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Comparison of feedstocks and technologies for biodiesel production: An environmental and techno-economic evaluation

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ABSTRACT

Due to their high productivity in both crops and algae, tropical countries are likely to be the future world suppliers of feedstocks as well as biofuels such as biodiesel. In this work five feedstocks: palm, jatropha, microalgae, tallow and waste cooking oil were analyzed and compared using techno-economic and environmental criteria. For each feedstock, technological configurations currently used in the industry were taken into account (acid catalysis, basic catalysis and cogeneration). In this work, it was found that productivities for the basic catalyzed process were comparatively higher (1.010 kg biodiesel/kg crude oil), than those catalyzed by acid (0.85–0.95 kg biodiesel/kg crude oil). After the simulation of the selected processes, the lowest production costs were obtained for jatropha (USD 0.15/L, basic catalysis) and for waste cooking oils (USD 0.23/L, acid catalysis). The PEI (Potential Environmental Impact) generated for basic catalyzed process ranged from −0.04 to −0.09, while the acid catalyzed case −0.020 and −0.06 PEI per kg of product. The jatropha and microalgae oil using basic catalyzed configuration with energy cogeneration were the best process alternative from the environmental and economical points of view.

1. Introduction

Biodiesel is defined as a clean-burning fuel with low viscosity and pour point, non-toxic, biodegradable and environmentally friendly due to its comparative low emissions and reduction of SO_2 production [1]. The main advantages of producing and using biodiesel come from the fact that foreign oil imports can be reduced, using the current installed distribution networks and the current engine technologies. The use of renewable sources for this biofuel industry helps to increase not only job generation and incomes, but also promoting energy self-sufficiency in rural areas [2,3]. Biodiesel is composed by fatty alkyl esters produced using different chemical routes according to the initial feedstock [4]. Transesterification and fatty acid esterification reactions are currently the most used [5,6]. However, other routes such as interesterification and thermal cracking can also be employed [7].

The increase in the petroleum prices and the diesel fuel consumption as well as the promotion of several bioenergy fuels policies and consumption incentives, project the biodiesel production above 50 billion liters by 2030 [8,9]. As a result, biodiesel has a rising potential market, that can be classified according to its end-use applications in: transportation, non-road applications (mining, forestry, construction, etc.), marine and heating [10]. Biodiesel can be produced from different oleochemical feedstocks, including animal fat, vegetable oils and algae oils, among others. These feedstocks are mainly composed by (85–98%wt) triglycerides, three long fatty acid chains joined to the glycerol molecule. Today the most common feedstocks are edible vegetable oils. United States, and Argentina mostly employees soybean oil, European Union countries use rapeseed oil; and tropical countries as Malaysia, Indonesia, Nigeria and Colombia prefer palm oil [5,11]. The main advantage of edible oil as a feedstock is that the plantations and the infrastructure are well established in most of these countries, making it easier the production of these edible oil crops to be expanded to meet the increasing demand. However, base biodiesel industry on edible feedstocks can be inconvenient due to their competition with food, and this may lead to food shortages and increase in food prices. Moreover, an expansion of these edible oil crops, would require monoculture plantations, affecting water resources and biodiversity [12,13]. Indeed, a good biodiesel feedstock should be easily available, without impacting negatively food security and environment.

Therefore, most of the countries are involved into a difficult decision regarding to what kind of feedstocks should be used to

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sustain their national biofuels policies. For instance, in Argentina soybean is the preferred raw material for biodiesel production due to its low cost, while in China this feedstock it is not accepted as biofuel due to the high demand of soybean oil from traditional Chinese food [14]. This situation has driven to promote the use of other feedstocks as jatropha, castorbean and karanja in countries such as India and Brazil [15]. In the same way, other alternative feedstocks different from edible oil crops are used in Japan (waste cooking oils), Canada and Australia (tallow and animal fats) [16]. Non-edible oils make possible to use degraded and waste lands, preserving most productive lands for food production [17]. Meanwhile, the use of animal fats and waste cooking oil is still limited at large scale due to their high free fatty acid content and, solidification points at room temperature, causing difficulties during their production and use. However, these non-conventional raw materials are also promising options for biodiesel production due to low cost [18,19]. On the other hand, microalgae are species with a high comparative potential to produce biodiesel given their high production rates and low land requirements [20,21].

In this work five promising feedstocks, under two different process configurations (basic catalysis with cogeneration and acid catalysis) available in tropical countries, were simulated and compared using techno-economic and environmental criteria. As a result, two feedstocks and one technological configuration were found to be the more convenient for biodiesel production in tropical countries.

2. Biodiesel feedstocks

Oil palm is a high-yield crop that requires small areas to be cultivated. Currently, it is one of the largest suppliers of edible oil in the world. It is produced in countries throughout the tropics, being Malaysia, Indonesia and Colombia the higher producers with almost 83% of total global production [22]. Crude palm oil (CPO) and crude palm kernel oil are obtained from the extraction process. Although CPO can be directly used in industrial activities, in order to be used on human food industries, palm oil must be refined, blanched and deodorized [23]. The obtained oil is known as refined–bleached–deodorized (RBD) oils and has free fatty acid content lower than 0.1%. Today, 70–90% of palm oil production is used for food and cosmetic industries, while the remaining 10–20% for other industrial applications. However, these values change according to fluctuations on demand and large competition with soybean oil [24].

Jatropha curcas is a bush which belongs to the family of Euphorbiaceae, distributed in the wild or semi-cultivated areas. It is a tropical and subtropical plant, and can grow at latitudes 30° north and south of the equator. This crop is a highly resistant plant able to survive in fallowed agricultural lands and from low to high rainfall areas, being easily cultivated with little efforts [25,26]. Jatropha oil finds different possible applications in lubricants, illumination, soaps, cosmetics, medicinal uses, biopesticides (phorbol esters) industries [24]. For biodiesel, low-jatropha production costs and possibilities to be grown in different lands can ensure competitiveness for this feedstock [27]. Microalgae are the most primitive form of plants. They have a huge range of genetic diversity and can exist as unicellular plants, colonies or extended filaments. Microalgae grow under the widest possible variety of conditions [28]. These microscopic aquatic plants, carry out the same process and mechanism of photosynthesis as higher plants converting sunlight, water and carbon dioxide into biomass, lipids and oxygen [10,24]. Nevertheless, they have more efficient access to water, CO_2 and other nutrients due to their simpler cellular structure and high specific surface area [12]. A microalgae with high oil productivity is desired for producing biodiesel, depending on the species, microalgae produce different kinds of lipids, hydrocarbons and complex oils [24]. The species of microalgae with higher oil content includes *Chlorella vulgaris*, *Chlorella protothecoides*, *Spirulina maxima*, *Nannochloropsis sp*., *Neochloris oleabundans*, *Scenedesmus obliquus* and *Dunaliella tertiolecta* among others [29].

Waste oil, includes residues from deep frying processes, such as soap stocks, yellow and brown greases, obtained from restaurants, hotels and industries. There are enough waste cooking oils and fats generated in the United States annually, to produce about 18 billion liters of biodiesel [6]. In United States the biodiesel made from waste cooking oil is known as McDiesel, because one large source of this oils is McDonald's restaurants [30]. It has been reported that waste oils still conserve still conserves most of its triglycerides groups, with chemical and physical properties very similar to those of its source oils [31]. The free fatty acid content of waste cooking oils ranges between 10 and 25%, as a result of the frying process where heating in presence of air and light increase the viscosity and specific heat [32]. Waste cooking oils can be used as a fuel, either directly in the engine after filtering or can be transesterified using short-chain alcohol to produce biodiesel and glycerin [33–35]. In biodiesel production process, fats, moisture, proteins, and animal fragments extracted from meats during the frying process are an important component of waste cooking oils affecting the process in terms of additional pretreatment is required [36].

Tallow oil is a rendered from beef fats obtained in slaughterhouses [24]. Human consumption of tallow has a negative effect on health; consequently, these feedstocks are addressed fundamentally to industry. Tallows are used in the manufacture of products such as cosmetics, soaps, shampoo, candles, lubricants, paints, tires, perfumes, textiles, plastics, inks, polishes, cleaners and solvents. Different grades of tallow are produced to meet the varying needs. They are also an important source of fatty acids and glycerol for the chemical industry [37]. However, when its market is overloaded, this oil is incinerated or disposed in landfills [38,39]. Therefore, biodiesel production from these feedstocks has been considered, since they are potential sources for biodiesel due to their high cetane number (typically 56–62), good stability and low price. The drawback of these feedstock is that still requires a pretreatment in order to remove impurities and treat those with high saturated fatty acids content, to avoid yield methyl esters with poor cold temperature properties.

3. Technologies for biodiesel production

As most of chemical processes, the biodiesel production can be generalized as three main sequential stages: Pretreatment, reaction and purification.

3.1. Pretreatment

In this stage, those elements in feedstock oil, which may have an undesired effect over the transformation reactions, are withdrawn. Particles, colloidal mater, pigments, extraction residues and other impurities can be removed using filtration. When water content (>0.06%) and free fatty acid (FFA) content (>4%) are high, a saponification reaction can be induced, generating a gel soap instead of biodiesel [40]. To avoid this it is necessary to dry the oil first, proceeding then to FFA elimination, using: neutralization or pre-esterification of FFA. Esterification as pretreatment method in biodiesel production, can be combined with transesterification to obtain almost a complete conversion to biodiesel [6]. There are two general methods used for esterification: the batch process and the continuous process. Esterification can be performed under batch operation at a temperature of 200–250 °C. As long as, it is an equilibrium reaction, the water must be removed continuously to