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Life cycle assessment of biodiesel production from free fatty acid-rich wastes

Javier Dufour [a,b,*], Diego Iribarren [a]

[a] Energy Systems Analysis Unit, Instituto IMDEA Energía, 28933 Mostoles, Spain
[b] Department of Chemical and Energy Technology, ESCET, Rey Juan Carlos University, 28933 Mostoles, Spain

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ABSTRACT

Environmental analyses of energy systems usually lack a comprehensive perspective that takes into account their life cycle and a set of relevant impact categories. The present study tries to fulfil this need in the field of biofuel production from free fatty acid-rich wastes, therefore providing a life cycle assessment of four biodiesel production systems including esterification–transesterification of waste vegetable oils (used cooking oil) and animal fats (beef tallow, poultry fat), and in situ transesterification of sewage sludges. Reference inventory data for these systems were gathered from a literature review. Thereafter, environmental characterization values were computed for a selection of impact categories: global warming, acidification, eutrophication, ozone layer depletion, photochemical oxidant formation, and cumulative non-renewable energy demand. A comparison among the environmental profiles of these second generation biodiesel alternatives and those of first generation rapeseed and soybean biodiesel fuels and conventional low-sulphur diesel was also performed through a well-to-wheels analysis. Thus, biodiesel from waste vegetable oils potentially entailed the most favourable environmental performance. Nevertheless, actions aimed at minimizing thermal and electric energy demands are encouraged as they would lead to relevant environmental improvements.

1. Introduction

The use of waste oils and agricultural and forest wastes as feedstocks for the production of second generation biofuels aims to support the development of sustainable transportation fuel production systems. In this respect, free fatty acid (FFA)-rich wastes arise as a potential source to yield biodiesel through esterification and transesterification processes [1,2].

This article undertakes the environmental assessment of biodiesel production from FFA-rich wastes. While environmental evaluations of bioenergy systems are often performed, they usually fail to provide traceability and comprehensiveness. The use of life cycle approaches is encouraged to avoid these concerns. For instance, Life Cycle Assessment (LCA) is an internationally standardized methodology to assess the environmental aspects and potential impacts associated with a product by gathering the relevant inputs and outputs of the product system, evaluating the potential environmental impacts linked to those inputs and outputs and interpreting the results obtained in the inventory analysis and impact assessment phases [3,4].

LCA studies on second generation biofuels usually focus on bioethanol and biodiesel production [5–10]. However, even though several publications have faced the environmental evaluation of biodiesel production from FFA-rich wastes such as waste vegetable oils [8–10], further efforts are needed to improve inventory data display, cover other alternative lipid feedstocks (in particular, animal fats [1] and sewage sludges [11,12]), and compare the environmental performance of different biodiesel production systems.

Within this framework, the present study reviews existing literature in the field of biodiesel production from FFA-rich wastes with the aim of providing reference inventory data for four systems: (i) acid-catalyzed esterification followed by alkali-catalyzed transesterification of waste vegetable oils (used cooking oils), (ii) esterification and transesterification of beef tallow, (iii) esterification and transesterification of poultry fat, and (iv) acid-catalyzed in situ transesterification of sewage sludges. Furthermore, this study not only seeks the supply of valuable inventory data, but also addresses the environmental characterization of these alternative biodiesel production systems as well as the comparison of these biofuels with other fuels from a life cycle approach.

* Corresponding author. Energy Systems Analysis Unit, Instituto IMDEA Energía, 28933 Mostoles, Spain. Tel.: +34 91 6645904.
E-mail address: javier.dufour@imdea.org (J. Dufour).

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2. Material and methods

2.1. Goal and scope

The goal of this study is to attain the environmental characterization of four production systems that yield biodiesel from different FFA-rich wastes, including biodiesel production from (i) used cooking oils, (ii) beef tallow, (iii) poultry fat, and (iv) sewage sludges. With this purpose, an LCA study was conducted on the basis of foreground data from a review of current literature in this field.

The functional unit for each of the four case studies was 1 t of biodiesel produced and dispatched from biodiesel plants. Fig. 1 shows a general description of the processes involved in these case studies. In the case of biodiesel production from waste vegetable oils or animal fats, system boundaries included rendering, acid-catalyzed esterification (catalyst: sulphuric acid) and alkali-catalyzed transesterification (catalyst: sodium hydroxide) along with the required transportation and waste management processes. On the other hand, for biodiesel production from sewage sludges, only acid-catalyzed in situ transesterification (catalyst: sulphuric acid) was included along with transportation and waste management processes. In this case, sewage sludge transportation was not necessary since the biodiesel production facility is based at the wastewater treatment plant. An in situ procedure was selected as, in addition to the avoidance of sludge transportation, it allows simultaneous extraction and transesterification of the fatty acids containing lipids [2]. In contrast to biodiesel production from waste vegetable oils or animal fats, this need for in situ operation is closely linked to the low ratio of biodiesel to raw material when dealing with sewage sludges [2,13]. It should be noted that capital goods were excluded from all the case studies.

Background processes are of paramount importance when a life cycle approach is followed. They refer to those processes indirectly embraced in the evaluated systems: electricity production, thermal energy production, water supply, and the production of chemicals.

2.2. Data acquisition

On the one hand, key data for the quantification of inputs (chemicals, water, electric and thermal energy demands, etc.) and outputs (products and wastes) were derived from current literature on biodiesel production from FFA-rich wastes. On the other hand, secondary data for background processes were taken from the ecoinvent database [14]. In particular, electricity production was considered by using the production mix for Spain as presented by Dones et al. [15].

As regards to the outcomes of the literature review, Table 1 gathers the main inventory data for the production of biodiesel from used cooking oils, which were inferred from the assessments previously undertaken by Morais et al. [8], Talens et al. [9], and López et al. [1]. Table 1 also shows the data computed – on the basis of previous evaluations by López et al. [1] and Nelson and Schrock [16] – for the inventory of biodiesel production from beef tallow and poultry fat. Additionally, Table 1 gathers the main inventory data for the production of biodiesel from dried primary and secondary wastewater sludges, which were adapted from techno-economic studies by Mondala et al. [2] and Revellame et al. [13]. In this respect, the in situ transesterification of dried sludges, rather than of wet sludges, was subject to evaluation as it is considered a more economical alternative for biodiesel production [17].

As observed in Table 1, inputs refer mainly to the lipid feedstock (waste vegetable oils, beef tallow, poultry fat or sewage sludges), chemicals (e.g. calcium oxide and phosphoric acid, which are used to remove sulphuric acid and sodium hydroxide from glycerol in the case study of biodiesel production from waste vegetable oils) and water (for instance, water needed to wash biodiesel) as well as to the electric and thermal energy requirements. Table 1 includes rendered beef tallow and rendered poultry fat as potential lipid sources. Input–output data relating to the supply of these rendered products are needed; they are gathered in the Appendix.

As shown in Table 1, biodiesel and glycerol were the two main products for every case study. Mass allocation was followed to distribute the environmental burdens between these products. Other alternatives for the allocation of environmental burdens when dealing with multifunctional systems include allocation by energy content, by economic value or by substitution [10]. However, a traditional mass allocation approach was selected as it is in-line with other life cycle analyses reviewed for the present study [1,8]. Although economic allocation is also a very common procedure, this option was dismissed as it tends to be largely affected by variations in market values [1]. Mass allocation factors were computed on the basis of the biodiesel and glycerol mass rates for each case study in order to allocate the potential impacts related to the biodiesel product (factors: 0.91, 0.90, 0.90, and 0.89, respectively). Regarding rendered beef tallow and meat and bone meal, as well as rendered poultry fat and poultry meal, a mass allocation approach was also followed according to the corresponding mass rates in the Appendix.

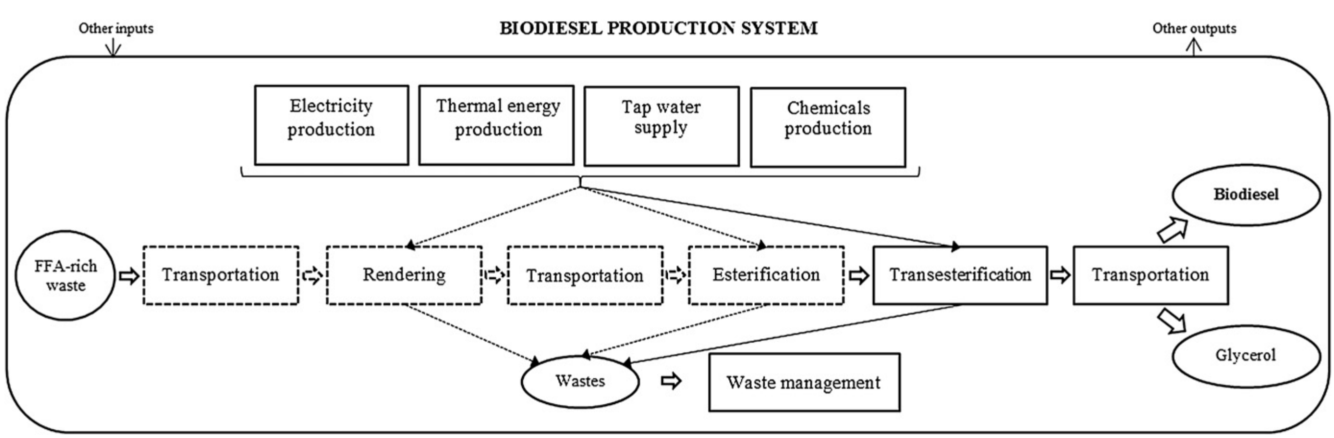

Fig. 1. General diagram for the biodiesel production systems subject to evaluation (dotted squares are used to distinguish those processes not involved in the case study of biodiesel production from sewage sludges).