Chapter 6
Life Cycle Assessment of Biofuels from Microalgae

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Abstract Recently, the use of mathematical tools, such as the life cycle assessment (LCA) methodology for ecologically sound processes, with the purpose of establishing a process designer involving the limits of "cradle to grave" in an efficient and flexible way with less subjectivity, has become an ambitious challenge to be won. Therefore, to generate biofuels with low atmospheric emissions and minimal energy requirements has become crucial to commercial competitiveness. Thus, the objective of this chapter is to approach the current situation of the different scenarios of microalgal biofuels production by an evaluation of them via a life cycle assessment. The chapter is based on three main topics: (1) fundamentals for structuring a life cycle assessment, (2) biofuels data set reported in the literature, and (3) application of LCA in microalgae biofuels.

Keywords Microalgal · Biofuel · Biodiesel · Life cycle analysis

1 Introduction

The emergence of ever larger global issues, such as the energy dilemma, the warming of the climate, and the scarcity of water resources, has boosted the search for tools capable of ensuring the reliability of the results published by the industries, becoming the focus of environmental sustainability (Blanchard et al. 2017).

To this end, the application of the life cycle assessment (LCA) assumes the character of ensuring better internal management in order to promote cleaner production,

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improve eco-efficiency, and assist in economic calculations within institutional organizations. In addition, in a broader conception, LCA also serves as the basis for reporting the data required by environmental regulatory agencies (Bicalho et al. 2017).

Given the above, the use of this mathematical tool emerges with the purpose of defining the performance of biofuels in order to assist in decision making, which provides an understanding of environmental impacts and possible increases in the efficiency of their biofuels processes, reducing costs, and promoting the marketing of its products in a sustainable way (Deprá et al. 2017).

Finally, with the objective of expanding the knowledge base and promoting the environmental importance of biofuels, the objective of the chapter was to elucidate the fundamental aspects of the implementation of an LCA as well as to report studies on microalgae biofuels.

2 Life Cycle Assessment for Biofuels

Life cycle assessment was devised in the late 1960s by the US Department of Energy. As a goal, the first studies were conducted to investigate the life cycle aspects of products and materials that address issues such as energy requirements and energy efficiency. In this context, life cycle analysis has become a key tool for assessing the sustainability potential of the processes. Therefore, this tool aims to establish an environmental approach with the objective of not restricting a systemic view of the productive chain, but rather an action on its environmental aspects and the opportunities for improvement that can be observed from a more comprehensive analysis (Curran 2006).

Afterward, in the early 1990s, the pressure of the environment and the need to use the LCA tool to be widely recognized led to the establishment of LCA standards mandated by the International Organization for Standardization (ISO) (ISO 14040 2006). This basis for implementation provided by the ISO series, in the current state, is applied in different ways and, therefore, often leads to divergent results (Gnansounou et al. 2009). Figure 1 shows the four basic steps that guide the implementation of the LCA in order to perform the analysis in a homogeneous and standardized way.

2.1 Definition of the Purpose and Scope

The first step in initiating a case study using the life cycle analysis tool is to establish the goal and scope definition. Depending on the purpose and scope of the LCA, there are four main options of the system boundary: cradle to gate, gate to gate, cradle to grave, and gate to tomb (Jacquemin et al. 2012). The cradle to grave option is the broader scope limit where the life cycle of a product undergoes at least

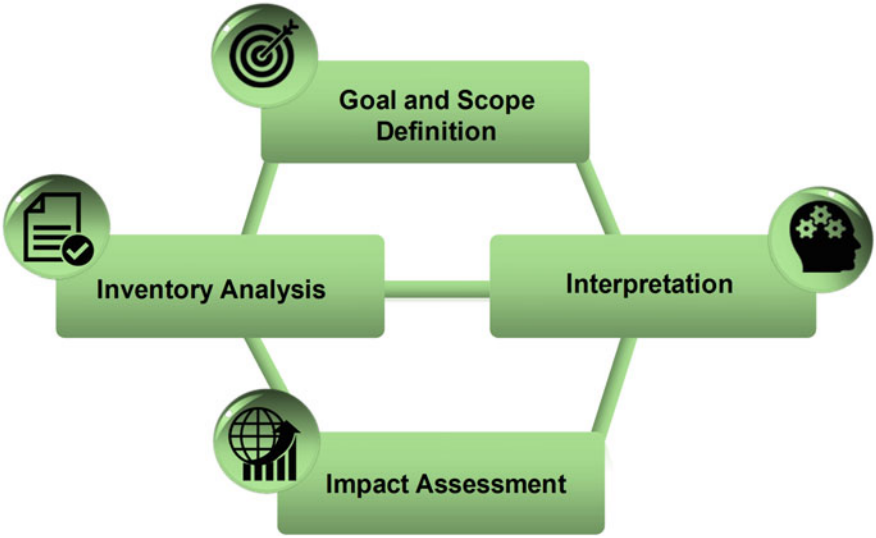

Fig. 1 Driving steps for life cycle assessment

three phases: production phase, phase of use, and phase of elimination. However, the goal usually includes the intended application, the reasons for conducting the study, the target audience, and the use of the results. Moreover, although the definition of the system is more detailed in case of project or operation improvement, the flowchart of the biofuels routes is simplified to LCA when related to the political–environmental reports (Zhang et al. 2015).

In addition, perhaps the greatest impasse of this realization is the delimitation of the process. Although this stage is inserted in all the works analyzed, they are not always structured with the same level of detail. They make the results restricted when comparisons are made.

Another important question about the starting point for reducing the constraints, the system boundary (unit operations involved), and the functional unit (calculation basis) should be clearly defined (Prox and Curran 2017). Therefore, the LCA for biofuels is configured from the process of obtaining the energy biomass, the process of extraction, transport, and use, commonly measured in units of 1 kg or 1 MJ of biofuel.

2.2 *Life Cycle Inventory*

The life cycle inventory (LCI) stage involves the compilation and quantification of inputs and outputs for each process included in the system boundary. Consequently, these inputs and outputs include the use of resources such as the release of greenhouse gases, water, and land associated with the system. In short, this stage of the process is the input to characterize the life cycle assessment (ISO 14040 2006).

In addition, as data are collected and more thoroughness is assigned to the system, new requirements or data limitations may be identified that require a change in the collection procedures so that the study objectives are still met (ISO 14041 1998). Problems that require revisions to the purpose or scope of the study can sometimes be identified.

2.3 *Life Cycle Impact Assessment*

The life cycle impact assessment (LCIA) aims to assess the magnitude and importance of the potential environmental impacts of a product/service (ISO 14042 2000). Therefore, as factors such as choice, modeling, and evaluation of impact categories can add subjectivity to the study, transparency in this stage of the LCA becomes extremely relevant, ensuring that the facilities are clearly described (Jolliet et al. 2003).

Due to this, flows are associated with the possible categories of environmental impact. The choice of an impact category is based on characterization methods according to the objectives and scope of the study. Each flow can contribute to various categories of environmental impact, as categories associated with human toxicity, acidification, and ecotoxicity (Carneiro et al. 2017).

In this sense, in order to compile and quantify the effects caused by the systemic process of producing microalgae biofuels, the quantification steps are subdivided into three categories: energy balance, water footprint, and greenhouse gas emissions.

2.3.1 Balance Energy

The concerns about energy balances are related to both the life cycle energy efficiency of biofuels and the saving of nonrenewable energy between biofuels and fossil fuels (Soccol et al. 2011).

The LCA literature defined, according to Eq. (1), the net energy ratio (NER) as the ratio of the total energy produced (energy potential of the oil or feedstock) to the energy content of the construction and materials, in addition to the energy required for all plants (Jorquera et al. 2010).

$$\mathrm{NER} = \frac{\sum \text{energy produced}}{\sum \text{energy requirements}} \tag{1}$$

Through this equation, it is possible to estimate the fossil energy needed to feed the process. The functional units used are megajoules (MJ).

2.3.2 Water Footprint

Water footprint (WF) is used to assess water use along the supply chains, sustainability of water uses within river basins, water use efficiency, water allocation equitability, and dependence of water on the supply chain. This is characterized by quantifying the freshwater consumption of a process or product per functional unit (Hoekstra 2016).

The concept of water footprint comprises three components: green WF, blue WF, and gray WF, according to Eq. (2). Green WF is defined as rainwater that is evaporated during the growing period of the culture. The blue water footprint is the volume of surface and groundwater consumed during the production of a particular product or service. Consumption includes the volume of freshwater evaporated or incorporated into a product or service. However, WF gray refers to the amount of water that cannot be reused, that is, the volume that needs treatment or that has been contaminated (Farooq et al. 2015).

$$\mathrm{WF} = \sum \mathrm{WFgreen} + \mathrm{WFblue} + \mathrm{WFgray} \tag{2}$$

Processes for microalgae biofuels, the direct withdrawal of water footprint represents the water that is consumed by each step in the process, including, for example, water for microalgae cultivation, water required to compensate evaporation of the bioreactor, water loss of the process during filtration, and the water reached during the conversion of the fuel (Mekonnen and Hoekstra 2010; Garcia and You 2015). These footprints are estimated by units of volume (m^3) per kilogram of biofuel (kg) or megajoules of biofuel (MJ) (Guieysse et al. 2013).

2.3.3 Greenhouse Gas Emissions

Absorption capacity, concentration, and residence time of the gases are used to evaluate the so-called global warming potential (GWP). In turn, the GWP is characterized as a simplified index in the Intergovernmental Panel on Climate Change (IPCC), along with the land use change coverage (LUCC) that quantifies the environmental impact generated by greenhouse gases as well as the potential of acidification, eutrophication, and depletion of the ozone layer (Forster et al. 2007).

In 2002, the United Nations Environment Program (UNEP) joined the Society of Environmental Toxicology and Chemistry (SETAC) to initiate the life cycle initiative which is an international partnership aimed at putting the cycle into practice and improving the tools of support through better data and indicators (Klöpffer 2006).

Usually, it can be quantified according to Eq. (3), sum the masses of substances that contribute to the impact (Mi), whether masses of gases (CO_2, CH_4, NO_x) contribute to these same substances impact that are published annually in reports from environmental such as the Department for Environment Food and Rural Affairs (DEFRA) (DECC 2010; Laratte et al. 2014).

$$E = \sum_{\mathrm{i}} \mathrm{Mi} \times \mathrm{Pi} \tag{3}$$

Impact factors are reported at different times and are commonly estimated at 20, 100, or 500 years. In this way, long-lasting compounds such as carbon dioxide (CO_2) tend to remain and concentrate for a longer period in the atmosphere (around 100 years). However, compounds with smaller residence ranges, such as methane, assume heating profiles capable of emitting heating potentials 60 times larger and 23 times more potent when compared to CO_2 (Yvon-Durocher et al. 2014). In this sense, the representation of the pollutant gas and the estimated residence time should be considered according to the profile of the system to be analyzed. Moreover, among the three-time horizons cited above, the 100-year level is most commonly used as a standard time horizon for expressing GWPs (Guo and Murphy 2012).

2.4 Interpretation

Interpretation is the phase of the LCA where the findings of the inventory analysis and the impact assessment are combined or, in the case of life cycle inventory studies, only the results of the inventory analysis consistent with the defined objective and scope to reach conclusions and recommendations. The results of this interpretation may take the form of conclusions and recommendations to decision makers as long as they are consistent with the purpose and scope of the study (ISO 14043 2000).

In addition, this phase may involve the interactive process of reviewing the scope, as well as making assumptions made during the study. In this way, since the verification of the quality and nature of the data collection occurs through the estimation of the scenario, the parameters are modified in a systematic way always considering the initial objective defined (ILDC 2010).

3 Data Set Reported in the Literature

Microalgae are indicated as a potential alternative to traditional fuel resources because of their ability to be used for the generation biofuels. The potential fuels include biogas, biohydrogen, bioethanol, and biodiesel (Brennan and Owende

2010), each of which has advantages and disadvantages due to the processing of raw materials and limitations. However, there is a significant focus on the growth of microalgae specifically for biodiesel applications (Soh et al. 2014).

The literature in this field does not fully address the fundamental stages of life cycle application. However, it is only mentioned that the main challenges associated with the production of biofuels in the environment are related to the raw material and its significant influence on the high-energy consumption required. Moreover, literary efforts are limited. In this context, Table 1 shows surveys that report the main parameters implementing the LCA, where the main focus is to establish the net energy index and greenhouse gas emissions. Nevertheless, most studies are lacking information on the use of water resources (Živković et al. 2017).

On the other hand, the literature reports the most diverse objectives of establishing LCA. Among the most cited are lipid extraction methods and studies that reduce energy input at harvest, centrifugation, and drying, as these are the main unit operations of the microalgal biomass production unit (Chen et al. 2011; Laamanen et al. 2016).

In addition, since the main operations included in microalgae cultivation are exposed in the scope of work, the objective is to establish and provide a solid basis for the implementation of zero carbon emissions, with the purpose of consolidating integrated biorefineries to produce biofuels of microalgae (Medeiros et al. 2015; Klein et al. 2017).

As a result of the implementation of biorefineries, the distribution of environmental costs or loads in a multiproduct system provides the emergence of the allocation issue. Consequently, the biggest bottleneck in implementing the LCA is to establish the best scenario and its allocation in order to process the products without neglecting the quantification of the necessary inputs of the system (Silva et al. 2017).

It is known that microalgal biomass presents a diverse range of products to be exploited from the defatted biomass. Therefore, defining a system boundary, which makes it possible to extract all co-products from this residue, makes the system boundary unlikely and complex.

At the same time, it is necessary to estimate scenarios that determine exactly which process will be chosen. Figure 2 shows the scope of three different scenarios of a biorefinery for the production of microalgae biodiesel. Moreover, since bioenergy includes low-value but high-volume biofuels such as biodiesel. In contrast, high-value but smaller-volume co-products are designed to increase the profitability of biorefineries (Chew et al. 2017). Therefore, at the same time as bulk chemicals such as defatted biomass can be obtained, fine chemicals such as pigments can increase the economic profitability of bioprocesses (Jacob-Lopes and Franco 2010).

Table 1 Studies of life cycle assessment in microalgae biofuels

Biofuel	Cultivation system	Goal	Unit Funtional	NER	GWP ($kgCO_2eq$)	Water footprint (m^3)	References
Biodiesel	nd	Lipid extraction	1 kg	5.98–7.10	0	0.23–0.31	Collotta et al. (2017)
Biodiesel	nd	Meta-analysis	1 m^3	1.4	−1066–8222	nd	Liu et al. (2012)
Biodiesel	Hybrid	Commercial scale	1 ton	31	2137	16.3	Adesanya et al. (2014)
Biodiesel	Open ponds	Lipid extraction	1 MJ	1.13–1.82	nd	nd	Jian et al. (2015)
Biodiesel	Open ponds	Cultivation	317 GJ	30×10^4	1.810^4	12×10^4	Clarens et al. (2010)
Biodiesel	Open ponds	Pathway routes	1 MJ	0.33–92.77	0.03–1.32	nd	Dutta et al. (2016)
Ethanol	Open ponds	Biorefinery	1 MJ	1.16–2.64	89.6–233.5	nd	Quiroz-Arita et al. (2017)
Ethanol	Raceway ponds	Solvent purification	1 MJ	0.20–0.55	12.3–29.8	nd	Luo et al. (2010)

nd not defined

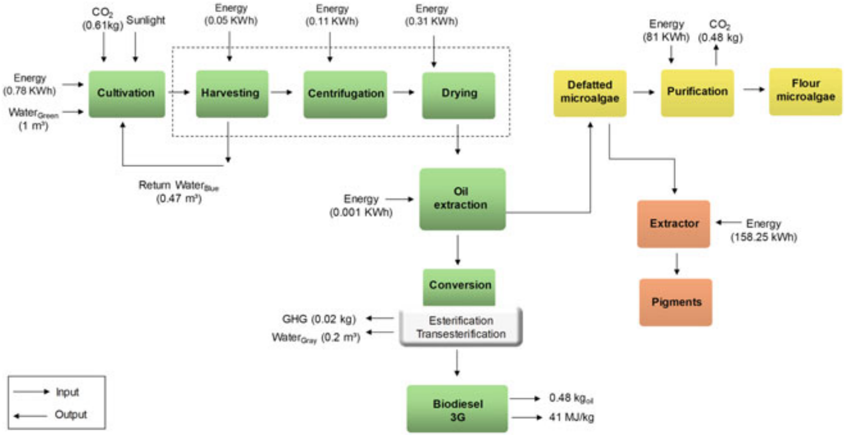

Fig. 2 Flowchart for obtaining microalgal biodiesel in an integrated scenario. Adapted from Monari et al. (2016)

Table 2 Bottlenecks of life cycle assessment implementation

Bottlenecks LCA implementation	Comment
Purpose and scope	Difficulty of delimiting cycles and establishing the inputs and outputs of process flows
Functional unit	It is very difficult to define equivalent quantities for different products. The functional unit can be a technical context, such as the amount of energy use or social functions, such as the mileage traveled by biodiesel and its different depreciation rates
Allocation	The comparative evaluation between several virtual products that have different functions. Here, it is important to know whether it is better to develop a simpler product that produces some weak pollutants and has fewer functions or if a more complex product is created with additional functions and additional pollutants
Standardization methodology	Standardize the means of computing the data. Since there are many software programs on the market, it is necessary to verify the veracity of these values stored in the databases
Environmental charges	There is a lack of understanding of impact categories and the prioritization of these categories
Interpretation	Difficulty of interpretation and comparison with the data reported in the literature

Yet, it should be noted that in the three scenarios presented, such as the generation of biodiesel, microalgae meal, or pigments, the system can be allocated in three fundamental stages in the collection, centrifugation, and drying process, which is extremely important for the production of dry biomass. In addition, it is known that these unit operations are those that require the most power from the system. Many studies that use the LCA as a tool erroneously determine the NER with less than 1, rendering the process of obtaining biodiesel by microalgae impossible.

In this context, in order for the application of the life cycle analysis does not make the microalgal biofuels process unfeasible, this methodology needs to combat some implementation bottlenecks. Table 2 lists the major obstacles that must be overcome before the LCA can be fully utilized as a standard environmental tool.

4 Application of LCA to Biofuels from Microalgae

In the case of microalgae, it is possible to use the LCA tool to apply to the process in order to define the environmental performance of biofuels. The baseline data to be quantified were adapted from Monari et al. (2016), where the energy values were expressed by hours/day and the units of volume and atmospheric emissions expressed per day.

First step: The aim of the application is to evaluate the energy demand in its environmental character in order to reveal the feasibility of this process to obtain microalgal biodiesel. The chosen alternative was to establish a simplified flow diagram of the process only for the measurement of the inputs and outputs of the procurement process, not taking into account the demands of materials required to manufacture the equipment. As a functional unit, 1 cubic meter of bioreactor volume was established, with the operating time of 24 h per day for 330 days per year. The target audience is to generate the final report, presenting perspectives on the application in a real scale of the process.

Second step: Data collection implies the quantification of system inputs. Therefore, it is necessary to fully clarify the energy demands of the equipment related to the process. Therefore, the equations related to their respective classes are applied (Box 1).

Box 1. Example of quantification of inputs and outputs of the process of obtaining microalgal biodiesel

Net Energy Ratio (Biodiesel)

$$\mathrm{NER} = \frac{\sum \text{energy produced}}{\sum \text{energy requeriments}}$$

$$\mathrm{NER} = \frac{(\text{Biomass} \times \text{energy potential})}{(\text{cultivation} + \text{harvesting} + \text{centrifugation} + \text{drying} + \text{extraction})}$$

$$\mathrm{NER} = \left[\frac{(0.48\,\mathrm{kg} \times 24\,\mathrm{h} \times 330\,\mathrm{d} \times 41\,\mathrm{MJ.kg}^{-1})}{[(0.78\,\mathrm{KWh} + 0.05\,\mathrm{KWh} + 0.11\,\mathrm{KWh} + 0.31\,\mathrm{KWh} + 0.001\,\mathrm{kwh}) \times (24\,\mathrm{h} \times 330\,\mathrm{d} \times 3.6\,\mathrm{MJ})]}\right]$$

$$\mathrm{NER} = \left[\left(\frac{155800\,\mathrm{MJ}}{35668.51\,\mathrm{MJ}}\right)\right]$$

$$\mathrm{NER} = 4.36$$

Water footprint (Biodiesel)

$$\mathrm{WF} = \sum \mathrm{WFgreen} + \mathrm{WFblue} + \mathrm{WFgray}$$

$$\mathrm{WF} = (\mathrm{WFcultivation} + \mathrm{WFcentrifugation} + \mathrm{WFnonreusable})$$

$$\mathrm{WF} = [(1\,\mathrm{m}^3 + 0.47\,\mathrm{m}^3 + 0.2\,\mathrm{m}^3) \times 330d]$$

$$\mathrm{WF} = 551.1\,\mathrm{m}^3$$

Global Warming Potential (Biodiesel)

$$E = \sum_i \mathrm{Mi} \times \mathrm{Pi}$$

$$E = \sum (\text{emissions} \times \text{impact factor value})$$

$$E = [(0.61 + 0.48) \times 0.542 + (35668.51 \mathrm{x} 0.542)]$$

$$E = 19332.92\ \mathrm{kgCO_{2eq}}$$

Net Energy Ratio (Pigments)

$$\mathrm{NER} = \frac{\sum \text{energy produced}}{\sum \text{energy requeriments}}$$

$$\mathrm{NER} = \frac{(\text{Biomass} \times \text{energy potential})}{(\text{cultivation} + \text{harvesting} + \text{centrifugation} + \text{drying} + \text{extraction} + \text{pigments extraction})}$$

$$\mathrm{NER} = \left[\frac{(0.48\,\mathrm{kg} \times 24\,\mathrm{h} \times 330\,\mathrm{d} \times 41\,\mathrm{MJ.kg}^{-1})}{[(0.78\,\mathrm{KWh} + 0.05\,\mathrm{KWh} + 0.11\,\mathrm{KWh} + 0.31\,\mathrm{KWh} + 0.001\,\mathrm{kwh} + 158.25\,\mathrm{kwh}) \times (24\,\mathrm{h} \times 330\,\mathrm{d} \times 3.6\,\mathrm{MJ})]}\right]$$

$$\mathrm{NER} = \left[\left(\frac{155800\,\mathrm{MJ}}{4555390.75\,\mathrm{MJ}}\right)\right]$$

$$\mathrm{NER} = 0.034$$

Global Warming Potential (Pigments)

$$E = \sum_i \mathrm{Mi} \times \mathrm{Pi}$$

$$E = \sum (\text{emissions} \times \text{impact factor value})$$

$$E = [(0.61\,\mathrm{kg} \times 0.542) + (4555390.75\,\mathrm{MJ} \times 0.542)]$$

$$E = 2469022.11\,\mathrm{kgCO_{2eq}}$$

Global Warming Potential (Flour microalgae)

$$E = \sum_i \mathrm{Mi} \times \mathrm{Pi}$$

$$E = \sum (\text{emissions} \times \text{impact factor value})$$

$$E = [(0.61 + 0.002 + 0.48) \times 0.542 + (2345140.51\,\mathrm{MJ} \times 0.542)]$$

$$E = 1271066.74\ \mathrm{kgCO_{2eq}}$$

Net Energy Ratio (Flour microalgae)

$$\mathrm{NER} = \frac{\sum \text{energy produced}}{\sum \text{energy requeriments}}$$

$$\mathrm{NER} = \frac{(\text{Biomass} \times \text{energy potential})}{(\text{cultivation} + \text{harvesting} + \text{centrifugation} + \text{drying} + \text{extraction} + \text{purification})}$$

$$\mathrm{NER} = \left[\frac{(0.48\,\mathrm{kg} \times 24\,\mathrm{h} \times 330\,\mathrm{d} \times 41\,\mathrm{MJ.kg}^{-1})}{[(0.78\,\mathrm{KWh} + 0.05\,\mathrm{KWh} + 0.11\,\mathrm{KWh} + 0.31\,\mathrm{KWh} + 0.001\,\mathrm{kwh} + 81\,\mathrm{kwh}) \times (24\,\mathrm{h} \times 330\,\mathrm{d} \times 3.6\,\mathrm{MJ})]}\right]$$

$$\mathrm{NER} = \left[\left(\frac{155800\,\mathrm{MJ}}{2345140.51\,\mathrm{MJ}}\right)\right]$$

$$\mathrm{NER} = 0.066$$

Third step: Thus, with the interpretation of the results, it was possible to conclude the process in question; microalgae are potential raw materials for obtaining biodiesel through solvent extraction. Therefore, a positive NER of 4.36 was obtained for biodiesel generation. However, if we followed the biorefinery process and opted to obtain the pigments extracted from the defatted biomass together with the biodiesel, we would obtain negative NER of 0.034. In this way, in addition to continuing with positive net energy, we could increase the profits of sales of this chemical by up to 30%. On the other hand, to get microalgae meal, the energy expenditure would have decreased, resulting in a NER of 0.066. As for water distribution, the process resulted in an expense of 551.1 m^3 and remains unchanged before this biorefinery system. In addition, the atmospheric emissions were quantified in relation to the fossil energy required for the operation of the system and those emitted by the equipment, resulting in a value of 19,332.92 kg CO_{2eq}, yet the CO_2 absorption required for the growth of microalgae was disregarded.

5 Final Considerations

The life cycle assessment can be used in the most diverse industrial segments, but it has become a key tool as a critical parameter in relation to microalgal biofuels reports.

Moreover, to take advantage of the benefits that the LCA provides, its application involves a series of steps established by the ISO that was developed with the objective of guaranteeing great results, but they need the time, resources, and qualified human resources to be executed.

Finally, even with its application complexity, LCA is an excellent option for the monitoring of environmental issues related to biofuels and can contribute to sustainable development, thereby providing an overview of the environmental aspects and impacts associated with the product and providing subsidies that enable the implementation of improvements throughout its life cycle.

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