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Process and techno-economic analysis of green diesel production from waste vegetable oil and the comparison with ester type biodiesel production

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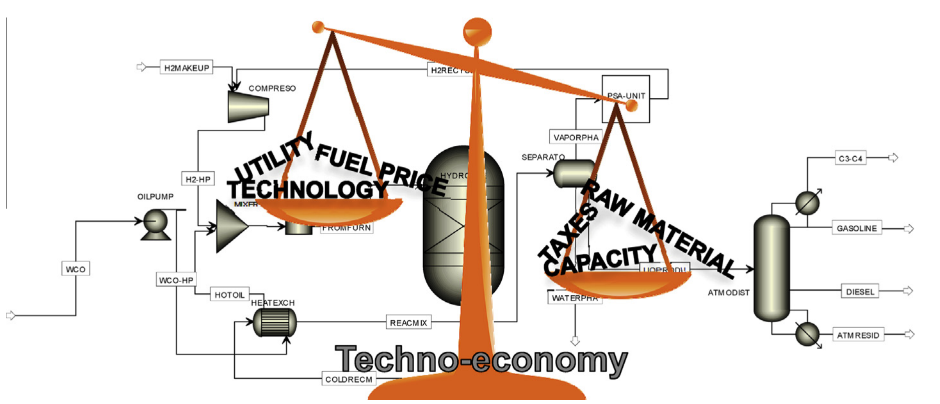
HIGHLIGHTS

- Production of green diesel and biodiesel from WVO are comparatively analysed.
- Hydrogenation process for green diesel is evaluated.
- Biodiesel production by commercial and supercritical technology are examined.
- Typical industrial scale capacities are analysed on process and economic level.
- Economics of these technologies strongly depend on capacity and price of feedstock.

GRAPHICAL ABSTRACT



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ABSTRACT

Like ester type biodiesel fuel, green diesel is a next generation transportation fuel emerging due to the need for a renewable replacement of internal combustion engine fuel, which is also fully compatible with existing automotive powertrain systems. Besides other limitations, the main obstacle for wider application of such renewable fuels is their relatively high production cost, depending mainly on the raw material cost and the application of more efficient processing technology. Green diesel and ester type biodiesel can be produced from waste vegetable oil by catalytic hydrogenation, homogeneous alkali catalysed transesterification and supercritical non-catalytic transesterification. Techno-economic analysis and the sensitivity analysis reveal that economics of these production technologies strongly depend on the process unit capacity and the cost of feedstock. Green diesel production by catalytic hydroprocessing located in a petroleum refinery appears to be the most cost effective option for unit capacity close to and above 200,000 tonnes/year. Conventional ester biodiesel process and non-catalytic ester biodiesel process under supercritical conditions are less profitable at specified capacity. Unit capacities of the investigated processes which are below 100,000 tonnes/year are likely to result in negative net present values after 10 years of project lifetime.

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1. Introduction

The majority of total worldwide energy consumption (around 80%) is resulting from the combustion of fossil fuels with global consumption projected to increase at an average annual rate of 0.9% to 2030, according to International Energy Agency (IEA) [1]. Renewable energy sources were reported to be the fastest growing sector of the world's energy resources, with consumption estimated to increase by 3.0% annually by 2030 [1]. Transportation sector is the world's largest consumer of fossil energy (around 40%) indicating the need to reduce high fossil fuels use in this sector in particular [2–11]. Considerable potential for the use of renewables within transportation sector has been recognised within diesel fuels, fatty acid methyl ester (FAME) biodiesel and hydrogenated vegetable oils or green diesel. These renewable energy sources have high potential being well-matched with existing automotive powertrains [4–10]. FAME biodiesel is a mixture of fatty acid methyl esters while green diesel is a mixture of diesel boiling range hydrocarbons essentially free of aromatic compounds. Green diesel is thus a product that is almost identical to petroleum diesel except for more narrow boiling point range while biodiesel is composed of oxygen containing fatty acid ester molecules that have distinctly different chemical identity than petroleum diesel [4,12–15]. The other differences include higher heating value, higher energy density and an extremely high cetane value of green diesel (values of 80–90 are common due to exclusively paraffinic content).

The increased level of fossil diesel fuel substitution is facing, and will continue to face, various obstacles; the crude oil price and the price volatility being the major ones [16–24]. Other outstanding issues are the impact on food supply, the energy supply security and the relatively high production cost of renewable diesel fuels [16–29]. The experience gathered has shown that the overall cost of biodiesel production needs to be reduced either by the reduction of raw material cost (vegetable oil, animal fat, used cooking oil), by the decrease of utilities consumption (energy) or by the application of more efficient processing technology [30–40]. Relatively high production cost of renewable diesel fuel is dominantly influenced by the feedstock cost (price of rapeseed, sunflower, soybean or other vegetable oil), which makes a significant fraction of the overall biodiesel cost (around 70–80%) [17–29].

The need to decrease the influence of feedstock cost on the production cost of renewable diesel fuels has resulted in the use of waste vegetable oils as lower-cost feedstock [16–18,28,41]. Nevertheless variability in quality: the content of free fatty acid (FFA), the amount of water and impurities, variations in composition and the type of triglycerides, represent the important disadvantages which have a major impact on production technology and production process economy [4,16–18,42]. Besides the waste vegetable oil, the non-edible oils are also highly optional for cheaper biodiesel or green diesel production. The main options within the non-edible oils are Jatropha oil, the lower quality palm oil and canola oil. However, these options would require additional oil extraction procedure which would make the fuel production cost highly sensitive to costs associated with extraction procedure and the solvent cost [30,43,44].

Sustainability of renewable diesel fuel production therefore relies on the technology which is capable of processing feedstock with high FFA content, typically seen in waste vegetable oils. Currently there are two processing options which could readily fulfil this requirement: non-catalytic transesterification under supercritical conditions and catalytic hydroprocessing. Conventional homogeneously catalysed process for FAME biodiesel production can be used to convert waste vegetable oils but limited to oils with relatively low FFA content.

Over the past two decades the green diesel production technology was patented [31–37] and investigated [38–40,45,46,10] by a number of research groups and companies. The process was applied on industrial scale at several locations and is believed to be ideally suited for existing complex petroleum refineries [4–9]. Neste Oil is operating two units with a combined capacity of 170,000 tonnes/year of green diesel in Finland as well as a production in Singapore and Rotterdam with 800,000 tonnes/year capacity [47]. Another green diesel commercial unit, UOP/Eni Ecofining process technology, is to become operational in Italy [48]. The same technology is installed at Diamond Green Diesel facility in Norco, Louisiana, with capacity of more than 130 million gallons/year. Petrobras/H-BIO is reported to be successfully developed as a hydrotreating process for converting vegetable oil into green diesel [49]. Green diesel production is based mainly on hydrodeoxygenation reaction using vegetable oils and animal fats as main reactants to produce n-paraffins in diesel fuel range [4,12–15,50]. Hydroprocessing of triglycerides requires heterogeneous catalyst operating in the stream of hydrogen under moderate to high pressure (2.5–15 MPa) at temperatures between 250 and 500 °C [4,12–15,50], depending on the catalyst, hydrogen to oil ratio and feedstock material [4,12–15,50]. Hydroprocessing reactions take place in a fixed bed reactor, in a three-phase system: the liquid feed trickles down over the solid catalyst in the presence of a hydrogen-rich gas phase [4,12–15,50–52]. For this purpose numerous catalyst have been investigated but common catalysts used in petroleum refineries for hydrotreating processes (removal of sulphur, nitrogen and product quality improvement), such as sulphided Co–Mo or Ni–Mo, are commonly employed and capable of processing various input blends including gas oil–triglycerides mixtures [13,12,14,15,50–52]. Catalytic hydrogenation of triglycerides, beside hydrocarbons as main products, also yield the following by-products: water and gaseous products including methane (CH_4), ethane (C_2H_6), propane (C_3H_8), propylene (C_3H_6), butane (C_4H_{10}), carbon dioxide (CO_2), carbon monoxide (CO), and in some cases hydrogen sulphide (H_2S) in varying degrees, depending on the source feedstock, catalyst and processing conditions. Process conditions are the key parameter and it has been observed that higher temperatures promote the formation of straight and branched chain aliphatic C6-C18 hydrocarbons [4,12–15,50]. Depending on the temperature and pressure conditions the reaction pathway of triglycerides hydrogenation could significantly differ and favour either decarboxylation or hydrodeoxygenation reaction. That can lead to a lower or higher hydrogen consumption, which can have a direct impact on the capital and operational costs due to the reduced size of the hydrogen compressor [4]. Capital and operational costs can be lower in the case of decarboxylation reaction pathway since it is favoured at lower pressures accompanied by lower amount of water being formed by the reaction [4,50].

The ester biodiesel technology based on the transesterification reaction under supercritical conditions has been investigated and developed over the past 20 years. This non-catalytic technology requires high pressure (17–35 MPa) and high temperature (230–350 °C) conditions. The high excess of alcohol reactant (20–42 M ratio of methanol to oil) is also necessary, resulting in a large quantity of alcohol in the recycle loop. When compared to conventional FAME biodiesel technology, alkali or acid catalysed reaction under atmospheric conditions, the supercritical transesterification has environmental benefits regarding wastewater and spent chemicals generation, as well as energy consumption. Along with very high production efficiency this technology has high feedstock flexibility as feedstocks with high FFA contents, like waste vegetable oil, are easily processed. Over the last 10 years several units applying supercritical (and subcritical) transesterification technology were successfully operated on industrial scale by several companies like