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Techno-economic analysis of the thermal liquefaction of sugarcane bagasse in ethanol to produce liquid fuels

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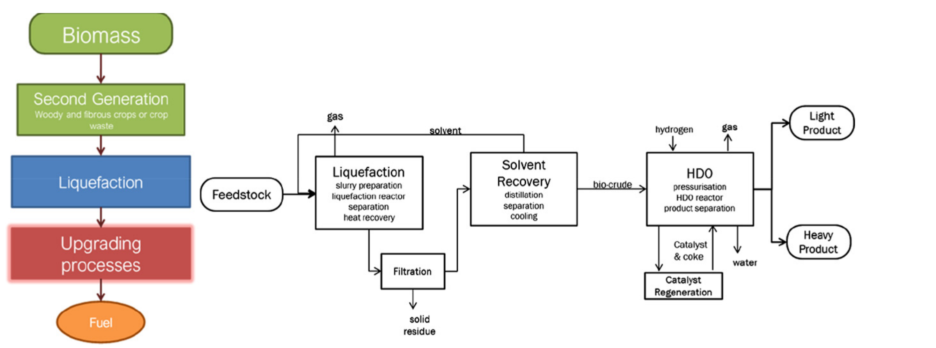
HIGHLIGHTS

- A plant using liquefaction of bagasse in ethanol to produce biofuels is modelled.
- Liquid fuel yield was 46% db for a total of 25.8 million L/y of biofuel product.
- Ethanol process losses contributed largely in operational costs.
- Minimum selling price was determined to be US$ 0.99/L.
- Hydrodeoxygenation conversion efficiency and biocrude yield critically affect production cost.

GRAPHICAL ABSTRACT



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ABSTRACT

A plant converting sugarcane bagasse to liquid fuels through thermal liquefaction in an Australian setting was modelled in ASPEN Plus. Ethanol was investigated as a liquefaction solvent due to its effect of higher yields and higher biocrude heating value compared to water (i.e. hydrothermal liquefaction). The plant produced 0.67 kg biocrude per kg dry feed, which was further processed to 0.46 kg liquid fuels per kg of dry feed for a total of 25.8 million L/y of biofuel product. Ethanol losses incurred the highest share in operating costs, although there are opportunities for cost reduction around lower solvent to biomass ratio. Over the plant life and with a corporate tax rate of 30%, it was determined that the minimum selling price for the fuel products is US$ 0.99/L, which was comparable to other liquefaction studies using water as solvent. It was demonstrated that continuous operation mode was economically more advantageous than semi-batch production. Product price, hydrodeoxygenation conversion efficiency and plant capacity were determined to be the factors to which NPV is most sensitive, while biocrude yield and hydrodeoxygenation conversion efficiency were the key factors in decreasing the minimum selling price of the product to a level that can be competitive.

1. Introduction

The development of biofuel production technologies has been increasingly important as a means of reducing greenhouse gases emissions due to the lower net CO_2 emitted over the fuel's life cycle [1]. Aside from carbon sequestration, biofuels also bring about socio-economic benefits, particularly in developing countries and areas with limited fossil fuel supply [2]. Compared with plant oil-based biodiesel or bioethanol produced from food sugars, technologies that convert non-food feedstock are preferred [3]. This is where thermochemical

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processes are useful since these do not discriminate against the nature of feedstock [4]. More versatile among the range of thermochemical processes is thermal liquefaction, which has been demonstrated to be effective in converting biomass of considerable water content to liquid products. The liquefaction process is carried out at temperatures of 200–370 °C and pressures of 4–40 MPa [5] producing gaseous, liquid and solid products from the decomposition of biochemical polymeric substances in biomass. The product of particular interest is the liquid organic product (i.e. biocrude), which consists of saturated and unsaturated hydrocarbons, and oxygenated and nitrogenated compounds of varying amounts, affected heavily by the composition of the feedstock [6]. The variety in composition and the presence of heteroatoms make biocrude less than satisfactory for direct use in internal combustion engines. Biocrude has higher viscosity and lower heating value, compared to petroleum-based fuels [7]. Therefore, aside from separation of the different liquefaction product streams, further processing of biocrude is necessary to be able to use it as a potential transportation fuel.

In the liquefaction of biomass, the use of a solvent is essential to take advantage of its decreased heat and mass transfer resistances and the improved properties at supercritical regimes [5]. Water is the most common solvent in liquefaction studies, owing to its abundance, low cost and low environmental impact [8]; however its high critical point and boiling temperature (T_c = 374 °C, P_c = 22 MPa, T_b = 100 °C) requires large amounts of energy in liquefaction and subsequent separations. On the other hand, ethanol has a lower critical point and boiling temperature (T_c = 241 °C, P_c = 6.3 MPa, T_b = 78 °C) that facilitates liquefaction and separation of solvent using less energy. Ethanol can also be sourced from renewable bioethanol processes, such as sugar industry-aligned molasses or cellulosic sugar fermentation [9], supporting CO_2 emissions reduction [10]. Moreover, in hydrothermal liquefactions (i.e. using water as solvent), the liquefaction yield is partitioned between water-soluble and water-insoluble fractions. This decreases the amount of water-insoluble, lower-oxygen-content biocrude that can be recovered [11]. From a comparison of water, acetone and ethanol used as solvents in liquefaction it was demonstrated that using ethanol resulted in the highest biocrude yield [12]. Ethanol can also convert organic acids formed intermediately to esters, which can reduce viscosity and increase stability of product oils [13]. Other studies have also tested the use of ethanol and water as co-solvents that have shown a synergistic effect in obtaining a higher biocrude yield and heating value [11,14–16].

Among several methods to upgrade biocrudes, petroleum refining analogues are ubiquitous. Since the expected upgrading product is fuel, it is reasonable to process biocrudes the same way as petroleum crudes. In petroleum refining hydroprocessing units, hydrogenation and heteroatom removal occur simultaneously [17], so while sulphur and nitrogen are removed in petroleum crudes, and oxygen needs to be removed in biocrudes, these units may be appropriate to handle both feeds with modification. Distillation of biocrudes has also been proposed either as an alternative to hydroprocessing [18] or for potential co-processing of biocrudes with petroleum crudes in conventional distillation equipment [19].

In order to facilitate commercialisation of biomass liquefaction technologies, analysis of technical and economic feasibility of processing biomass to produce biofuels is necessary. Biomass hydrothermal liquefaction has now been demonstrated at the pilot scale, as shown in Table 1. Commercial scale modelling will be essential to determine gaps in data and challenges in technical feasibility, feedstock supply, and enable life-cycle analysis, among others. Furthermore, converting product yields, energy and material balances and equipment requirements to cash flows enables a pragmatic analysis of the liquefaction process' position in the energy industry.

Thermal liquefaction is projected to be a significant pathway to generate drop-in fuels. Techno-economic studies of the HTL process have been conducted for virgin and residual wood, and algae liquefied using water as solvent in the USA [26–28] and Finland [29]. Zhu et al. [28] concluded that a woody biomass HTL, upgrading and in-house hydrogen plant modelled in 2007 can produce a gasoline-equivalent fuel that can be sold for at least US$ 1.17/L for the plant to be profitable (i.e. minimum selling price). Using lipid-extracted microalgae, a similar plant but with hydrocracking can be sold for US$ 0.70/L, which is still above gasoline price [27]. A similar plant using whole algae and additionally, hydrothermal gasification to process the aqueous phase of the HTL product resulted in a minimum selling price of US$ 1.19/L [26]. These values were 1.5–2.5 times more expensive than the prevailing wholesale price for gasoline at the time. Only the lipid-extracted microalgae was seen as competitive, although its viability is dependent on a lipid extraction biofuel plant and the profitability of the plant is considered to be only incremental. A more recent study by Magdeldin et al. [29] in Finland using cheaper biomass to produce a gasoline-like fuel through HTL and upgrading, the minimum selling price was US$ 1.95/L. With a hydrogen plant, the price improves to US$ 1.81/L, but with an additional char combined heat and power (CHP) plant the price soars to US$ 2.28/L. An additional water gasification plant to augment hydrogen production lowers the price to US$ 1.20/L and the same plant without the char CHP, the price drops to US$ 0.83/L. These studies in the USA and Finland support conversion of biomass that are specific to their local feedstock supply. Conditions such as natural environment, markets, and government policies that affect biofuel projects also differ from country to country. The development of local economic models can demonstrate the viability of a similar plant for a different feedstock or blend of feedstock, if necessary.

In the Australian setting, Queensland is a prime location for the development of commercial biomass liquefaction plants. This is predicated on the state's Biofutures Roadmap and Action Plan, which is based on its strong agricultural sector and mature transport market [30]. This setting was chosen because it also represents a potential location with favourable policy conditions complementing the availability of different kinds of lignocellulosic feedstock in the region [32]. Among the variety of feedstock suitable for biocrude production, sugarcane bagasse is a sustainable choice due to its abundance and availability as a waste by-product of sugar manufacturing. Up to 35 million t of sugarcane is produced in Australia annually, most of it coming from Queensland, and although the crops are spread over 380,000 ha, the cane is aggregated at sugar mills located along major transport hubs. Following sugar manufacture, 11 million t of sugarcane bagasse are produced [31]. Due to bagasse being produced centrally in sugar mills, collection and transportation costs are minimised [32]. The proposed bagasse liquefaction plant is hinged on the successful demonstration of biocrude production from bagasse using ethanol as solvent in small and large laboratory scale studies [11,15].

In this study, a novel thermal liquefaction plant using bagasse as feedstock and ethanol as solvent was modelled. The feasibility of using a solvent other than water to produce biocrude in liquefaction, and subsequently, fuel products that are similar to gasoline and diesel was explored in this techno-economic study. The key difference from previous models using water as solvent was in obtaining liquefaction products in one biocrude phase, rather than two phases that split the total organic yield. A biofuel plant set in Queensland, Australia was used to represent an agro-industrial area where lignocellulosic biomass is abundant for feedstock [32]. The effect to capital expenditure and operational cost of using ethanol in liquefaction and its recovery for recycle is also of interest since this has not been explored in past studies. ASPEN Plus has been chosen to take advantage of its built-in property estimation tools and ubiquitous utility in modelling solid processing and petroleum processes [33]. The suitability of ASPEN for modelling liquefaction processes has been demonstrated in a number of studies [28,29,34]. The resulting mass and energy balances were then integrated into an economic model and economic indicators were calculated to provide insight to the economic feasibility of the plant. Critical design and operational conditions were identified and their