^e	219,900
CO ₂ utilization efficiency by algae (%) ^f	58.3
Final CO ₂ consumption at PBR (kg CO ₂ /kg biomass (DW))	2.92
Annual algae production (DW) (t/yr)	75,270

^a [53]. ^b 0.22 kg CO₂/kg biomass. ^c [54]. ^d 1.7 kgCO₂/kg biomass. ^e CO₂ recovery efficiency = 90% [13]. ^f [50].

Glycerol produced in the biodiesel plant (4,800 t/year) is insufficient to meet the algae's demand for organic carbon (14,300 t/year). Hence, the biorefinery needs an additional 9,500 ton per year of glycerin, which is equivalent to 2.9% of Brazilian glycerin production in 2012 [55]. We assumed that this additional glycerin is purchased from a soybean biodiesel plant whose environmental burdens was adapted from Souza and Seabra [56].

The lipid extraction is performed by using di-methyl ether (DME). The choice for this solvent is because DME consumes less energy and lower GHG emissions are associated with its life cycle, when compared with the hexane extraction [57].

Emission factors and fossil energy use for glycerin production were adapted from Souza & Seabra [41] where the heat source for soybean oil extraction is a weighted mean of fuel oil, firewood and natural gas, in accordance with the energy consumption per source in the foods and beverages sector in Brazil [58].

The mass flows throughout the integrated system are presented in a Sankey diagram in the Supplementary Data (Figure S1).

4.2.Uncertainty analysis

The uncertainties were assessed through a detailed Monte-Carlo analysis. We used field and literature data to estimate the statistical parameters for the sensitivity and uncertainty

analyses (Appendix E). Crystal Ball® was the tool employed to fit the probability distribution and to run the Monte-Carlo simulation.

5. Results

5.1. Algae biodiesel life cycle assessment

The Monte-Carlo analysis indicates that the life cycle GHG emissions of algae biodiesel are 23 ± 3.5 gCO₂e/MJ fuel (mean $\pm$ std. dev.) (Figure 2). We calculated that algae biodiesel production uses 280 ± 37 kJ of fossil/MJ fuel on a life cycle basis (Figure 3).

Batan et al. [48] and Delrue et al. [57] reported values around 40 and 80 gCO₂e/MJ biodiesel for GHG emissions and 417 and 1075 kJ/MJ for fossil energy use, respectively. Most of these emissions and fossil energy use are related to the energy and steam consumption for cultivation and processing of algae. In our LCA study, the energy demand is supplied by the cogeneration system of the ethanol plant.

Figure 2. Algae biodiesel life cycle GHG emissions

Figure 3. Algae biodiesel life cycle fossil energy use

N application rate, direct N₂O emission from managed soil and glycerol consumption are responsible for about 27%, 26% and 19% of the variance in the GHG emissions, respectively. Glycerol content of glycerin accounts for 16% of the variance. As for fossil energy use, N application rate contributes to 79% of the variance in the results, followed by glycerol consumption (7.7%) and P application rate (5.7 %) (Figure 4).

Figure 4. Sensitivity analysis for the algae biodiesel life cycle: GHG emissions (a), fossil energy use (b).

Note: Only parameters with explained variation higher than 0.1% are presented. The units for the “*” parameters are presented in Table S4.

These life cycle indicators are considerably sensitive to the allocation method. Using price-based allocation instead of the mass-based procedure leads to greater life cycle impacts: 32 ± 4.8 gCO₂e/MJ (mean $\pm$ std. dev.) for GHG emissions, and 380 ± 54 kJ/MJ for fossil energy use. The reason for that is because the price of biodiesel is nearly two times higher than the price of algae meal. The dispersion of the results and the standard deviations are also higher due to the high uncertainties regarding the products prices. This corroborated our option for the mass-based allocation for the base case assessment of the algae-sugarcane biorefinery.

5.2. Sugarcane ethanol life cycle assessment

The integrated algae-sugarcane biorefinery can reduce the life cycle GHG emissions of ethanol from 23.5 gCO₂e/MJ in the traditional system to 21 gCO₂e/MJ (Figure 5). The sensitivity analysis shows that direct N₂O emissions accounts for 58% of the variance, followed by sugarcane yield, which is responsible for 24%. The significance of the direct N₂O emissions is due to its wide variation in the probability distribution (Table S4).

In the reference case, residue use, including trash decomposition, stillage, filtercake, boiler ash, soot, and bagasse burning, account for 33% of the GHG emissions over the traditional ethanol life cycle. Nitrogen use, which includes its production and direct and indirect emissions during the use, is responsible for 27% of the total emissions in the traditional case. Although the diesel represents 23% of the GHG emissions, it is responsible for around 2% of the variance in the MC analysis, even assuming 100 L/ha.yr of amplitude between minimum and maximum values. The major contributions to the dispersion of results come from the direct N₂O emission (52%) and sugarcane yield (30%).

In the integrated biorefinery, where no diesel is consumed in the agriculture activities, algae biodiesel is responsible for only 6% of the life-cycle GHG emissions. Residues, nitrogen, and lime are responsible for 41%, 33% and 15%, respectively (reference case). From the sensitivity analysis, we found that the direct N₂O emissions from managed soil and sugarcane yield are the most influential parameters, responsible for 58% and 24% of the GHG emissions over the ethanol life cycle (Figure 6).

Figure 5. Monte-Carlo results for the GHG emissions – comparison between the traditional system and the integrated algae-sugarcane biorefinery.

Figure 6. Sensitivity analysis of the integrated algae-sugarcane biorefinery: ethanol's life cycle (a) GHG emissions, and (b) fossil energy use.

On energy use, the MC analysis shows that the integrated biorefinery is able to reduce fossil fuel consumption by approximately 50% compared to the traditional system. As noted in Figure 7, the traditional system has larger variance, 2.5 times higher than the integrated biorefinery. The reason for this is the diesel consumption, which represents about 25% of the dispersion of results in the traditional system.

In the reference case, nitrogen use is the second largest fossil energy use input, accounting for 25% in the traditional system. Diesel accounts for 63% of the fossil energy use. From the sensitivity analysis, diesel is responsible for about 10% of the variance in the MC analysis; sugarcane yield represents 66% of the variance, and sugarcane transportation distance accounts for 11%, which is also directly related to the diesel consumption.

In the integrated case, nitrogen and algae biodiesel are responsible for 53% and 21% of the fossil energy use, respectively (reference case). Once again, from the sensitivity analysis, we found that the sugarcane yield is the most sensitive parameter for the fossil energy use, accounting for 78%, followed by nitrogen application (6%) and ethanol yield (6%) (Figure 6).

Figure 7. Monte-Carlo results for the fossil energy use – comparison between the traditional system and the integrated algae-sugarcane biorefinery.

6. Discussion

The MC simulation showed that the integration is more advantageous with respect to the reduction of fossil energy use. The uncertainty analysis also demonstrated that replacing diesel by biodiesel reduce the dispersion of the results for fossil energy use. However, a high variation is associated to the GHG emissions mainly because of the uncertainties related to the direct and indirect N₂O emissions from synthetic and organic fertilizers. For this reason, strategies to improve the management of synthetic fertilizers and residues are important additional actions to reduce the GHG emissions in the sugarcane ethanol life cycle.

The glycerol consumption in our model corresponds to 2.9% of the total national production (up to 300,000 tons per year). Although glycerol is widely available due to the large biodiesel production in Brazil and has a low market price, this carbon source can be constrained depending on the biodiesel plant location.

Regarding the CO₂ use, it is important to highlight that if fermentation is the only source, algae production will follow the ethanol production season, which is interrupted for at least 3 months each season. For this reason, an economic assessment should be performed to

1 identify which CO₂ source would be more feasible: CO₂ from fermentation or CO₂ from
2 biomass burning. Ideally, a plant should work 12 months per year to keep the algae alive. In
3 this case, two approaches may be considered: 1) the storage of CO₂ from fermentation; 2) an
4 exclusive boiler running with biomass (stored bagasse). Note that many sugarcane mills are
5 already producing electricity during the sugarcane offseason. Again, an economic assessment
6 will indicate which option is more economically attractive. In our model, we did not consider
7 the CO₂ from biomass burning because the carbon dioxide supplied by fermentation is
8 sufficient to replace 100% of the onsite diesel demand.
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12 In order to assess the likelihood that the proposed integrated biorefinery will be built,
13 we looked at Brazilian biodiesel policy and market conditions. Brazilian federal law n.
14 11097/2005 requires a blend of 5% biodiesel and 95% diesel by volume (B5), except for
15 maritime diesel. The biodiesel commercialization is carried out through public auctions
16 organized by Petrobrás and the Brazilian National Agency of Petroleum, Natural Gas and
17 Biofuels (ANP). The average price of biodiesel in the auction has decreased in recent
18 auctions, but it is still higher than the diesel price. For this reason, the Brazilian policy has
19 supported the biodiesel production and commercialization. Therefore, it is important to note
20 that although replacing diesel by biodiesel in a sugarcane ethanol biorefinery may result in
21 lower life cycle GHG emissions and fossil energy use, biorefinery owners are more likely to
22 sell algae biodiesel on the market and continue to use petroleum diesel for operations. Hence,
23 in the absence of any environmental performance incentives, the integrated system we
24 propose may operate differently in practice. Further, Omega-3 production can also be more
25 attractive than biodiesel production given its high market price. However, this market can be
26 limited by the total demand and by the location.
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40 As for the assumptions made in the algae production system, there are still many
41 uncertainties regarding the algae yield under different locations and process conditions as
42 well as technological barriers, especially for production and de-watering. All these conditions
43 could affect the results of this study. Although this study has given special attention to the
44 uncertainties of the parameters, it is important to develop further studies including different
45 technological and process conditions as well as an economic assessment.
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51 Estimates of production costs have showed values between US\$2.38 and US\$7.93 per
52 liter when algae is produced in open ponds, and between US\$3.96 and US\$10.57 per liter
53 when photobioreactor is used [8]. Thus, the microalgae biodiesel is not cost-effective yet to
54 compete with diesel unless additional support such as subsidies are applied [6].
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7. Conclusion

The significant contribution from diesel consumption to the environmental profile of sugarcane ethanol encourages the pursuit for production systems less reliant on fossil fuels. Previous analyses have shown that the displacement of diesel by biodiesel can help not only in the mitigation of some environmental burdens of sugarcane ethanol, but also curb logistical issues in Brazil. In this work, we evaluated a proposed algae-sugarcane biorefinery that combines the production of ethanol and algae biodiesel, which can be used as diesel substitute in the sugarcane cultivation activities. The results show that such system is be able to reduce the GHG emissions and, especially, the fossil energy use in the ethanol life cycle.

Uncertainties, however, are high as the analysis relied on projected performances, while there are still significant technological and economical barriers associated with algae biodiesel. On the other hand, the integration can be alternatively viewed as a promising pathway for the deployment of algae biodiesel in face of the local availability of pure CO₂ streams and utilities. Despite representing a good option to improve the environmental performance of ethanol, those gains may not be observed in the absence of economic incentives, as operators may choose to not displace diesel, or to produce other algae-based products with higher added-value.

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