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Computer-aided Exergo-environmental Analysis of Biodiesel Production Process from Microalgal Biomass

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Abstract

Nowadays, biodiesel is recognized as one of the best alternative to fossil fuels due to its renewability, environmentally-friendly nature and simple preparation from different feedstocks such as microalgae. In this work, biodiesel was produced from *Chlorella vulgaris* microalgae and its environmental performance was evaluated applying an exergo-environmental analysis. This process was simulated using Computer Aided Process Engineering (CAPE) tools in a commercial software to determine the main operating conditions of all streams. An exergy balance around the system was carried out to determine both exergy losses and exergy inlets, which were used to determine exergo-environmental parameters. The Sustainability Index (SI), Renewability Indicator (RI), Net Energy Ratio (NER), and Net Energy Value (NEV) were calculated. It was obtained a SI value of 8.18 indicating that the input exergy is higher than the exergy destruction. The NEV and NER parameters were 38,846.31 MJ/kg BD and 1.19, respectively. The effect of use of fossil fuel-derived energy on the RI was also analyzed and it was found an improvement opportunity in this parameter by increasing the percentage of non-renewable energy substitution. These results revealed that third-generation biodiesel production from microalgae represents an exergy efficient, environmentally sustainable, and renewable alternative for replacing fossil fuels.

Keywords: Exergy, environment, CAPE, microalgae, biofuels

1. Introduction

The rapid depletion of crude oil reserves prompts the seek for alternative fuels from renewables [1]. Fossil fuels exhibit many disadvantages such as a non-renewable nature and the negative environmental impacts produced by the combustion of them [2]. The use of biodiesel as a renewable fuel that is an alternative to petrodiesel is increasing worldwide due to its renewable nature, reasonable cost, and simple preparation [3]. Biodiesel can be generated from renewable lipids such as vegetable oils, animal tallow, and microalgal oils [4, 5]. Different kind of biofuels offers many advantages related to the environment and socio-economy [6]. Among these, third-generation biofuels from microalgae have been seen as an important alternative in the research of renewable energy [7].

Microalgae has gained attention as the most promising feedstock for biofuels production due to its rapid growth rate, vigorous vitality, short life cycle, and diversified cultivation conditions [8, 9]. Several fresh water microalgae species have been focus of attention for biofuel production. However, *Chlorella vulgaris* is the most used due to its high oil content and availability [10]. On the other hand, significant efforts have been made on evaluating the environmental performance of bioenergy production [12]. Exergy analysis using computer aided tools is useful to generate, evaluate, and determine sustainable processes and its improvement potential [11]. In fact, exergy analysis provides information related to irreversibilities and efficiency, which are used in calculate exergo-environmental parameters as renewability indicator and sustainability index [13]. The aim of this work is to study third-generation biodiesel from *Chlorella vulgaris* microalgae from an environmental point of view using a computer-aided exergy analysis.

2. Materials and Methods

2.1 Process description:

The third-generation biodiesel production using *Chlorella vulgaris* microalgae is described in Figure 1. It was considered as basis a production rate of 7,676.37 kg/h of biodiesel. Firstly, the feedstock consisting in microalgal biomass (8,051.42 kg/h) is pretreated with 1% (wt.) of glycerol ($C_3H_8O_3$) in presence of $ZnCl_2$, which serves as inhibitor of alkaline metals formation. The composition of this feedstock was defined according to Petkov & García [14]. Triglycerides and water are products of reaction that takes place in pretreatment reactor at 200°C. The outlet reactor stream passes through a flash vessel in order to remove water content. Before sending to transesterification stage, the resulting stream enters a cooler to reach a temperature of 60°C. The transesterification reaction is carried out in a continuously-stirred tank reactor (CSTR) using 1% wt. NaOH and methanol (CH_4O) solutions. The products of this reaction are biodiesel and glycerol [15] that requires to be separated. Hence, the outlet stream is sent to decanting stage in which glycerol is separated from biodiesel. The glycerol is treated with sulfuric acid (H_2SO_4) to neutralize it. A distillation column is used to purify biodiesel and remove traces of methanol. Finally, the biodiesel is subjected to washing and decanting stages for further purification (96.5%).

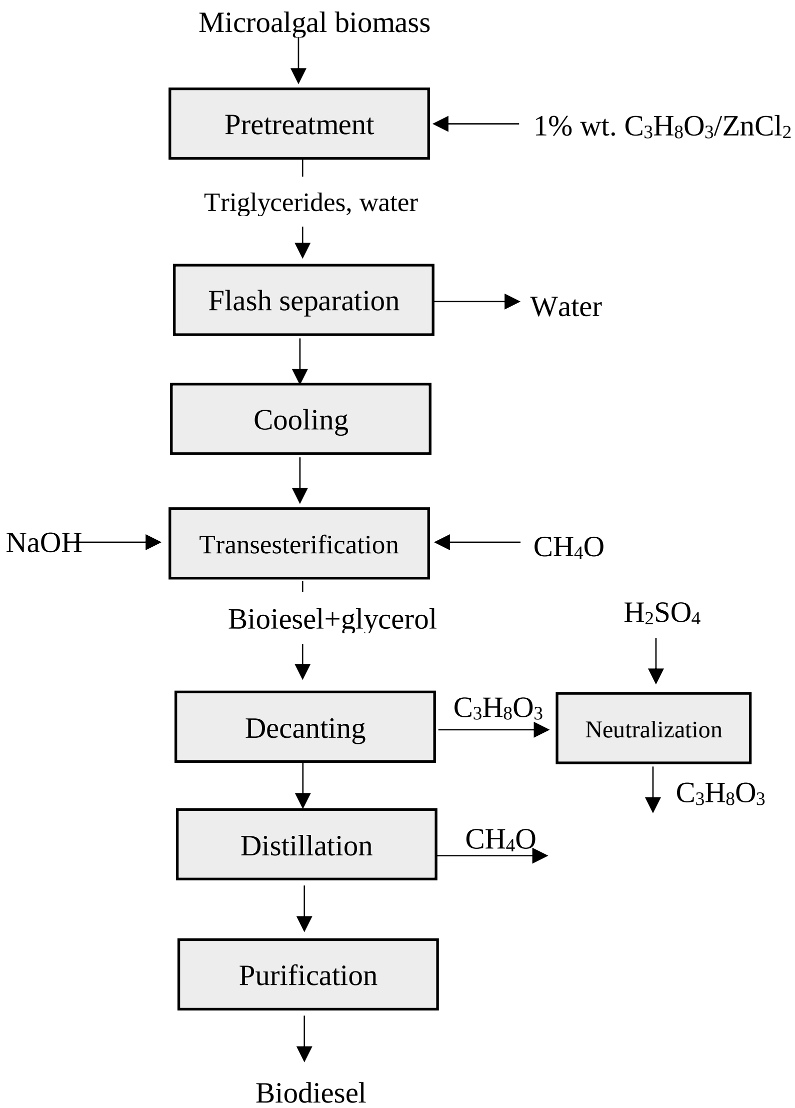

Figure 1. Flow diagram of biodiesel production from microalgal biomass

2.2 Exergo-environmental analysis

This process was simulated using a commercial process simulation software in order to obtain main operating conditions (e.g. mass flows, pressure, and temperature) of all process streams. The specific exergies were found in literature for given substances and the semi-empirical equation of Szargut, Morris & Steward [16] was also used. The exergy balance around the system is given by Equation 1.

$$\dot{B}_{mass,in} - \dot{B}_{mass,out} + \dot{B}_{heat} - \dot{B}_{work} = \dot{B}_{loss} \quad (1)$$

Where the exergy of process stream ($\dot{B}_{mass}$) is defined as a contribution of chemical and physical exergy assuming negligible both potential and kinetic exergy. The physical and chemical exergy were calculated according to the equations provided by Cogollo-Herrera et al. [11].

It is well known that exergy analysis can help to develop strategies and guidelines for more effective use of energy that improves exergo-environmental parameters as RI, SI, NER and NEV [17].

Renewability indicator (RI): It is an exergo-environmental parameter used in bioenergy production systems and allows to identify if there is net gain of bioenergy. It is calculated by Equation 2 as a ratio of bioenergy outlet to fossil fuel-derived energy inlet.

$$RI = \frac{\text{Outlet of bioenergy}}{\text{Inlet fossil fuel} - \text{derived energy}} \quad (2)$$

Sustainability index (SI): This is a measure of environmental impacts reductions by reducing exergy destruction. It is defined as the inverse of depletion number according to Equation 3. The depletion number is expressed as the ratio of exergy destruction to input exergy by Equation 4.

$$SI = \frac{1}{\text{DF}} \quad (3)$$

$$DF = \frac{\text{Exergy destruction}}{\text{Input exergy}} \quad (4)$$

The SI is widely used to link up environmental impact, process sustainability, and exergetic efficiency.

Net energy ratio (NER): The NER parameter is defined as the ratio of the renewable energy output to the non-renewable energy consumed over the production process. A value of NER higher than one (NER>1) indicates that the system has a net energy gain.

$$NER = \frac{E_{out}}{E_{in}} \tag{5}$$

Net energy value (NEV): This parameter is a measure of sustainability and is expressed as the energy output in biodiesel after accounting for energy input requirements during biofuels productions [18]. The NEV was calculated as follows:

$$NEV = E_{bio} - E_{in} \tag{6}$$

3. Results and Discussion

Exergy analysis is a useful tool for identifying causes, locations and magnitudes of process inefficiencies [19]. It is widely implemented in environmental assessments for process improvements as reducing non-renewable fuel consumption and environmental emissions. Table 1 summarizes exergo-environmental parameters of biodiesel production from *Chlorella vulgaris* microalgae.

Table 1. Exergo-environmental parameters results

Parameter	Value
SI	8.18
Renewability indicator	1.15
NEV [MJ/kg BD]	38,846.31
NER	1.19

The SI provides information relate the use of sustainable sources of energy and the efficient use of non-renewable source as natural gas fuels, which reduce environmental impacts [17]. This index exhibited a value of 8.18 indicating that input exergy is higher than destruction exergy. Hence, this third-generation biodiesel production process results to be both efficient from an exergetic point of view and sustainable.

The RI compares the inlet of fossil fuel-derived energy and the outlet of useful bioenergy. As is shown in Table 1, RI parameter was calculated in 1.15 (RI>1) indicating that biodiesel from microalgae is a renewable process because of the bioenergy production is higher that the requirement of fossil fuel-derived energy over process chain. It is important to point out that RI parameter was calculated assuming that the energy entering to the system due to utilities is obtained from fossil fuels. Figure 2 shows the behaviour of renewability indicator over different percentages of fossil fuels substitution by renewable energy.

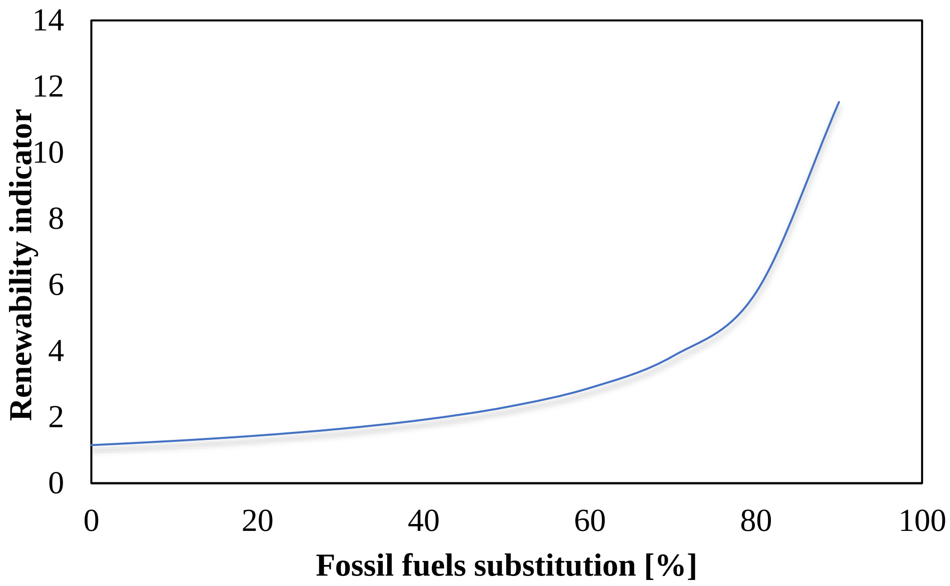

Figure 2. Effects of bioenergy entering to the system on RI

The NEV parameter was calculated in 38,846.31 MJ/kg BD, which indicated that the energy of biodiesel is greater than utilities (energy entering to the system for producing this biofuel). According to these results, the implementation of biodiesel production process is justifiable. Persson et al. [18] also reported positive values for NEV parameter (2.64 MJ/L BE) in the production of bioethanol from maize grown. Taylor et al. [20] pointed out NEV values of 91,397 Btu/gal BD in biodiesel production from soybean oil.

In addition, it was found a NER of 1.19 suggesting a net energy gain due to the consumption of non-renewable energy is lower than renewable energy input. This parameter offers a comprehensive description of the energetic performance of the biodiesel production system and can be improved by using approaches related to energy integration. Other work also stated values for NER higher than 1; Faleh et al. [12] calculated a NER of 2.3 for biodiesel production from mutton tallow transesterification. Batan et al. [21] calculated a NER value of 0.93 for biodiesel production from microalgae including the harvesting and extraction of microalgal oil. Hence, it was recommended to reduce the energy requirements in stages before transesterification. Mishra et al.[22] also applied exergo-environmental analysis to a second-generation bioethanol from wheat straw and calculated a NER value > 1. It is important to point out that the biodiesel from microalgae (NER<2.5) is not comparable with fossil diesel (NER=5)[9]. In general, the process proposed in this work represents an improvement of other biofuels production process in terms of renewability and sustainability.

4. Conclusions

In this work, exergo-environmental analysis was carried out in order to assess the environmental performance of third-generation biodiesel process using microalgae by computer-aided exergy approach. The sustainability factor exhibited a value of 8.18, which indicated that input exergy is higher than destruction exergy. The NER value was higher than 1, similar to that reported by other studies for bioenergy production. In addition, the NEV and RI parameters were estimated in 38,846.31 MJ/kg BD and 1.15, respectively. The renewability indicator can be improved by substituting fossil fuels-derived energy with renewable energy. These results suggested that the process described in this work is sustainable, renewable, and exergy-efficient and can be used in bioenergy production without the generation of significant environmental impacts.

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