



Research article

Multicriteria analysis of sewage sludge-based biodiesel production

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ABSTRACT

There is increasing attention on developing efficient processes including circular economy principles, and obtaining fuels from wastewater treatment feedstocks is among the most promising. As a wastewater treatment byproduct, sewage sludge is a source of lipids that can be converted to biodiesel in a transesterification process. Economic and environmental analysis have been applied to a 60 m³/h sewage sludge plant, exploring 32 process alternatives. Using solvent extraction from wet sewage sludge, the high cost associated with the drying step is skipped. The wet alternatives with low amounts of solvent and acid usage depicted higher performance compared to the dry ones. Incorporating additional extraction stages increases both the financial gains and environmental impacts. As a result, a multicriteria analysis is implemented to ascertain the optimum process based on different priorities. The case with 0.5:1 (v/v) of hexane to biomass ratio, 3-stage extractor, 60 min residence time and pH 4 was the optimum alternative in most criteria.

1. Introduction

The rising awareness of environmental issues, such as global warming, air quality and water scarcity, makes the environmental performance of a process a key indicator for their competitiveness in the market. There is an increasing demand from society for reliable information for traceability of the products. This issue is more significant when dealing with fuels production due to the large dependence of the current lifestyle in developed countries, the environmental burdens and the rising prices as consequences of resource depletion and geopolitical events.

All these factors promote the research on alternative sources of energy to reduce (and in the mid-range replace) the use of fossil fuels. In this line, biofuels will be part of the solution. The world demand for biofuels was around 2 million barrels of oil equivalent per day in 2020 and projections indicate about a 50% growth rate until 2030, while to align with the net-zero emission scenario, it is expected to have a nearly triple biofuels production rate (IEA, 2021). Increasing attention is paid to the processing technologies to achieve, or at least approach, this challenging objective.

Biodiesel, the second most common form of biofuels, can be obtained from vegetable and animal fat oils by catalytic transesterification with linear monohydroxy alcohols. First-generation biodiesel, mainly based on edible vegetable feedstocks, has been gradually replaced by second-

generation biodiesel, produced from different types of non-edible biomass such as woody crops and agricultural wastes, thus avoiding the threat over food supplies and biodiversity. However, second-generation biodiesel based on vegetable raw materials depends on agricultural crops, so they compete for scarce cropland, fresh water and fertilizers. Also, the feedstock cost represents the main part of the production cost. In the literature, different feedstocks have been investigated from non-edible crops: *Jatropha* (Singh et al., 2021), *Cynara cardunculus* (Torres et al., 2013b), waste animal fat (Andreo-Martínez et al., 2022), waste cooking oil (Wallace et al., 2017) and algae (Ríos et al., 2013). Nevertheless, the research on these potential resources must face difficulties related to the quality of the biodiesel produced, especially in the case of wastes and residues.

Considering all these issues, sludge-based biodiesel is among the most feasible solutions. Sewage sludge (SS) is less expensive than other raw materials considering that its production in wastewater treatment facilities is expected to increase due to growing urbanization and industrialization (Capodaglio and Callegari, 2018; Jiang et al., 2021; van Loosdrecht and Brdjanovic, 2014). The SS has been used in vast applications such as adsorbents, catalysts and fertilizers (Ye et al., 2022). Data in some countries shows that wastewater sludge has one of the highest potentials for biodiesel production in comparison with other feedstocks in terms of quantity, collection, and cost (Ruhani et al., 2022). On the other hand, the handling, treatment and disposal of this

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waste will pose additional costs and environmental burdens. The municipal SS is a good quality source of polar lipids fraction and fatty acids (C_{10} to C_{18}) to produce Fatty Acid Methyl Esters (FAME) (Bora et al., 2020). The biodiesel is produced through the transesterification of the oil or fat with a short chain alcohol (usually methanol or ethanol) in the presence of an acid, alkali or enzyme catalyst, where the quality of the resulting biodiesel (e.g., octane number and oxidative stability) depends on the ratio of the different fatty esters. Although the alkali catalyst has a high reaction rate, they require high energy consumption and their feedstock's Free Fatty Acid (FFA) content is limited. Recently, enzyme catalysts have emerged, providing high catalyst activities and specific surface area but from the operational point of view, it is expensive due to the complex preparation steps (Liu et al., 2021). The sewage sludge can be collected at two different points of the wastewater treatment plant: the primary sludge, located after the primary clarifier, and the second or activated sludge after the aerobic biological treatment. Fig. 1 shows a schematic representation of a wastewater plant connected to a biodiesel production plant. The maximum yield of FAME that can be achieved with primary sludge is higher than with the secondary sludge ($\approx 14.5\%$ and $\approx 2.5\%$, respectively). For feedstocks with a high amount of Free Fatty Acids (FFA) and water contents, acid catalysts with transesterification reactions are the best option (Olkiewicz et al., 2016a; Zhang et al., 2020).

The economy of this process is the main bottleneck to make it competitive with the state-of-the-art technologies. There are many studies about the feasibility of using lipid from sewage sludge as a source for biodiesel. Dufreche et al. (2007) compared the conversion of secondary sludge to biodiesel with different solvents obtaining the most significant conversion using an extraction stage with a mixture of methanol, n-hexane and acetone before an *in situ* transesterification. The authors also presented an estimation of the processing cost on which subsequent studies were inspired. Mondala et al. (2009) propose an *in situ* transesterification of primary and secondary sludge with methanol to dry sewage sludge ratio of 12:1 (w/w) and 5% (v/v) of H_2SO_4 . Pokoo-Aikins et al. (2010) modeled the process to optimize the economic aspect, including safety evaluation, compare several extraction

solvents, acid esterification pretreatment and alkali transesterification. Kwon et al. (2012) presented an economic analysis of the thermochemical non-catalytic conversion of lipids but assumed that the drying costs are compensated by government subsidies for avoiding the sludge disposal. In the study of Zhang et al. (2013), the sludge lipids conversion to biodiesel in one (direct transesterification) and two stages (extraction plus transesterification) are compared to microalgal-based biodiesel production in terms of energy balance and CO_2 emissions.

In all the aforementioned studies the sewage sludge has to be dried before extraction. The sludge drying typically comprises a concentration step with centrifugation or flocculation plus settling, followed by dewatering plus thermal drying (Schnell et al., 2020). The route is similar to the one used for microalgae biomass dewatering (Lassing et al., 2008). As mentioned before, some authors did not include these costs (assuming that government subsidies will cover this part), while others estimate the expenses well below the values resulting from our calculations, although for the best of our knowledge, it can represent $\approx 50\%$ of the operating cost of the plant. Therefore, new routes for eliminating the costly drying stage and extracting lipid from wet sludge could enhance the feasibility of the process. The experimental result shows that for materials with high lipid content, using direct extraction methods is more efficient (Babayigit et al., 2018; Olkiewicz et al., 2016b; Wang et al., 2021).

It is expected that using wastewater for biodiesel production should strongly decrease the environmental impact compared to conventional fossil fuels. Solvent usage clearly affects the environmental impact of the process, so assessing the environmental impact from a life-cycle approach will provide the perspective to compare different alternatives (di Bitonto et al., 2020; Liu et al., 2021; Mayer et al., 2021). Regarding the environmental criterion, the literature is not rich on biodiesel production from wastewater, although environmental assessment was done for other types of feedstocks, processes, and products (Aghbashlo et al., 2020; Singh et al., 2020; Sousa et al., 2017; Zhuang et al., 2022). Zhang et al. (2013) calculated the greenhouse gas emission (GHG) of a two-step biodiesel production from wastewater sludge based on emission coefficients. Dufour and Iribarren (2012) reported

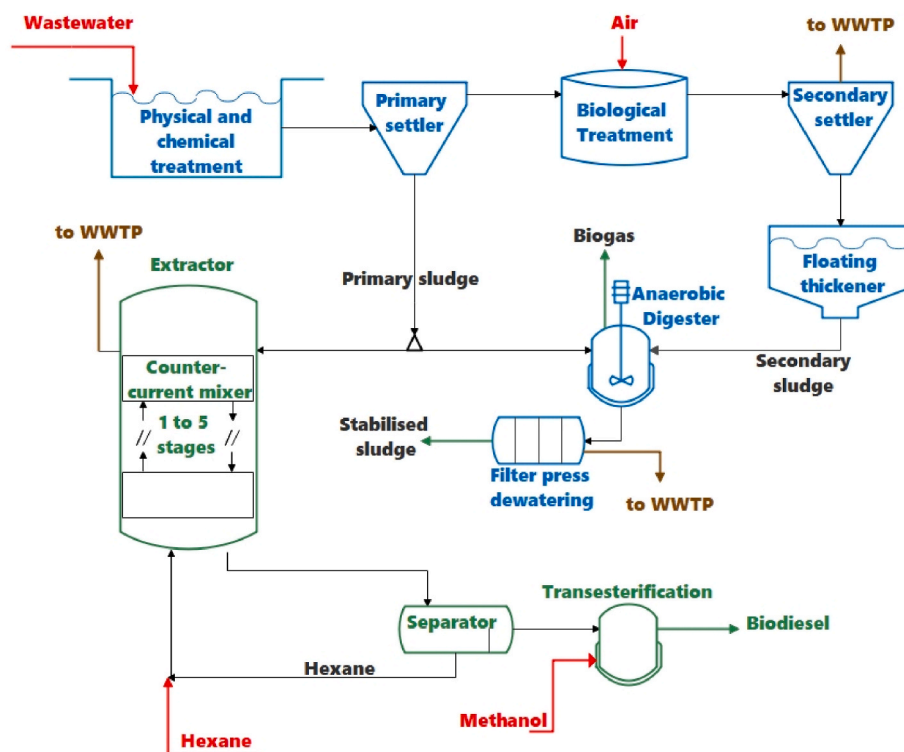


Fig. 1. Schematic of a biodiesel production plant connected to the wastewater treatment.

greenhouse gas emissions of biodiesel production comparing different sources of free fatty acid-rich wastes, including sewage sludge, although only the dry route was evaluated based on the economic results of Revellame et al. (2011). The mentioned studies in the context of biodiesel production from sewage sludge did not consider the trade-off between economic and environmental assessment simultaneously to recommend the most efficient process based on different aspects.

Herein we present a simultaneous economic and environmental evaluation, including Life Cycle Analysis (LCA) of the biodiesel production after lipids extraction from primary sludge directly in the aqueous phase (wet route), by conventional liquid-liquid extraction. The lipids wet extraction route and the effects of pretreatments were studied by Olkiewicz et al. (2015, 2014) which laid the foundations for building a simulation based on experimental data. The wet extraction pathway is compared with two dry extraction routes: conventional extraction followed by lipids conversion and *in situ* transesterification, where extraction and conversion occur in one stage.

The multicriteria evaluation of the 32 different scenarios and technological alternatives is based on the rigorous simulation of all alternatives. The use of Aspen Hysys® v11 allows modeling unit operations based on pre-built and/or customized modules, that enables access to the material and energy balances, and the equipments sizing. These data are required to compute the economic and environmental indicators. Furthermore, Aspen Hysys® can be linked to external tools like Matlab® R2021a. The Matlab® toolbox empowers accessing, registering, modifying and optimizing the simulation, enabling the automation of the evaluation by computing the corresponding metrics and analyzing different scenarios. Moreover, a sensitivity analysis of process variables was carried out.

The aim of this work is to analyze the biodiesel production from primary sewage sludge based on the experiments carried out at the laboratory scale focused on the lipid extraction stage. The comparison of different scenarios and technological alternatives is performed by the simulation-based automated evaluation tool (Torres et al., 2013a). This computational procedure includes the calculation of economic and environmental indicators to characterize the current state of the technologies and the key variables in their economic and environmental performance. To the best of our knowledge, there is no similar study in the literature that follows a multi-criteria approach with detailed economic and environmental calculations.

Particularly, the presented study aims at demonstrating the feasibility of the best wet extraction route among the different potential alternatives for primary sludge lipids recovery. The same approach and methodology can be used for similar processes to define the benefits and drawbacks of different scenarios. This methodology will unveil the prospective effects of each alternative on different aspects simultaneously, as implementation can be based on different priorities.

2. Materials and methods

The procedure followed in the multicriteria analysis is presented in this section. For the ensuing calculations, the location of the biodiesel production plant is a key element in the definition of the system boundaries. Specifically, expenses and emissions related to transport activities of the primary sewage sludge entering the process and the resultant sludge after extraction must be carefully regarded. The philosophy behind this analysis has a wider scope: the efficient design of integrated technologies and management for the energy valorization of different effluents from Wastewater Treatment Plants (WWTP).

We assume that The biodiesel production facility is supplied by a WWTP located at the same site. In this sense, a nearby urban WWTP producing 60 m³/h of sewage sludge was considered, which corresponds to a capacity of 2 million of equivalent inhabitants. The hypothetical biodiesel production plant has a capacity of treating 475,000 metric tons per year of primary sludge (4% of solids), which is equivalent to produce between 2000 and 4700 t/year of biodiesel depending on the yield

achieved by the different process alternatives. These technological options and how they have been modeled are described in subsections 2.1 and 2.2. Subsection 2.3 details the computational approach followed to automate the simulation-based multicriteria evaluation and the subsequent monetisation and sensitivity analyses.

2.1. Process simulation assumptions

The automated characterization approach is based on the simulation of the plant in Aspen Hysys v11. Some components have been defined as hypothetical solid; this is the case of the inorganic matter and ash content in the sludge, the organic matter different from lipids, the non-saponifiable lipids and the potassium sulfate, for which average molecular weights and densities are defined. Moreover, proxy compounds are used to represent similar substances. More precisely, a mixture of m-palmitate and m-oleate was selected to characterize the biodiesel product, the palmitic acid represents the FFA content, the triolein assumes the role of triglycerides and a saturated fatty acid ester was selected to characterize the non-saponifiable lipids (*i.e.*, cetyl palmitate). The composition of primary sewage sludge, and particularly its lipids composition, was simulated based on to the experimental results obtained by Olkiewicz et al. (2014) (see Table 1).

The Peng-Robinson Soave (PRSV) equation of state was selected to predict all physico-chemical properties. PRSV can predict more accurately the phase behavior of hydrocarbon systems and handle non-ideal systems with equivalent, or better, accuracy than activity coefficient models. Furthermore, PRSV performs rigorous three-phase flash calculations for aqueous systems containing water, methanol or glycols, as well as systems containing hydrocarbons in the second liquid phase.

Fig. 2 outlines the process alternatives assessed in this study. The base case scenario is defined for each alternative in subsection 2.2 as reference points for the subsequent sensitivity analysis; it comprises the composition of the sewage sludge, including the lipid content, extraction and reaction conditions, flue gas availability for drying, sewage sludge availability, etc.

2.2. Process alternatives

Three process alternatives were selected to find the best technological solution. Particularly, this paper compares the wet extraction procedure developed at laboratory scale (Olkiewicz et al., 2014) over traditional alternatives that include lipids extraction from dry sludge. The key aspect to developed wet extraction route is that the primary sludge is not dehydrated, with the consequent significant reduction in the costs.

2.2.1. Wet extraction

The simplified flowsheet for the liquid-liquid extraction route (Wet route) and the material balance are shown in Fig. 3. The primary sewage sludge composition is based on Table 1 and the complete stream balance is detailed in Fig. S1 of the Supplementary materials. The primary sludge

Table 1
Primary sewage sludge composition (Olkiewicz et al., 2014).

Component	Total %
Water	96
Solids (4%):	
Inorganic content (21.4%)	0.86
Organic content (78.6%):	
Protein (33.2%)	1.04
Carbohydrates (32.0%)	0.96
Lipids (34.8%):	
Non-saponifiables (20%)	0.22
Saponifiables (80%):	
Triglycerides (4%)	0.04
Free fatty acids (96%)	0.84

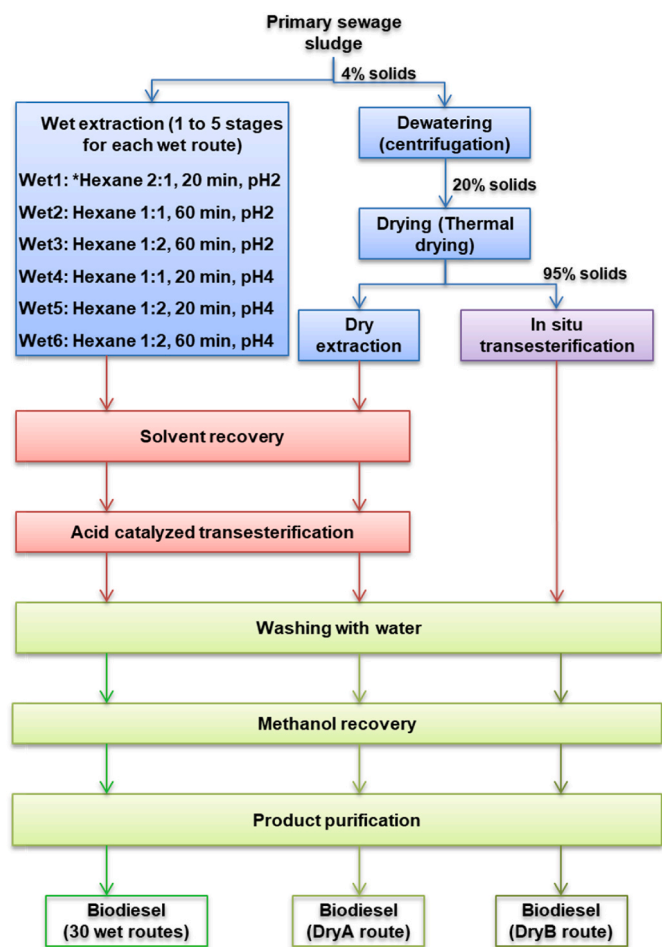


Fig. 2. Simplified flow diagram of the 32 alternatives for biodiesel production of sewage sludge (*Hexane to sludge volumetric ratio).

is stabilized with acid prior the extraction, promoting the separation of the lipids in the sludge. Approximately 1.5% v/v of hydrochloric acid is needed to reach operating conditions (pH = 2). However, working with pH = 4 decreases the extraction efficiency by around 5% but improves

the overall economic results by reducing the amount of acid in the input, thus 0.8% v/v is added. The lipid extraction takes place in a series of countercurrent liquid-liquid extraction mixers, where n-hexane is used as a solvent. The equilibrium and operating data were taken from the experimental work carried out by *Olkiewicz et al. (2014)*.

For the base case scenario, the economic analysis yields better results when combining three mixer/settlers in series (*Extractor*) with 0.5:1 (v/v) of hexane:sludge ratio and 60 min of residence time (see *Table S1* of the Supplementary materials). However, a multicriteria analysis of the number of stages, hexane ratio, extraction time and pH was carried out, including both economic and environmental indicators as decision criteria.

After the extraction stages, more than 96% of water can be reused in the wastewater treatment plant for further processing and exploitation; therefore, no additional expenditure is considered for the waste treatment in the base case scenario. On the other hand, the extract is headed to an equilibrium-flash separator (*F1*), where over 99% of n-hexane is recovered and recycled to the extraction stage. Along with the lipid content, a percentage of wax and sterol are extracted, but they must be removed from the lipids stream before the esterification and transesterification reactions to improve the quality of the biodiesel. Therefore, crystallization fractionation is applied to split fats and oils into a liquid part with the low-melting point and a solid fraction with the high melting point. Particularly, traditional fractionation consists of two stages: temperature-controlled crystallization combined with moderate agitation, and separation by filtration (*Haas and Foglia, 2010*).

Since the FFA content in the lipids is considerably high, an acid catalyzed reaction system with methanol as a reactant is proposed to produce FAME. Under these conditions, two reactions take place (*R1*): acid esterification of the FFA to process FAME and water, and acid transesterification of the triglycerides to procure FAME and glycerol. Based on the experimental data (*Olkiewicz et al., 2014*), almost 100% of the esterification occurs instantaneously, while a yield of near 99% is achieved for the transesterification under the following conditions: methanol to lipids molar ratio of 6:1, 1% (v/v) of sulfuric acid as catalyst with respect to the methanol input, reactor temperature of 60 °C and 4 h of residence time. Those results are in agreement with *Usman et al. (2023)* study.

The product stream is sent to a decanter (*LLD2*), where contact with washing water forces the separation of two phases. The light phase is forwarded to a flash separation (*F2*) to further reduce the amount of n-

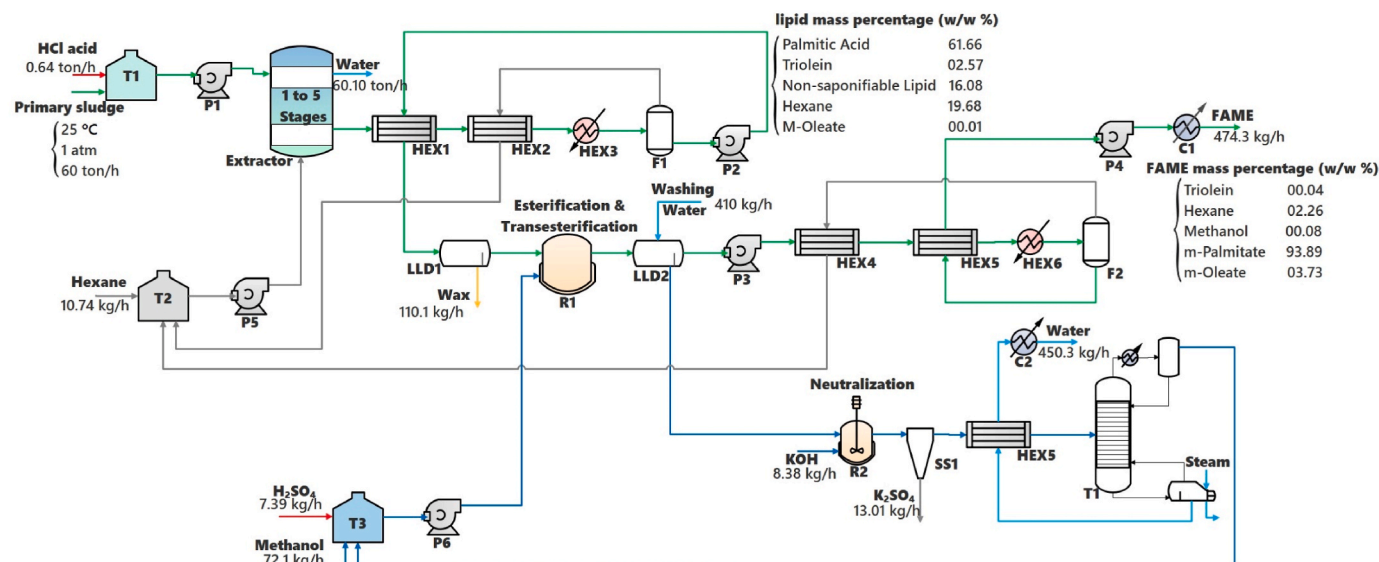


Fig. 3. Simplified flow diagram for biodiesel production from primary sludge: 'Wet' alternative. T: tank; HEX: shell and tube heat exchanger; C: cooler; H: heater; P: pump; R: reactor; T: distillation column; F: 2-phase flash; SS: solid separator; LLD: liquid-liquid decanter.

hexane and traces of methanol that accompanied the biodiesel, achieving a product with 98% of FAME (Kumar and Thakur, 2020). The heavy phase contains water, methanol, a low quantity of glycerol as a by-product of the transesterification reaction, and the acid used as catalyst. To recover the excess methanol to be recycled in the esterification/transesterification reaction, the heavy phase is first neutralized (R2) by the addition of potassium hydroxide obtaining a salt (K_2SO_4) that is segregated (SSI) and may be ascertained as a valuable by-product. Then, the neutralized stream is sent to a distillation column (T1) to recover the methanol and to obtain water with traces of glycerol (0.4%) that may be reused in the wastewater treatment plant.

2.2.2. Dry extraction

This alternative, called DryA hereinafter, includes the drying of the sludge prior to the extraction stage. We modified the model of Zhang et al. (2013) based on experimental results (Olkiewicz et al., 2014). The primary sewage sludge is dewatered in a same way to the microalgae biomass, first by centrifugation from a concentration of 5–20% of solids and then thermally dried until 95% as described in previous works (Ríos et al., 2013; Torres et al., 2013a). The new emerging methods for dewatering sewage sludge such as vacuum preloading or pressure filtration are not considered in this study due to the associated maintenance difficulties they entail (Zhang et al., 2022). The calculation of the drying stage is modeled and automatically linked as an input to the simulation.

A mixture of hexane, methanol and acetone (3:1:1 v/v/v) is used as a solvent in an extraction reactor at 50 °C for 1 h. For an extraction efficiency of 96% (Zhang et al., 2013), 1 L of the solvent mixture is needed for each kilogram of dry sludge. After the solvent recovery, the lipids are mixed with methanol (6:1 M) and sulfuric acid (1% v/v in methanol), at 50 °C to carry out the esterification and transesterification reactions, with an efficiency of 99% (Olkiewicz et al., 2015). The experimental results showed that the drying stage reduces the percentage of saponifiable lipids in the sludge, and thus it can be equivalent to a reduction of nearly 40% in the reaction yield (Olkiewicz et al., 2015). Then, the process follows a similar sequence to the wet extraction: solvent recovery, water washing and product purification. For more information about the base case scenario of alternative DryA, see Fig. S2 of the Supplementary materials.

2.2.3. In situ transesterification

This process alternative, from now on called DryB, is based on the route proposed by Dufreche et al. (2007) and Mondala et al. (2009), where the acid catalyzed esterification-transesterification reaction takes place simultaneously with the extraction, driven by a mixture of 12:1 methanol to sludge mass ratio and 5% (v/v) of H_2SO_4 . This process intensification reduces the number of equipment involved. The comparison of alternatives and the sensitivity analysis (Section 3) provide further insights into the advantages and disadvantages of this pathway. The yield of FAME used by Mondala et al. (2009) was 10 wt% of the total processed sludge; however, we simulated a winterization step (i.e., removing saturated fatty acid content by improving the cold flow properties) prior to the reaction step like in the previous alternatives. The process is similar to the Dry extraction for product purification and solvent recovery sections. A water washing column forces the separation of the heavy and the light phases, mostly composed of m-palmitate, until the biodiesel purity is reached. Meanwhile, 95% of the methanol is recovered after the neutralization in a distillation column. See Fig. S3 of the Supplementary materials for additional information of DryB route.

2.3. Automated evaluation tool

An evaluation tool programmed in Matlab® R2021a was used for the multicriteria analysis of the process alternatives and scenarios (Torres et al., 2013a, 2013c). The evaluation procedure comprises the following main steps:

- The bidirectional connection between Matlab® and Aspen. Hysys®.
- The automation of the scenario and corresponding parameters in the simulation enables performing sensitivity analysis and optimization in a straightforward manner.
- Collection of data needed to evaluate the performance of each scenario. These data comprise the operating conditions and design parameters of the equipments, the streams, and the energy requirements of each process alternative.
- Calculation of the specific metrics for the economic (see subsection 2.3.1) and environmental characterization (see subsection 2.3.2) of each scenario.
- Optionally, the different metrics are aggregated by impact categories or in a unique score indicator for comparison (Torres et al., 2011).
- Finally, the evaluation results are recorded and depending on the purpose of the study are used to establish the new scenario. For instance, if a variable, or a set of variables, has to be optimized, the algorithm programmed in Matlab Toolbox® starts the iterative procedure.

Fig. 4 illustrates the procedure of the automated evaluation tool to clarify the connections between each step and the tools used.

2.3.1. Economic module

The Total Capital Investment (TCI) and the Total Manufacturing Cost (TMC) are calculated for each process alternative based on reference (Turton et al., 2008). The TCI is formulated based on the total bare cost using the equipment module costing technique (Ulrich, 1984). The tool also collects all data from all units modeled. By adding the contingencies and fees, and the auxiliary facilities to the total bare module, we

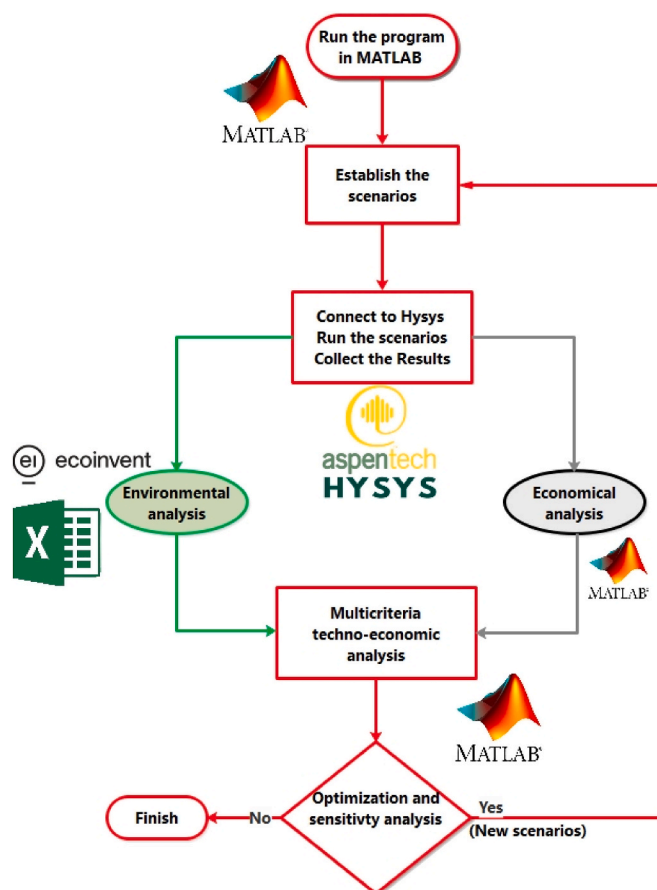


Fig. 4. Algorithm of the automated evaluation tool.

estimated the fixed capital cost, to which the working capital including energy expenses is finally added to obtain the TCI. The TMC is based on the direct manufacturing cost that includes the raw material, utilities, labor fees, and other costs directly related to the process. Then, the fixed manufacturing cost (e.g., overheads, taxes, insurance, etc.) and the general expenses (e.g., research and development, administration, distribution and selling, etc.) are summed to the direct expenses to obtain the TMC. Finally, the tool also calculates additional economic indicators like the Break-Even Price (BEP), which is the minimum selling price of the product, and the profitability of the plant which is used to compare alternatives.

2.3.2. Environmental module

The environmental evaluation of the alternatives is carried out using Life Cycle Assessment (LCA) (ISO, 2006). The scope covers from cradle-to-gate, thus including all the activities before producing biodiesel (extraction, transformation and transport of raw materials and utilities). The functional unit is 1 kg of wastewater. The data for the Life Cycle Inventory (LCI) is obtained from the input and output flows provided by the simulation (LCIA data is extracted from Ecoinvent v3.8 APOS by Matlab, see Table S2 of the Supplementary material). The ReCiPe method (Huijbregts et al., 2017) was selected as the Life Cycle Impact Assessment (LCIA) to link the inventory data and the environmental damages. The allocation system used is the point of substitution (APOS). Although the ReCiPe procedure proposes default normalization and weighting factors so the damaging impact can be expressed by an overall score, an alternative to fixed weights is used in this study to incorporate into the analysis economic considerations. In this sense, the aggregated index is calculated by varying the values of the weighting factors within the [0,1] interval (i.e., null and total predominance, respectively). The results are processed to extract a set of predicting rules to identify the most promising options corresponding to regions of weighting factors dominance.

3. Results and discussions

3.1. Alternatives comparison for the base case scenario

Both economic and environmental criteria yield almost the same ranking (see Tables S1 and S3 of the Supplementary materials for the detailed results). Table S3 shows the LCA results of the alternatives, including a dry path and the six wet extraction alternatives that combine different solvent ratios, extraction times, pH, and number of extraction stages. The DryB path is the worst case from both the environmental and economic perspectives. According to ReCiPe and economic profit, the DryB route has 10 times more impact in environmental assessment and around 5 times worst economic performance, compared to the other routes. Thus, this alternative is not further considered in the following analysis. High usage of utilities imposed negative impacts on the DryB case which confirms Dufour and Iribarren (2012) conclusions. In Fig. 5 the ReCiPe impacts of scenarios are ranked basically by the amount of hexane, acid usage and number of extraction stages. It is worth mentioning that almost the same ranking is obtained when the alternatives are sorted based on energy criteria. Energy consumption has a direct relation with the environmental impacts of each scenario (Dufour and Iribarren, 2012) (Check Table S1 of Supplementary materials).

The distribution of impacts among the different categories in Fig. 6 reveals that global warming and fine particulate matter formation account for up to 70% of the impact.

The base case scenario releases 272 g of CO₂ eq/kg biodiesel can be classified in the low-range emission compared to the biodiesel production from waste cooking oil (Hosseinzadeh-Bandbafha et al., 2022). A deeper insight into global warming and fine particulate matter formation is demonstrated in Fig. 7, where raw materials and steam generation (heating utility) indicators impose the highest effects on the environmental terms. The results are relative values and the base

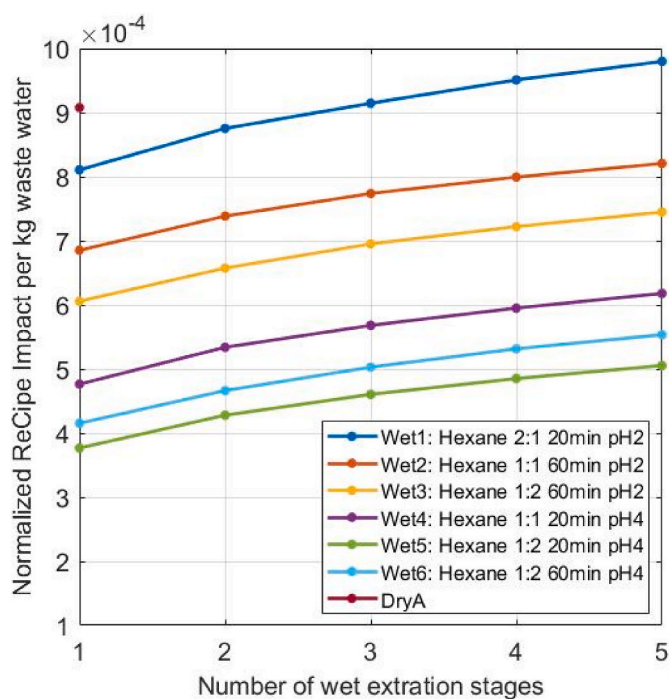


Fig. 5. ReCiPe impact comparison between alternatives.

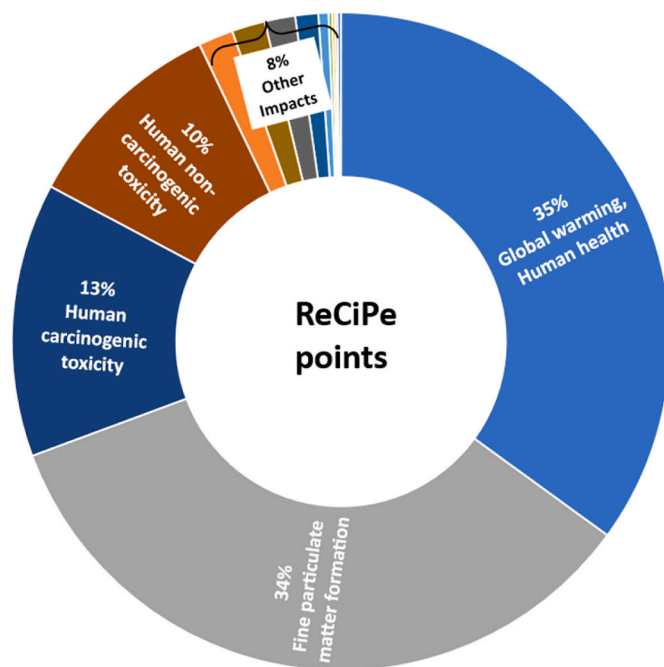


Fig. 6. Distribution of ReCiPe impact factors for the base case (Wet3).

(maximum value) is the contribution of fine particulate matter formation impact by the acquisition of the raw materials. The coefficient of the byproduct is negative, as a credit for the system. In this way, the production of K₂SO₄ is also considered as a negative impact in the subsequent calculations. A critical parameter is the amount of energy used for heating (90 °C) the stream before the separation of solvent (H1 unit in Fig. 3). The heating required ranges from 0.3 MW to 1.3 MW, thus having a high environmental impact for the scenarios associated with higher hexane to sludge ratio. Another important parameter in the environmental analysis is the amount of acid used. In the wet route, the

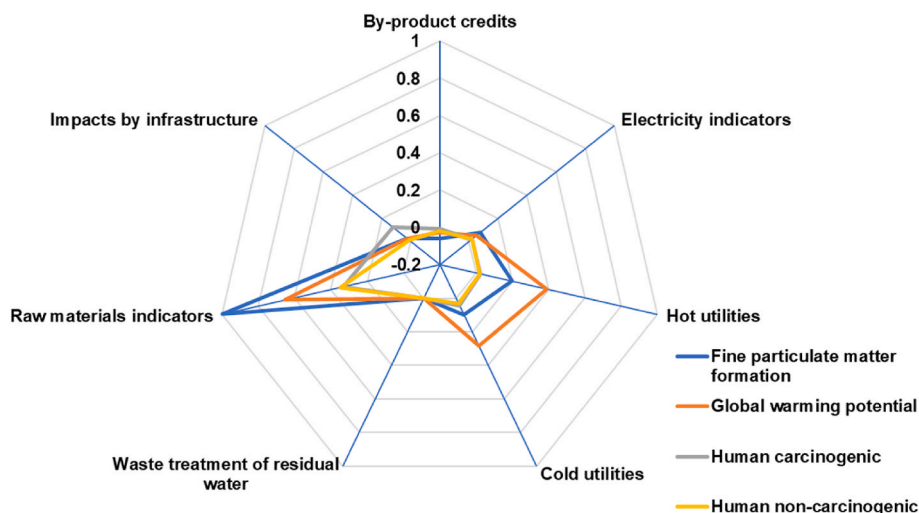


Fig. 7. Comparison of each indicator’s effects on global warming potential and fine particulate matter.

use of hydrochloric acid can be reduced by increasing the pH during operation from 2 to 4, in a trade-off between the acid consumption and the extraction efficiency.

3.2. Multicriteria evaluation

Although the minimum environmental impact coincides with the minimum number of extraction stages, the maximum profit is achieved in the scenarios with two and three extraction stages which is aligned to [Olkiewicz et al. \(2016b\)](#) experimental work. Cases with lower environmental impacts and higher profit are the best options to convert sewage sludge (Fig. 8). Wet6 turns out to be the first selection alternative due to the best economic result and the second least harmful scenario for the environment. The vertical placement of alternatives represents that residence time has a significant effect on the profit of the process (60 compared to 20 min) and the amount of hexane and acid have the subsequent effectiveness in the profit of the plant.

In the cases with high extraction efficiency and reactor conversion or high-price biodiesel, scenarios with greater production capacity are better ranked (wet cases with a higher number of extractions and Dry1 case) and vice versa. For instance, by decreasing the biodiesel by 10%,

the Wet6 with two stages is the best alternative. Therefore, the slope and the maximum point in Fig. 8 will change accordingly.

In all multicriteria analyses (Fig. 8), there is no straightforward answer to which is the best scenario, as it might depend on the specific criteria prioritized by the decision-makers. A weighting factor analysis was conducted to guide decision-makers in considering the preferences on the different impact categories: human health, ecosystem quality, resource depletion and economic profitability. Therefore, each category impact is treated individually without applying the fixed weighting factors assigned in the midpoint to endpoint calculation phase of the life cycle impact assessment. The geometric mean of the ratios of the different indicators with respect to the Wet1 route ([Torres et al., 2011](#)) is used to normalize the environmental and economic indicators to obtain a single score. The resulting total index for a given process alternative represents its position with respect to the base case: i.e., better (lower than 1) or worse option (higher than 1). Finally, the mixing triangles ([Hofstetter et al., 1999](#)) in Fig. 9 show the areas of the predominance of a particular alternative. In this case, due to the challenges to show 4 dimensions, the mixing triangle plots with a summation of two vertex were used as projections of the solution. Fig. 9 shows two areas of predominance, on the left sides, the best alternative is the Wet5 route with 1 stage extraction when more importance is given to the environmental concerns, while on the right sides the economic criterion is predominant and the best alternative is Wet6 route with 3 stages extraction. In the boundary layer between these two scenarios, the Wet6 with 2 stages becomes more favorable. In the central area of equitable weights, the best alternative is by rough Wet6-3.

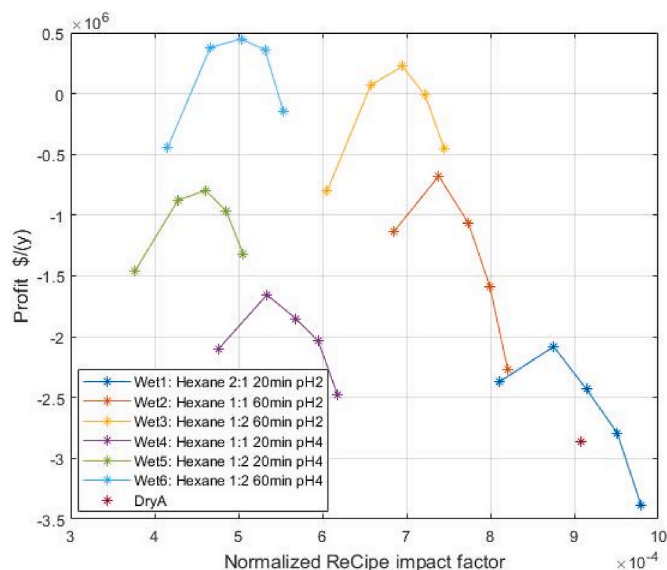
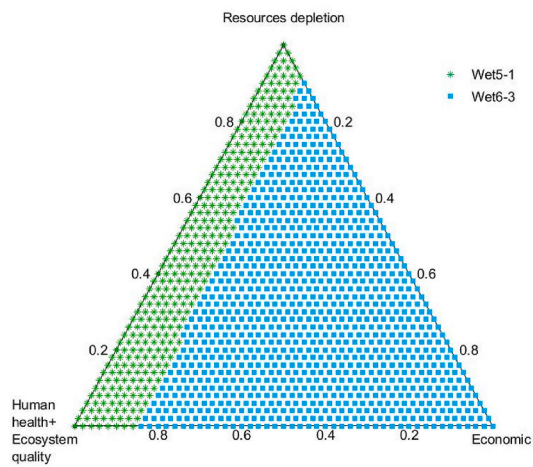


Fig. 8. Profit vs. ReCiPe impact score for process alternatives.

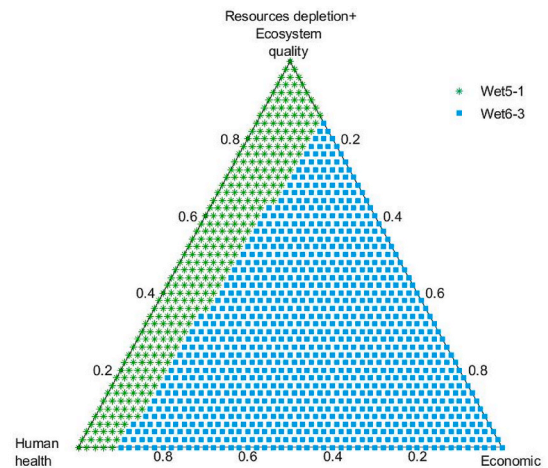
3.3. Monetisation

There are several approaches to highlight environmental impacts and make them more tangible for the decision-maker. Monetisation is an approach to objectivize the environmental effects by considering the external costs. Although this method is sensitive to the initial assumption and has uncertainties associated, the monetized environmental impact can be aggregated with the plant expenses to consider the trade-off between the economic and environmental results.

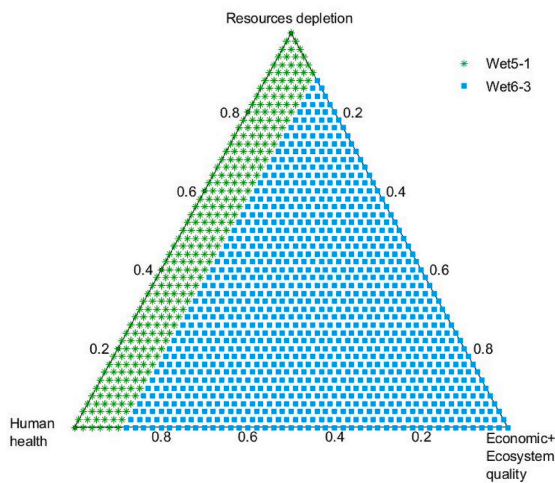
The monetized impact values are based on the ReCiPe 2016 midpoint categories; whenever the midpoint values were not available, the endpoint values were used. According to [Ponsioen et al. \(2020\)](#), for each Disability-Adjusted- Life Years (DALYs) in the human health category we should include 72,000 €, while for each species-year in the ecosystem category 11.5×10^6 € is considered to quantify the external environmental costs. The monetized impact for the two main scenarios from



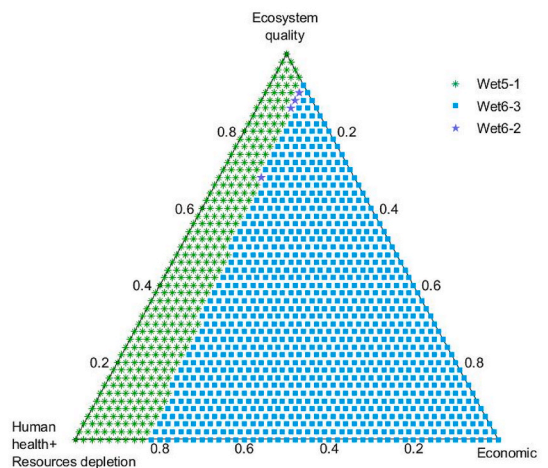
a) Human health and ecosystem quality in the same vertex



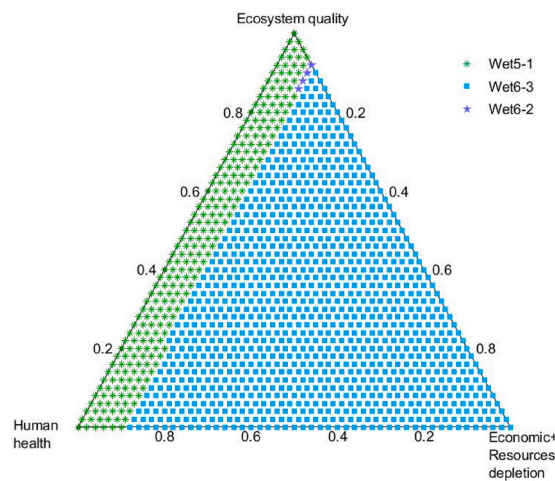
b) Resource depletion and ecosystem quality in the same vertex



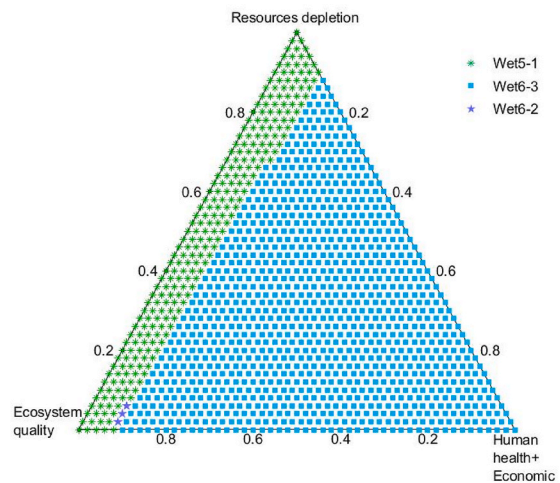
c) Economic and ecosystem quality in the same vertex



d) Human health and resource depletion in the same vertex



e) Economic and resource depletion in a same vertex



f) Human health and economic in the same vertex

Fig. 9. Mixing triangles analyzing the best process scenarios as a function of the weighting factors.

Fig. 9 (Wet5, Wet6) was 3.3×10^4 \$ and 4.8×10^4 \$, respectively. Fig. 10 depicts the economic results of all the scenarios by considering the externalities. Final results indicate that the alternative with 1:2 (v/v) of hexane:sludge ratio, 60 min residence time, pH 4 and 3 extraction stages has the best performance.

3.4. Sensitivity analysis

The sensitivity analysis was conducted between three alternatives covering the overall range: The best economic case (Wet6-3 extractive stages), the best environmental case (Wet5-1 extractive stage) and the best dry route (DryA). To do so, six different scenarios were defined for the selected alternatives while three of them were generally applied for all the cases. The three other remaining were defined based on the unavailability of flue gas for drying in the dry route, the transport distance for the dried biomass in the dry route, changing the pH from 4 to 2 for the Wet6-3 case to show the effect of the hydrochloric acid on the biodiesel selling price. Fig. 11 illustrates the significant advantage of extra flue gas for the drying route by 90% effectiveness in the economic and 38% effectiveness in the environmental indicator, respectively. On the other hand, a 10% change in the methanol to lipid ratio has less than a 3% effect on the process performance. Disregarding the wastewater treatment for the wet routes has a crucial effect on the profit of the plant while it does not affect the environmental aspect in the dry route due to the low amount of water in the primary sludge. Fluctuations in the biodiesel market may lead to choosing different scenarios as optimum. For instance, by 10% decreasing the biodiesel price, the Wet6 with two stages will be the best alternative among all scenarios.

4. Conclusions

Our analysis revealed an alignment between economic and environmental criteria in ranking different alternatives. Multicriteria analysis clarified that the wet routes are the preferred alternative for biodiesel production under the defined conditions, although the availability of flue gas for drying the biomass makes the dry routes competitive. Hexane, acid usage, and energy consumption were identified as

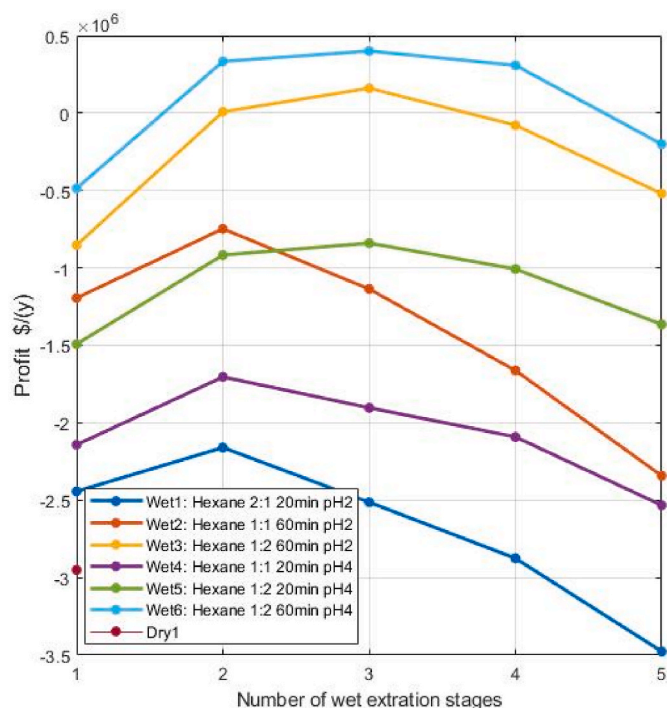
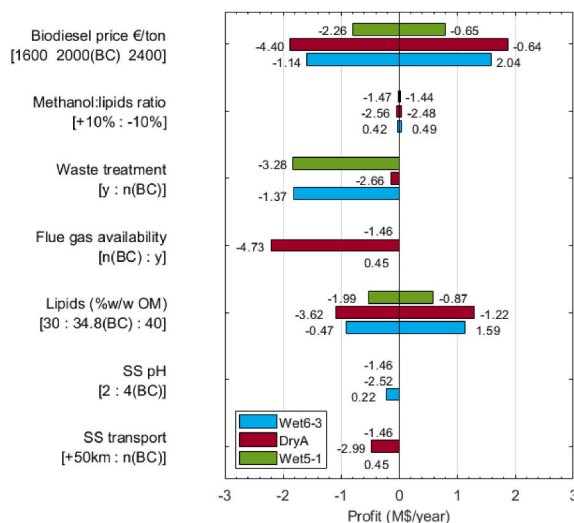
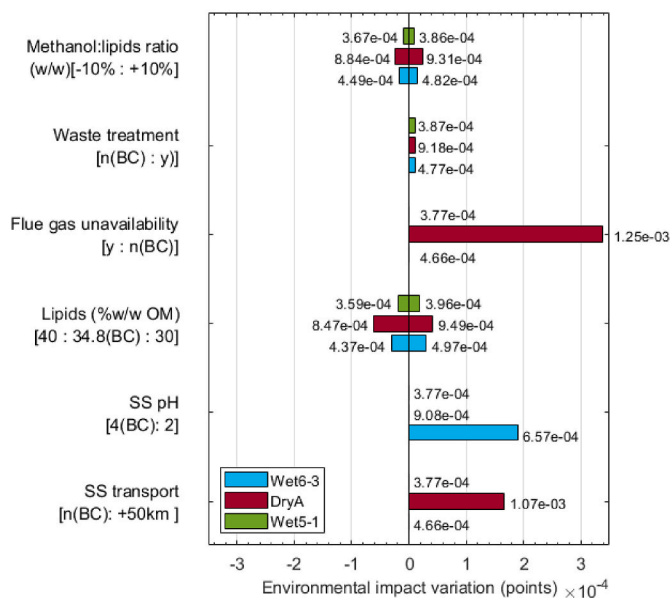


Fig. 10. Profit of the scenarios by considering the externality costs.



(a)



(b)

Fig. 11. Sensitivity analysis of the selected alternatives for the economic (a) and environmental (b) aspects.

key parameters affecting environmental impacts. Multicriteria evaluation favored scenarios with two or three extraction stages for optimal economic performance and relatively low environmental impacts.

A weighting factor analysis allowed for decision customization by indicating the best process scenario based on specific weightings of the different criteria. The monetisation is also used to accumulate the environmental impacts in terms of costs. Although these externalities do not change the ranking between the scenarios, considering the avoided cost of establishing a WWTP and higher externality costs due to the strict regulation on environmental damage could change the priorities if new policies such as government subsidiaries are implemented.

Author contribution

Mostafa Zarandi: Writing-original draft, Software, Methodology, Investigation, Formal analysis, Data curation. Carmen Torres: Visualization, validation, methodology. Josep Maria Mateo: Resources, Project administration, funding acquisition. Laureano Jimenez: Supervision, Writing-review and editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2023.119269>.

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