Life cycle assessment of biodiesel production from cardoon (Cynara carduncculus) oil obtained under Spain conditions

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Abstract In this study, the life cycle of the biodiesel production from cardoon oil has been evaluated, following the ISO standard 14040 an using the Gabi software v4.3 as calculation tool. In accordance with this methodology, the functional unit selected was 1 ha·year cultivated with *Cynara cardunculus* to obtain biodiesel by transesterification of the oil obtained from cardoon seeds. The indicators considered for the life cycle impact assessment (LCIA) were resources consumption, the net energy ratio (NER), and the IPCC 500 year method to evaluate the global warming impact. LCIA results showed that the stage with highest contribution to consumption is cultivation and water is the main natural resource consumed. The estimated NER of 1.6 indicates that the process has a positive energy balance. The particular indicator of the global warming impact category indicates that the system has a favorable balance as a sink of CO_2.

1 Introduction

The energy goals fixed both Europe and in Spain are on the side to increase the biomass use as energy source in a medium term. The cardoon (*Cynara cardunculus*) is recognized as one of the potential source of biomass for energy purposes in Spain, as well as other industrial applications [1-3].

One of the most interesting options are the use of the seed to obtain oil for biodiesel production [4]. The oil can be extracted from seeds by means of a cold press extraction and can be processed conveniently for biodiesel production, by means of the transesterification of the triglycerides using ethanol in presence of an alkaline catalyst, yielding the ethylic esters of the fatty acids (biodiesel), with similar characteristics to the diesel N2 [5].

The cardoon (Cynara cardunculus) it is a perennial cultivation, of annual cycle, with an about ten year-old useful life. It is an adaptive plant to the cultivation under unirrigated land conditions [2].

The Cynara cardunculus cultivation for industrial use includes an initial period, during the first year, to implement the cardoon plant. The cultivation task starts with the basal dressing, with the recommended addition of 1,000 kg / ha of 9:18:27 NPK complex fertilizer [2]. Next step is preparing the land for planting with a couple of passes of ploughing and harrowing. After planting and before crop emergence, it is necessary to provide treatment with a herbicide: 1.5 kg / ha of alachlor and 0.4 kg / ha of linuron. In the second year of cultivation, fertilizer must be restored. It has been determined that each dry cardoon ton extracts 12.6 kg of nitrogen, 3.5 kg phosphorus and 20.8 kg of potassium [4].

In experiments about cardoon biomass production under rainfed conditions in central Spain, more than 10 years of productive life of crop with an average production of 14 t dry matter / ha·year (used in this study) was obtained [6]. The biomass is harvested by a tractor-trailer and then transported from parcel to industrial plant.

In factory, the crop is fed to a fractional separation system for cardoon biomass. The seeds represents 10% of the whole plant [5]. Biomass is subjected to mechanical separation to get the seeds and then to proceed to the extraction of oil using a cold press, where it is estimated it can be extracted by 25% in oil [6].

For the transesterification process of oil from Cynara cardunculus, it is recommended the use of ethanol to obtain ethyl ester, with a molar ratio of alcohol / oil 9:1, at temperature between 25 and 75 º C, with reaction times of 120 min., and sodium hydroxide or potassium hydroxide catalysts, with a concentration of 1% p/p referenced to the total mixture of oil-ethanol [7]. The reaction yields obtained are about 92%, reaching a production of 323 kg of biodiesel from 1400 kg of cardoon seeds harvested [7].

2 Methodology

The life cycle assessment (LCA) methodology was followed to evaluate the whole process. This procedure is performed to identify the materials consumption, energy used and emissions released into the natural environment [8]. There are four phases in an LCA study, acording to standard ISO 14040:2006, definition of objectives, analysis inventory, impact evaluation and interpretation of results.

The evaluation is done in the full life cycle of the process, including cultivation of raw material, transportation, manufacturing and distribution.
According to this methodology, the functional unit selected is the cultivation of 1 ha·year with cardoon (Cynara cardunculus) to produce oil seed, in order to get biodiesel through alcaline-catalysed transesterification.
The main objective is to evaluate materials consumption, emissions and energy used and the main environmental impacts related to biodiesel production from cardoon oil seeds cultivated in Spain, to determine the most impactant stages and assess the energy performance of the system. The system boundary has been defined with the stages: cultivation, transportation, mechanical separation, oil extraction by cold press, transesterification with ethanol and biodiesel distribution.
The calculation tool was the Gabi Software version 4.3 (PE International). Using this software the main processes of the subsystems cultivation, mechanical separation, oil extration from seeds and transesterification were generated.
The process inventories defined in database Ecoinvent V2.0 for transportation, fertilizer, pesticides, alcohols and chemicals were used. Table 1 shows the major flows of materials and energy used in each stage of the analysis of life cycle inventory of biodiesel production from cardoon oil seeds.

Tab.1: Inventory data of the biodiesel production from cardoon oilseeds.

Stage	Flow	Value	Unit
Cultivation	Fertilizer	148.7	kg
	Pesticides	0.21	kg
	Diesel	37.91	kg
	Carbon dioxide	2,895.2	kg
Biomass transportation	Diesel	19.457	kg
Mechanical separation	Power	19.96	MJ
Oil extraction	Power	181.03	MJ
Transesterification	Alcohol (ethanol)	62.36	kg
	Potassium hidroxide	3.32	kg
	Steam	107.47	kg
	Power	55.7	MJ
Distibution	Diesel	0.82	kg

In addition, it was determined the net energy ratio, defined as the ratio of energy produced and total primary energy consumed by the system under consideration [9]. This value was calculated using the following expression:

$$NER = \frac{Energy_{output}}{Non-renewable \cdot energy_{Input}} \tag{1}$$

Due to the characteristics of the system studied, the most significant environmental impact was related to emissions of greenhouse gases. Therefore, the indicator Global Warming, 500 years, calculated by IPCC methodology, expressed as kg CO_2 eq to air was selected.

3 Analysis inventory of biodiesel production

3.1 Mass balance

The results of the consumption of material resources for industrial purposes are showed in Fig.1, for each life cycle stage. The entire process of production of biodiesel from Cynara cardunculus oilseeds consumes a total of 7,817.2 kg of material resources. These resources are mostly renewable ones, being the most important the consumption of carbon dioxide (32%), water (31%) and air (9.8%).

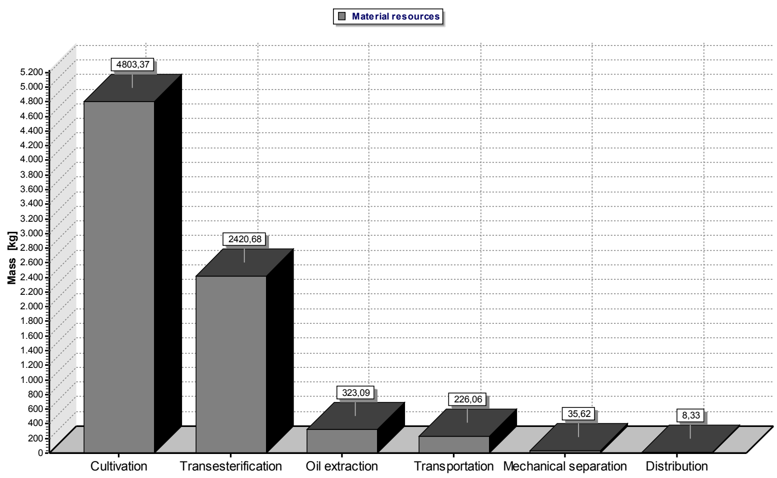

Fig.1: Material resources consumption by stage of the life cycle of Cynara carduncululs biodiesel production.

The stage with the highest impact on resource consumption is cultivation, with 4,803.4 kg of material resources. This consumption is due to the manufacture of agricultural inputs (mainly fertilizer compounds and pesticides) as well as fuel for the operation of machinery in field operations. Phosphate fertilizers are derived from phosphate rock and potassium salts are used as potassium fertilizers.

Industrial processing steps are the following significant processes in the consumption of resources. The transesterification consumes about 31% of resources (24,207 kg), whereas the extraction of oil from the seeds of cardoon, 4.1% (323 kg). This result is attributed to chemical reagents, as well as energy and fuel use for industrial purposes.

On the other hand, some air emissions were produced in the overall process, resulting in a flow of 1,760 kg, mainly emissions of inorganic compounds, carbon dioxide and exhaust gases. These emissions are attributed to the combustion of fossil fuels in agricultural equipment, transportation vehicles, manufacturing of fertilizers and production of heat needed in industrial facilities. Therefore, it is determined that the stage with the highest flow of air emissions is the stage of cultivation, with about 66% of total issuance.

4 Energy balance

The energy consumption in the entire process for the production of biodiesel was estimated to be 7,750 MJ. Non-renewable energy resources are largely consumed oil (29%) and natural gas (26%), and in lower level uranium (7.7%), coal (5.3%) and lignite (2.7%), all associated with the local energy mix and to fossil fuel for transport vehicles and machinery.

Fig. 2 presents the results for the consumption of energy resources for the life-cycle stages of the production of biodiesel. The most intensive phase in energy consumption is cultivation, with about 52% of total resources, followed by transesterification stage with 26.75%. The energy consumption of the cultivation stage is associated with the combustion of fossil fuels in agricultural machinery operation and processes of manufacturing of fertilizers. This result is relatively lower than that reported by Angelini [3], which ruled for the cultivation stage consumption of 10,992 MJ / ha, which is attributed to the initial assumption of considering an average year of biomass production per hectare of land. Transesterification stage involves the consumption of natural gas in the generation of steam in boilers for industrial plants and electric power required for industrial operations.

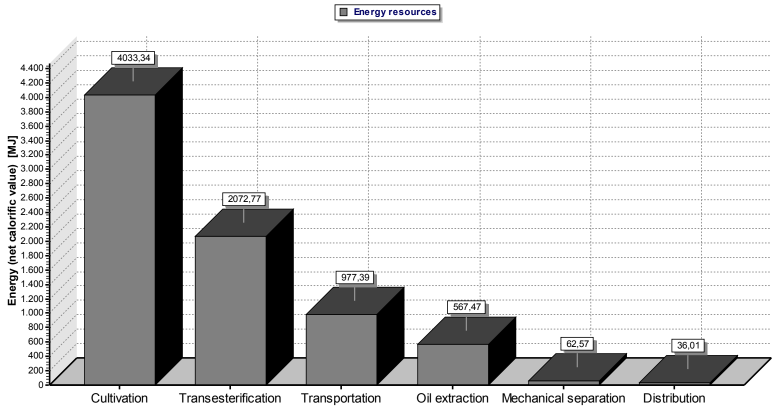

Fig.2: Energy resources consumption by stage of the life cycle of Cynara cardunculus biodiesel production.

Moreover, with the value estimated for the primary energy consumption under the assumption that 323 kg of biodiesel produced, which has a calorific value of 40 MJ / kg, it is estimated that the energy produced is 12,920 MJ. Using equation (1) the estimated value of NER is 1.67, indicating that the process has a positive energy balance, since it produces 67% more than the input energy used throughout the process chain of production of biodiesel from cardon oil seeds. This value has been estimated without considering the energy use of the rejected parts of the plant during the process. There are studies [10, 11] that demonstrate the usefulness of the leaves and crop residues for the production of solid fuel for steam boilers (pellets), which would raise the energy performance of the system.

5 Impact assessment of global warming of biodiesel production from Cynara cardunculus oil

The global warming potential for the biodiesel production system from cardoon oil is showed in Fig. 3, with the results of the indicator kg CO_2 eq in each life cycle stage.

The cultivation stage resulted in a value of -2,895.51 kg CO_2 eq which represents the amount of CO_2 fixed by oilseeds of cardoon. This carbon dioxide credit belongs to the quantity of CO_2 captured by the seed, wich has been estimated from its composition. Moreover, transesterificación stage has an aditional carbon dioxide credit of -224.23 kgCO_2 eq due to the use of ethanol from renewable sources in the reaction scheme.

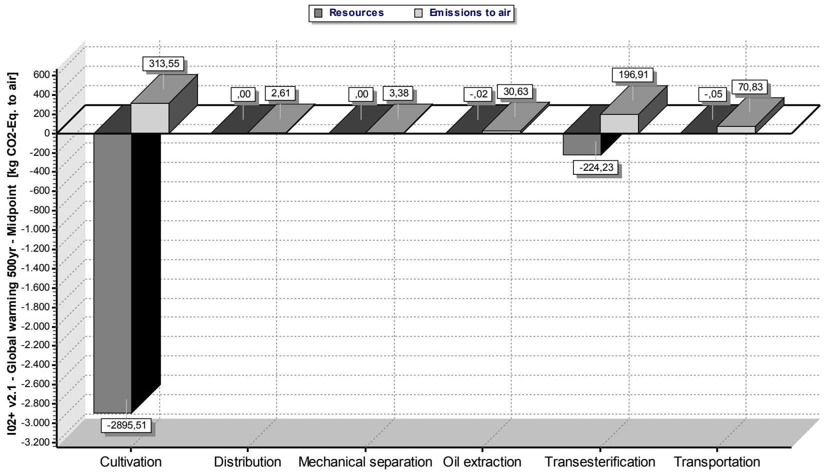

Fig.3: Global warming impact assessment by stage of the of Cynara carduncululus biodiesel production.

The indicator kgCO_2 eq of the emissions to air have the most significant value during the cultivation stage (313.55 kg CO_2 eq). This value is attributed to emissions related to combustion of fossil fuels, the manufacturing of fertilizers, pesticides and other agricultural inputs as well as emissions associated with the use of agricultural machinery. Besides, the others significant values in air emissions belong to the transesterification stage (196.91 kgCO_2 eq), transportation (70.83 kgCO_2 eq), oil extraction (30.63 kgCO_2 eq), mechanical separation (3.38 kgCO_2 eq) and distribution (2.61 kgCO_2 eq). Considering the whole process of biodiesel production from Cynara carduncululus oil, the indicator of global warming result of -2,501,8 kg CO_2 eq, because of the resources flow has a credit of -3119,7 kg CO_2 eq to air, while the flow emissions was calculated in 617.9 kg CO_2 eq to air, so the entire system studied can be considered as a CO_2 sink.

6 Conclussions

The life cycle impact assessment of the system biodiesel obtained from oil seeds of Cynara carduncululus revealed the high contribution of the cultivation stage on the consumption of material and energy resources. Considering the whole process, water is the highest resource consumed, along with the carbon dioxide captured by the biomass during crop development due to the photosynthetic process.

The estimated value of NER (1.67) indicates that the process has a positive energy balance, since it produces 67% more than the input energy used throughout the process chain of production of biodiesel from cardon oil seeds.
The overall production process of biodiesel from Cynara cardunculus can be considered a sink for CO_2, because the flow of CO_2 captured by biomass in the cultivation stage for plant development (considered a carbon credit) is greater than the flow of emissions to air. So, the net CO_2 flow is -2,501.8 kg CO_2 eq/ha·year

7 References

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