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Scale-up and economic analysis of biodiesel production from municipal primary sewage sludge

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HIGHLIGHTS

- Biodiesel production from wet sludge is more cost-effective than from dry sludge.
- The required biodiesel selling price was estimated at 1232 $/t.
- The price is lower than current cost of fossil diesel and biodiesel from microalgae.
- Municipal primary sludge is a plentiful and cost-competitive biodiesel feedstock.
- Improvement in lipid extraction and biodiesel purification can even lower the price.

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ABSTRACT

Municipal wastewater sludge is a promising lipid feedstock for biodiesel production, but the need to eliminate the high water content before lipid extraction is the main limitation for scaling up. This study evaluates the economic feasibility of biodiesel production directly from liquid primary sludge based on experimental data at laboratory scale. Computational tools were used for the modelling of the process scale-up and the different configurations of lipid extraction to optimise this step, as it is the most expensive. The operational variables with a major influence in the cost were the extraction time and the amount of solvent. The optimised extraction process had a break-even price of biodiesel of 1232 $/t, being economically competitive with the current cost of fossil diesel. The proposed biodiesel production process from waste sludge eliminates the expensive step of sludge drying, lowering the biodiesel price.

1. Introduction

Biodiesel is one of the most promising renewable fuels that is biodegradable, less toxic, may generate similar amount of energy to fossil diesel and can be directly used with current engine and refuelling technology/infrastructure without major modification (Siddiquee and Rohani, 2011; Kwon et al., 2012; Atabani et al., 2012). Biodiesel, *i.e.*, fatty acids methyl ester (FAME), is mainly produced from edible vegetable oils, however the high cost of vegetable oils which constitutes between 70% and 85% of the overall biodiesel production cost, strongly influences the final price of this biofuel, limiting its expansion (Mondala et al., 2009; Siddiquee and Rohani, 2011; Kwon et al., 2012; Atabani et al., 2012). Furthermore, the cultivation of edible oilseeds for biofuels raises the concerns of food shortage, which competes with fuel production (Atabani et al., 2012; Khan et al., 2014).

The possibility of using municipal sewage sludge as non-edible lipid feedstock is gaining more attention due to the large amounts of sludge generated in the developed countries, and high amount of lipids contained within these wastes, up to 30 wt% (Dufreche et al., 2007; Olkiewicz et al., 2014, 2015a; Tyagi and Lo, 2013; Yi et al., 2016). The amount of lipids strongly depends on the sludge type. The lipid yield in secondary sludge was found in the range of 2–12 wt% (Huynh et al., 2010; Siddiquee and Rohani, 2011; Tyagi and Lo, 2013; Olkiewicz et al., 2012, 2015a), while in primary sludge usually ranges between 15 and 30 wt% (Willson et al., 2010; Siddiquee and Rohani, 2011; Pastore et al., 2013; Olkiewicz et al., 2015a, 2015b; Yi et al., 2016).

On the other hand, the sludge formed during treatment of wastewater needs specific management before disposal and represents a major cost in wastewater treatment plant (WWTP) operation (Dufreche et al., 2007; Pastore et al., 2013). Therefore, the sewage sludge can be envisaged as a low-cost, readily available in abundance and non-edible feedstock, which can make biodiesel production profitable. Recent studies have indicated that the lipid

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contained in sewage sludge could be a potential feedstock for biodiesel production (Dufreche et al., 2007; Mondala et al., 2009; Huynh et al., 2010; Willson et al., 2010; Siddiquee and Rohani, 2011; Kwon et al., 2012; Pastore et al., 2013; Olkiewicz et al., 2012, 2014, 2015a). Nevertheless, the cost of energy necessary to eliminate the high water content (95–98 wt%), before lipid extraction, is the main limitation to scale-up, as dewatering and drying constitutes more than 50% of the total biodiesel production cost (Dufreche et al., 2007; Mondala et al., 2009). On the other hand, previous research demonstrated the feasibility of lipid extraction from liquid sludge (~96% of water) by direct liquid–liquid extraction using hexane as a solvent (Olkiewicz et al., 2014). Since the production of biodiesel from liquid sewage sludge is feasible, the expensive sludge drying step can be eliminated, and therefore the overall biodiesel production cost can be reduced. However, in order to confirm the stated hypothesis, the economic feasibility of the wet process (direct use of liquid sludge) and its comparison with dry process (use of dry sludge) has to be done.

Economic analysis of the production of biodiesel from dry sewage sludge has already been reported. Dufreche et al. (2007) estimated the cost of biodiesel production from dry sludge by direct *in situ* transesterification, without the extraction step, to be 933 $/t. However, in this research short-cut economic methods were used without giving details about the cost of methods used. A more detailed breakdown of estimated costs also for *in situ* transesterification was calculated by Mondala et al. (2009), based on data published by others, *e.g.*, the cost of sludge drying was taken from Dufreche et al. (2007). They obtained a break-even price of biodiesel of 970 $/t. Pokoo-Aikins et al. (2010) presented a full economic feasibility study, based on process design and simulation, to choose the best option to produce biodiesel from sludge, using two-step process: preliminary lipid extraction, evaluating four solvents (hexane, toluene, methanol and ethanol), and subsequent conversion of the lipids into biodiesel. The results indicated that hexane and toluene were cheaper solvents, giving 868 and 838 $/t of biodiesel, respectively. These excellent results were obtained considering that dry sludge was free of cost, charging the sludge drying to WWTPs. Certainly, if sludge drying were also taken into consideration, the final price of biodiesel would increase significantly.

In short, on the one hand, in the aforementioned economic studies, some assumptions were underestimated and in some cases not all process steps were considered for the estimation of the final biodiesel cost. Therefore, to fairly estimate the biodiesel production cost from sewage sludge, all assumptions must be taken with a constructive criticism and include realistic values. On the other hand, the biodiesel production from wastewater sludge has a promising future but it is still in research stage. Therefore, further large scale studies are required to realise the benefits of this new biotechnology.

The purpose of this research is to critically review the biodiesel production from sewage sludge using the know-how acquired at bench scale experimental work. Laboratory scale data obtained in our previous study (Olkiewicz et al., 2014), where the feasibility of lipids extraction directly from liquid sludge was demonstrated, is analysed by computational tools in order to carry out the scale-up of this novel biodiesel production process. In particular, the lipid extraction from liquid primary sludge is optimised by using computational tools to model the process performance and the economic evaluation of the process alternatives. Process options are envisaged to estimate a realistic scenario considering the technology currently available. Finally, the optimised biodiesel production process from liquid sludge is compared to the *in situ* and two-step processes using dry sludge (also simulated in this study) in order to decide on the most economically favourable process.

2. Materials and methods

A production plant with a capacity of around 4000 t/year of biodiesel produced from primary sewage sludge is studied. The capacity of the facility will depend on the sewage sludge availability. In this sense, a nearby urban waste water treatment plant (WWTP) to feed 60 m^3/h of primary sewage sludge was considered. This set-up (Fig. 1) can eliminate the cost of transporting the sludge feedstock into the biodiesel production facility, which therefore was not taken into account in the economic study as well as the cost of raw sludge, which is a waste generated during treatment of wastewater. The proposed process aims to improve the biodiesel production from sewage sludge, *i.e.*, lipid extraction process, by the elimination of the energy intensive step of sludge dewatering and drying and also the elimination of the heating process during extraction. Particularly, the process developed is compared with those described in other works, whose main differences are: on the one hand, the use of sludge previously dehydrated, with the consequent increased costs of the raw material, that in some assessments seem to be understated or dismissed (Pokoo-Aikins et al., 2010; Zhang et al., 2013; Dufreche et al., 2007; Mondala et al., 2009); and on the other hand, the use of heating during extraction, which also increases the cost of the process (Pokoo-Aikins et al., 2010; Zhang et al., 2013; Dufreche et al., 2007); and finally, the conversion of all lipids into biodiesel (Zhang et al., 2013), since based on experimental studies approximately 70–85% of lipids can be converted into biodiesel (saponifiable lipids) (Pastore et al., 2013; Olkiewicz et al., 2014). The economic evaluation of the process and its potential alternatives is performed based on the previous results experimentally tested (Olkiewicz et al., 2014).

2.1. Approaches and assumptions

The presented study aims to put some light in the potential of the wet route that so far has been underrated with respect to dry routes. The hypothesis considers experimental results in laboratory and also the pilot-scale experience with other lipid sources in water solutions of similar features (microalgae, vegetal oils, etc.). In this sense, although the economic analysis to probe the feasibility of the process is based on conceptual design (specifically in laboratory-scale experiments), it is in line and even more complete than previously mentioned studies about better-known dry options that can be found elsewhere in the literature. The simulation software supports the customisation of unit processes allowing the implementation of specific complexities that the simulator cannot solve in a realistic way related with the sewage sludge properties. Two main objectives are pursued, on the one hand, obtaining preliminary profitability indicators of sewage sludge-based biodiesel processing through wet pathway; and on the other hand, comparing the wet route with dry alternatives (*in situ* and two-step processes using dry sludge) under the same basis, that are the same process simulation and economic modelling procedures.

2.1.1. Primary sludge

The calculations of the economic feasibility study were performed with the data of primary sludge collected from the municipal WWTP in Reus (Tarragona, Spain) with a capacity to process near 25,000 m^3 of wastewater per day, which serves 200,000 inhabitants. The WWTP of Reus produces an average of 135 m^3/day of primary sludge. For the calculations, the flow rate was approximated to 60 m^3/h to assimilate the production of a big town, as for example the WWTP near Barcelona, which serves approximately to 2 million inhabitants.