Techno-economic analysis of guayule (Parthenium argentatum) pyrolysis biorefining: Production of biofuels from guayule bagasse via tail-gas reactive pyrolysis

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ABSTRACT

The tire industry is currently considering natural rubber from guayule (Parthenium argentatum Gray) as a viable alternative to imported Hevea natural rubber, or petroleum-based synthetics, to meet expanding materials needs of the industry. However, only 5–10% of the harvested guayule plant is converted into rubber latex. For economic sustainability, the industry must identify viable uses for the balance residual, termed bagasse. Bioenergy production has been considered, but conversion facilities must be co-located to avoid additional costs in transportation of the bagasse. This study investigated the economics of processing a minimum of 200 metric ton per day (MTPD) of guayule bagasse to produce biofuels in a biorefinery co-located with a guayule latex processing facility. A unique aspect of the simulated process was the use of the tail gas reactive pyrolysis (TGRP) technology that formulates an intermediate bio-oil with less oxygenates and therefore requires only mild upgrading to fuel products. This achieved a yield of 16.2%, distributed in the gasoline (9.7%), jet fuel (5.6%), and diesel (0.9%) carbon ranges. The capital cost was estimated at $58.74 million (MM), and the annual operating cost was estimated at $14.19 MM. A discounted cash flow rate of return (DCFROR) analysis was conducted to evaluate the economic feasibility based on a 30-year plant life and 10% internal rate of return. The minimum fuel selling price (MFSP) calculated was 1.88 $/L for gasoline, 1.84 $/L for jet fuel and 1.91 $/L for diesel fuel, clearly showing the limitations imposed by economies of scale of the current guayule bagasse availability. However, there is a potential to reduce the MFSP by increasing the facility capacity and utilizing the valuable co-products that accompany guayule pyrolysis biorefining. Sensitivity analysis indicates the MFSP of gasoline can be lowered to 0.96 $/L considering the most optimistic scenario, comprising an integrated large facility of 2000 MTPD, lower cost of hydrogen, and the sale of a premium-quality residual guayule biorefinery coke.

1. Introduction

The worldwide annual production of natural rubber (cis 1,4-polyisoprene) is about 12.2 million metric tons (MMT) (IRSG, 2015), with over 90% produced in Asia (UN-FAO, 2013), harvested from the Hevea (Hevea brasiliensis (Willd. ex A. Juss.) Müll. Arg.) rubber tree. Most industrial countries depend on imported natural rubber e.g., the US imports about 1.7 MMT annually (IRSG, 2015). It is foreseeable, therefore, that if an alternative source of domestic natural rubber were made available in temperate climates, it would provide an opportunity to lower the environmental impacts of a major commodity, to support rural economies, and reduce the tire and other rubber utilizing industries’ dependence on non-renewable petroleum sources and rubber imports (Rasutis et al., 2015).

Guayule (Parthenium argentatum Gray) is a hardywood desert shrub native to Mexico and southern Texas that biosynthesizes rubber and has gained considerable interest recently as an alternative natural rubber source. Guayule rubber quality is comparable to Hevea natural rubber with an added advantage of being safer for people with Type I latex allergy compared with Hevea rubber (Cornish et al., 2001; Ray, 1993). To extract the latex from guayule, the whole shrub is harvested and ground prior to the extraction in buffer (Cornish, 1996), with about...
5–10 dry wt% of the biomass resulting in the rubber product. Ongoing breeding efforts target increasing the rubber content to > 10 wt% in the near future. The residual biomass is termed guayule bagasse. Since the acquisition cost of harvested guayule ranges from $100 and $200 per metric ton and only a small amount of this is extractable rubber, the successful development of the guayule-rubber industry will ultimately depend on developing an economic use of the bagasse (Seir et al., 2014). Various research efforts have evaluated utilizing the bagasse for a variety of applications, including bio-energy production (Boateng et al., 2009; Chundawat et al., 2012; Kuester, 1991; Nakayama, 2005). One challenge is the small scale of the present guayule rubber industry, currently estimated at hundreds of MT per day, and the starting point for this analysis. At the current scale producers might struggle to operate profitably before expanding to the required scale for economically sustainable bio refineries. However, in the near term expanded levels of rubber production, up to 1000 metric tons per day (MTPD) bagasse may be available, a modest volume which nevertheless probably requires collocated distributed bio refineries (Bridgestone, 2017).

Guayule bagasse can be rich in terpene resin and also contains small amounts of residual rubber, each with high calorific value. The presence of these hydrocarbon dense components suggest that guayule bagasse has a chemical advantage in the production of higher quality liquid fuels via pyrolysis methods compared with most biomass sources (Boateng et al., 2015; Boateng et al., 2009). This unique characteristic combined with the fact that it is already collected, dried, and size-reduced via the latex extraction process makes guayule bagasse represents an opportunity fuel feedstock for a co-located pyrolysis bio refinery for the production of renewable hydrocarbon fuels.

Pyrolysis is thermal decomposition that occurs in the absence of oxygen. In conventional pyrolysis, biomass decomposes into three products: bio-oil, biochar, and gases (Bridgewater, 2012). The main product, bio-oil, is thermally unstable due to its high oxygen content and acidity (pH ~ 2). This limits the direct use of typical lignocellulosic derived bio-oils as alternative fuel in power and heat generation (Alonso et al., 2010; Boateng et al., 2016; Boateng et al., 2015). Furthermore, they are immiscible with petroleum, making co-processing difficult in existing refinery infrastructures such as fluid catalytic cracking (FCC) (Al-Sabawi et al., 2012). Most bio-oils must be hydrotreated to be potentially introduced as current existing refineries for production of renewable transportation fuels (Alonso et al., 2010; Boateng et al., 2016; Boateng et al., 2015; Thilakaratne et al., 2014). For the reasons stated above as well as the harsh conditions and multiple catalysts required to effectively treat the highly-oxygenated oils, the upgrading of typical pyrolysis oils is a costly process (Zacher et al., 2014). Alternative processes seek to decrease the oxygen content during the incipient pyrolysis process to improve its properties such that it can be more easily handled in the downstream upgrading processes. Production of bio-oils with lower oxygen content can be accomplished by catalytic fast pyrolysis (CFP) over zeolite catalysts or by tail gas reactive pyrolysis (TGRP) (Mullen et al., 2013). The latter has been very successful in achieving low oxygen bio-oil similar to the former but without the added cost or the fouling problems of heterogeneous catalysts. In the TGRP process, part of the gas formed during the reaction is recycled back in the reactor. This recycled gas creates a reactive atmosphere that produces a more stable bio-oil with lower oxygen content and lower viscosity. TGRP also permits the successful processing of feedstocks that are difficult to pyrolyze in conventional pyrolysis such as highly proteinaceous materials and resin-laden guayule (Boateng et al., 2009; Mullen et al., 2015). Boateng et al. (2015) were able to produce hydrocarbon fuels from guayule bagasse by TGRP plus mild upgrading that included simple distillation followed by single-step hydrotreating with a conventional noble metal catalyst. Using this technology, Larkin et al. (2016) have modeled a 200 MTPD plant to measure the sustainability of the process through exergy assessment.

Techno-economic analysis (TEA) is often carried out following process simulation by sizing necessary equipment available for the costing of plant components. Process calculations for pyrolysis flow streams using simulation software like Aspen Plus, Chemcad, and Pro/II have been used to estimate costs for techno-economic analysis and evaluate their economic feasibility (Brown and Brown, 2013; Carrasco et al., 2017; Thilakaratne et al., 2014; Wright et al., 2010). Carrasco et al. (2017) investigated bio-fuel production via pyrolysis of forest residues (hog fuel). The minimum fuel selling price (MFSPP) was determined to be 1.65 $/L. Li et al. (2017) evaluated a 2000 MTPD red oak pyrolysis bio refinery plant with upgrading into drop-in fuels. Their MFSPP was calculated at 0.75 $/L when producing hydrocarbon fuels. One major in the difference in the estimated MFSPP of these two studies is the yield of bio-fuel, with the former estimating a finished fuel yield of ~16 wt% and the latter a yield of ~25%. The difference can be attributed to the quality of the biomass and its effect on bio-oil yield from pyrolysis. Other factors that sensitivity analysis showed to be the largest contributors to MFSPP included feedstock cost, followed by capital cost and catalyst lifetime. It is therefore important to explore economic considerations for the so-called opportunity fuel feedstocks that utilize byproducts of an existing industry that are already collected and pre-sized. This is especially important when the feedstock has high energy content such as guayule bagasse.

This paper presents the results of a techno-economic analysis of a co-located guayule bagasse pyrolysis bio refinery facility as suggested by Boateng et al. (2015). For this evaluation a 200 MTPD TGRP plant was modeled, followed by condensed-phase upgrading processes to produce an array of carbon range hydrocarbons, co-located at a guayule latex processing facility.

2. Methodology

2.1. Process model description

The process model was developed using SimSci Pro/II Software assuming an 10th plant design for a 200 MTPD facility, representing the current availability of the industry. The industry anticipates expansion to 1000 MTPD bagasse availability in the near future so alternative capacities of 1000 MTPD and also a nominal 2000 MTPD were also modeled to compare the economies of scale. The process was modeled after the results from Boateng et al. (2015). In that study, the guayule bagasse enters the TGRP process with 5.69% moisture, HHV of 22 MJ/kg and 5.69% ash. A co-located facility was considered with a guayule latex extraction plant in Arizona, USA. Guayule bagasse (following aqueous process extraction, where only the latex is extracted and most of the resin is therefore associated with the bagasse) is in the size range (2–3 mm), needs no further grinding, and is directly fed to the pyrolysis reactor. Thermodynamic properties were calculated using the Peng-Robinson equation of state employing the default Pro/II property database. Three separate processes were modeled: pyrolysis, atmospheric distillation and hydrodeoxygenation (HDO), and distillation for final separation into fuel products.

2.1.1. Pyrolysis

The pyrolysis system design was modeled after the Combustion Reduction Integrated Pyrolysis System (CRIPS) (Heydenrych et al., 2017) incorporating the TGRP process described by Boateng et al. (2015).

The CRIPS system consists of a dual fluidized bed reactor that integrates the pyrolysis bed (PYREACTOR, Fig. 1A) and combustion bed (COMBREACTOR, Fig. 1B), with the latter providing the needed heat for the endothermic pyrolysis reaction in the former. The biomass (stream 100) is converted in the pyrolysis bed at 500 °C. The nitrogen (stream 101) and recycled non condensable gases (NGG) (stream 111) are the fluidizing agents. At the exit of the pyrolysis reactor, biochar and sand are separated from the vapor phase by a cyclone (CYCLONE1). The combustion bed provides heat to the pyrolysis bed by burning char and some NGG. Sand (stream 117) is the heat carrier between the two
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